Exploring the Data Needs and Sources for Severe Weather Impact Forecasts and Warnings

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Sara Ebony Zylka Harrison

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Abstract

Early warning systems offer an essential, timely, and cost-effective approach for mitigating the impacts of severe weather hazards. Yet, notable historic severe weather events have exposed major communication gaps between warning services and target audiences, resulting in widespread losses. The World Meteorological Organization (WMO) has proposed Impact Forecasts and Warnings (IFW) to address these communication gaps by bringing in knowledge of exposure, vulnerability, and impacts; thus, leading to warnings that may better align with the position, needs, and capabilities of target audiences.

A gap was identified in the literature around implementing IFWs: that of accessing the required knowledge and data around impacts, vulnerability, and exposure. This research aims to address this gap by exploring the data needs of IFWs and identifying existing and potential data sources to support those needs.

Using Grounded Theory (GT), 39 interviews were conducted with users and creators of hazard, impact, vulnerability, and exposure (HIVE) data within and outside of Aotearoa New Zealand. Additionally, three virtual workshops provided triangulation with practitioners. In total, 59 people participated in this research. Resulting qualitative data were analysed using GT coding techniques, memo-writing, and diagramming.

Findings indicate a growing need for gathering and using impact, vulnerability, and exposure data for IFWs. New insight highlights a growing need to model and warn for social and health impacts. Findings further show that plenty of sources for HIVE data are collected for emergency response and other uses with relevant application to IFWs. Partnerships and collaboration lie at the heart of using HIVE data both for IFWs and for disaster risk reduction.

This thesis contributes to the global understanding of how hydrometeorological and emergency management services can implement IFWs, by advancing the discussion around implementing IFWs as per the WMO's guidelines, and around building up disaster risk data in accordance with the Sendai Framework Priorities. An important outcome of this research is the provision of a pathway for stakeholders to identify data sources and partnerships required for implementing a hydrometeorological IFW system.

I hear hurricanes a-blowing
… I fear rivers overflowing
… Hope you got your things together
Hope you are quite prepared …
Lyrics adapted from “Bad Moon Rising,”
written by John C. Fogerty of *Creedence Clearwater Revival*

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"It takes a village to support a PhD student." – unknown

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List of Acronyms and Abbreviations

ACRONYM / ABBREVIATION	FULL TERM
ACC	Accident Compensation Corporation
AR	Action Research
API	Application Programming Interface
BAU	Business As Usual
CAP	Common Alerting Protocol
CDEM	Civil Defence and Emergency Management
CIMS	Coordinated Incident Management System
COP	Common Operating Picture
CRI	Crown Research Institute
DHB	District Health Board
DOC	Department of Conservation
DRR	Disaster Risk Reduction
DSS	Decision Support System
DSR	Design Science Research
EF SCALE	Enhanced-Fujita Scale
EM	Emergency Management
EOC	Emergency Operations Centre
EQC	Earthquake Commission
ES-GT	Evolved-Straussian Grounded Theory
EWS	Early Warning Services
FENZ	Fire and Emergency New Zealand
FEWS	Flood Early Warning System
GIS	Geographical Information System
GIS4EM	Geographical Information System for Emergency Management
GNS SCIENCE	Te Pū Ao Institute of Geological and Nuclear Sciences Limited
GOV.	Government
GT	Grounded Theory
GWE	Global Weather Enterprise
HIVE	Hazard, Impact, Vulnerability, and Exposure
HYD.	Hydrological
HIWEATHER	High Impact Weather
IBFW	Impact-Based Forecasts and Warnings
IDSS	Impact-based Decision Support System
IFRC	International Federation of Red Cross and Red Crescent Societies
IFW	Impact Forecast and Warning
IFWS	Impact Forecasting and Warning System
IS	Information Systems
LGGA	Local Government Geospatial Alliance
LGNZ	Local Government New Zealand
LINZ	Toitū Te Whenua Land Information New Zealand
MBIE	Ministry of Business, Innovation, and Employment
MET.	Meteorological
METOFFICE	United Kingdom Meteorological Office

ACRONYM / ABBREVIATION	FULL TERM
METSERVICE	Meteorological Service of New Zealand Limited – Te Ratonga Tirorangi
MCDEM	Ministry of Civil Defence and Emergency Management
MFE	Ministry for the Environment
MOH	Ministry of Health
MPI	Ministry of Primary Industries
NAT.	National
NEMA	National Emergency Management Agency
NHP	Natural Hazards Partnership
NIWA	National Institute of Water and Atmospheric Research
NMHS	National Meteorological and Hydrological Services
NMS	National Meteorological Services
NWP	Numerical Weather Prediction
NWS	National Weather Service
NZ	Aotearoa New Zealand
NZD	New Zealand Dollars
NZDF	New Zealand Defence Force
NZTA	Waka Kotahi NZ Transport Agency
PACRIS	Pacific Risk Information System
PIMS	Project Information Memoranda
RC	Regional Council
REG.	Regional
RIACT	Real-time Individual Asset Attribute Collection Tool
RNC	Resilience to Nature's Challenges Kia manawaroa – Ngā Ākina o Te Ao Tūroa
STATS NZ	Statistics New Zealand
SOE	State-Owned Enterprise
SWFM	Surface Water Flooding Model
TA	Territorial Authority
TAG	Technical Advisory Group
(EX-)TC	(ex-)Tropical Cyclone
UK	United Kingdom
USA	United States of America
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction (formerly UNISDR)
UNISDR	United Nations International Strategy for Disaster Reduction (now UNDRR)
VGI	Volunteered Geographic Information
VOT	Vehicle OverTurning Model
WMO	World Meteorological Organization
WWRP	World Weather Research Programme

This illustration will be provided at the beginning of each chapter to position the reader in the thesis.

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter One: **Introduction**

The World Meteorological Organization (WMO) recommends that Impact Forecasts and Warnings (IFWs) are implemented to reduce the impacts from hydrometeorological hazards (WMO, 2015). Yet there is a lack of knowledge about where the supporting data are and how they can be connected (e.g., Potter et al., 2021). This thesis sets out to resolve this. This chapter sets the scene for this doctoral thesis by introducing the research problem. The chapter begins with a review of the researcher's role (Section 1.1) and the significance of the research in the context of hydrometeorological hazards and their impacts on society (Section 1.2), including the role of hydrometeorological warnings and the need for Impact Forecasting and Warning (IFW) systems (see a list of acronyms and abbreviations on page xiii). The research problem and aims are introduced in Section 1.3, along with the research question and objectives. A thesis outline is provided in Section 1.4, and a summary concludes this chapter in Section 1.5.

1.1 My Role as Researcher

My interest in studying severe weather and hydrometeorological hazards came from my experiences with severe weather as I grew up in Midhurst, Ontario, Canada. Midhurst is a small village outside of the City of Barrie, situated in central Ontario between the Great Lakes. This location sets Midhurst and Barrie up for a wide range of active weather in all four seasons. In the winter months, Midhurst falls in the 'snowbelt', where the lake-effect results in heavy snowfall on the leeward side of the Great Lakes (Goldfinger, 2020). Midhurst can receive heavy snowfall from the lake-effect snow coming off Lake Huron and Georgian Bay, accumulating 10-25cm of snow in one event (Current Results, 2021). During my childhood, these snowfall events resulted in many 'snow-days', where school buses were cancelled due to hazardous road conditions and schools were closed due to extremely cold temperatures.

During the summer months, Midhurst and the surrounding area experiences many moderate to severe thunderstorms including tornadoes, dubbing Southern and Central Ontario the 'Tornado Alley' of Canada (Harrison et al., 2015). In 1985, before I was born, an F5[1] tornado struck the City of Barrie, damaging much of the downtown core, and unfortunately killing 16 people. During my childhood, many of my outdoor soccer games were cancelled due to lightning and the occasional tornado watch or warning. In one instance, a tornado warning was issued for my area when a funnel cloud was observed, and I sheltered with my parents, sisters, and pets in our basement. Fortunately, no tornado resulted from that storm. Recently, an EF2 tornado struck the southern end of Barrie on 15 July 2021, damaging several homes and resulting in minor injuries. Almost every summer a tornado threat presents itself

[1] The Fujita Scale (represented by the letter F) was used to classify tornado intensity based on damage prior to use of the Enhanced Fujita (EF) Scale, which phased out the Fujita Scale in Canada in 2013 (Government of Canada, 2018).

around the Barrie and Midhurst area, which led me to fear strong gusts of wind (so it is a good thing I chose to move to Wellington, New Zealand, for my PhD!).

My experiences with these severe weather hazards sparked a desire to study and understand them. When it came time to decide on a university program, I chose to pursue a bachelor's degree in Geography for the opportunity to study natural hazards. For my honour's thesis, I investigated the process of conducting post-storm damage surveys following potentially tornadic events in Canada to understand the strengths and barriers of the damage surveys (Harrison et al., 2015). I did this by interviewing officials from Environment Canada (the National Meteorological Service of Canada) and wind engineers who conduct these damage surveys. Towards the end of my thesis, a tornado struck the town of Angus, Ontario, just 20 km away from Barrie; I was invited by my interviewees to accompany them on the damage survey to observe their process. One key challenge identified in my honours thesis research was difficulty accessing damaged sites, collecting the data from remote locations, and collecting it quickly enough before clean-up-efforts began (Harrison et al., 2015). This led me to question how crowdsourcing and social media could potentially fill this data gap.

I then pursued my master's degree in Geography to explore the opportunities and challenges of using social media and crowdsourcing tools in the Canadian emergency management context. I interviewed emergency management officials across Canada to understand the role of social media and crowdsourcing in emergency management (Harrison & Johnson, 2016), and to identify the challenges of and barriers to using it (Harrison & Johnson, 2019). This research concluded with some practical suggestions for emergency management officials to ease their adoption of social media and crowdsourcing.

Upon completing my master's degree, I remained curious about severe weather and its impacts on society, how severe weather risks are communicated, and how social media and crowdsourcing have been used to aid response efforts in large-scale disasters like Hurricane Sandy in 2012, Hurricane Harvey 2017, and the Fort McMurray wildfire in 2017. I decided to pursue my PhD on the initial topic of exploring how social media and crowdsourcing can be used to collect impact data to inform Impact Forecasts and Warnings (IFW) for severe weather hazards in New Zealand. This is a type of warning recommended by the WMO with the aim of increasing understanding of the potential impacts of hydrometeorological hazards (see Sections 1.2.2 and 2.2).

After exploring the literature and conducting preliminary interviews with meteorologists, emergency managers, and other stakeholders both within and outside of New Zealand, I began to realise that social media, crowdsourcing, and impact data are one small part of the larger picture of the kind of data that we need for IFW systems and how to access it. I decided to shift the focus of my PhD topic from investigating social media and crowdsourcing for collecting impact data, to exploring the overall data needs of IFWs and how we can access this data. As I found out from talking to my participants, the data exists in many formats, it is just not stored in such a way that it can be easily accessed and used. This sparked my new, and final research question that I aimed to answer in this doctoral thesis (discussed further in Section 1.3):

> Which data are needed to support Impact Forecasting and Warning (IFW) systems for hydrometeorological hazards, and how are they currently collected, stored, and shared in New Zealand?

To begin answering this question, we first need to know why we want to implement IFWs. This justification will be summarised in the following sections, with further elaboration provided in Chapter Two.

Before we begin this journey, I would like to acknowledge New Zealand's response to the COVID-19 pandemic. In the last 18 months, I, and 'the team of 5 million', have witnessed the importance of communicating clear, understandable, relevant, and relatable information to the public to incite the desired responses. This is done, in part, by focusing on the impact on New Zealanders' daily lives, being empathetic, and providing clear and easy steps to protect each other (Hunt, 2021). There is much to be learned from this communication approach, which can inform communication of other risks and hazards, such as hydrometeorological hazards.

1.2 Severe Weather and Society

Weather influences everyday life, from deciding how to dress and how to commute to planning weekend activities. Severe weather conditions can also produce hazards that present a risk to people, property, and infrastructure. When these hazards present themselves, people are faced with more serious decisions to protect life and property.

Hydrometeorological hazards continue to cause significant impacts to society worldwide. A hydrometeorological event becomes a disaster when the hazard affects the lives, wealth, or livelihoods of people such that community functions are disrupted to the point where external help and support are needed for recovery (UNDRR, 2016).

Meteorological phenomena that have caused the above impacts include extreme temperatures such as cold waves, heat waves, and extreme winter conditions; and storms, such as tropical cyclones, convective storms, and extra-tropical cyclones (UNDRR, 2021a). These storm events produce further hazards including lightning and thunderstorms, tornadoes, winter storms/blizzards, hail, severe storms, derechos (wind storms), heavy rainfall, sand/dust storms, and storm surge (UNDRR, 2021a). Meteorological phenomena can also produce hydrological hazards, consisting of floods (e.g., flash floods, riverine floods, and coast floods), and landslides (debris flow, avalanche, mudslide, rockfall, and subsidence) (UNDRR, 2021a). Wildfires and droughts are additional meteorological/climatological hazards that continue to impact society (UNDRR, 2021a; WMO, 2021).

From 2000 to 2021, hydrometeorological hazards have affected over 24.9 million people and resulted in over 9.1 million deaths, and 33.2 million injuries (UNDRR, 2021a). Furthermore, these events have caused over 15.8 trillion USD in damages globally (UNDRR, 2021a). These impacts are attributed to the interaction of the hydrometeorological phenomenon with the underlying exposure and vulnerabilities of people, properties, and infrastructure (WMO, 2021). Hazards and disasters caused by this interaction have been well documented (e.g., Ching et al., 2015; Wagenmaker et al., 2011).

Prevention and mitigation of hydrometeorological-induced impacts, and thus disasters, may be achieved by reducing the hazard (e.g., reducing emissions to improve air quality by reducing NOx and O_3 (smog)/PM_{10} particulates), reducing the exposure of the people and assets (e.g., land-use planning and/or evacuations), and/or reducing vulnerability (e.g., strengthening infrastructure; Golding et al., 2019). These actions require extensive knowledge of hazards, vulnerability, and exposure to inform policy decisions (Golding et al., 2019).

As well as policy changes for long-term mitigation, better systems are needed to improve immediate safety decisions for life and property. Such systems need to not only adequately inform individuals of the hazard, but also of the likely impact(s) and consequence(s), such that they can make appropriate decisions (WMO, 2015). Early Warning Systems (EWSs) are used worldwide to monitor, forecast, assess, and communicate hazard and risk information to enable individuals, communities, governments, businesses, and other stakeholders to take timely action to reduce the risks of disaster (UNDRR, 2021b). However, EWSs for hydrometeorological hazards continue to face critical challenges around the world, resulting in devastating impacts.

1.2.1 Severe Weather Warning System Challenges

Notable historic high-impact weather events exposed major communication gaps between meteorologists, warning services, and target audiences, resulting in widespread losses (Basher, 2006; Ching et al., 2015; WMO, 2015; Zhang et al., 2021). This communication gap is a result of both technical failings and human behaviour (Wagenmaker et al., 2011). Research has shown that meteorologists and warning services do not typically consider the warning audiences' current state of vulnerability and exposure at the time of the warning or at the expected time of impact (WMO, 2015). For example, a recent tragedy occurred on 22 May 2021 in Baiyin, Gansu Province, China where 21 ultramarathon race runners died due to exposure to high winds combined with low temperatures and precipitation (Zhang et al., 2021). The forecasts for this weather phenomenon were timely and accurate, yet the race continued (Zhang et al., 2021). Zhang et al. (2021) argued that while this weather phenomenon would not normally have been a high-impact weather event, the vulnerability of runners in shorts and vests to the low temperatures resulted in unfortunate deaths, making this a high-impact event. Thus, there is a need for warning systems to consider the current exposure and vulnerability of people at the time and location of the hazard, and to translate the hazard-based warning into an impact warning such that appropriate decisions can be made around protective actions (Zhang et al., 2021).

Furthermore, some warning recipients may fail to understand and respond to the warnings effectively due to ambiguous terminology (Ching et al., 2015), lack of trust in the warning system and service provider (Taylor et al., 2018), and warning fatigue (Mackie, 2013). As such, EWSs have continued to evolve in attempts to reduce the effects of these factors. The examples listed in Table 1.1 exemplify some of these factors such as warning fatigue (e.g., the Joplin tornado) and poor terminology and understanding (e.g., Typhoon Haiyan and the Uttarakhand floods).

Table 1.1. Summary of notable, historic events in which some members of the public failed to understand and respond to warnings.

Event	Warnings	Impacts	Causes	Recommendations
Joplin Missouri EF-5 Tornado USA May 2011	Issued by National Weather Services in days and minutes lead-up.	159 deaths, over 1,000 injuries.	Warnings and sirens lacked sense of urgency; residents desensitised to tornado warnings in 'Tornado Alley' (e.g. warning fatigue) (Wagenmaker et al., 2011).	Tornado warnings include simplified and localised information to convey the severity of the storm (Wagenmaker et al., 2011).
Tropical Cyclone Haiyan (Yolanda) Category 5 Philippines November 2013	Issued by Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) Heavy rain and wind warnings during peak rush hour.	6,201 deaths, 28,626 injuries, 1,785 missing people, Storm surge the leading cause of death.	88% of warning recipients did not understand message about 'storm surge'; 95% of warning recipients did not evacuate because they did not expect the storm to be so catastrophic (Ching et al., 2015).	"Warning messages … should be conveyed in terms understood by the population at risk" (Ching et al., 2015, p. 34).
Tropical Cyclone Fitow China October 2013	Issued by China Meteorological Administration/Shanghai Meteorological Service to over 18 million people during peak rush hour.	97 roads and 900 communities were flooded, 1 death, 1.2 million people directly affected.	Public perception was that the warnings were too late; many people were in the middle of their morning commute on the first day back to school and work after a national holiday (WMO, 2015).	Meteorologists need to consider vulnerability and exposure of population at risk when issuing warnings (WMO, 2015).
Uttarakhand Floods India June 2013	Floods were accurately forecasted, and warnings issued by the Indian Meteorological Department.	5,700 deaths, over 900,000 people affected.	Majority of deaths were tourists on a pilgrimage; the wording in the warning messages was ambiguous, did not communicate the impacts of "very heavy rain" (WMO, 2015).	Meteorologists need to consider vulnerability and exposure of population at risk when issuing warnings, and convey the expected impacts in clear and understandable terms (WMO, 2015).

These examples demonstrate the communication gap that exists between meteorologists and other agencies that distribute warnings, and the public. While great advances have been made in improving the timing and accuracy of high impact weather warnings, these efforts are fruitless unless the target audiences understand the warnings and understand how best to respond or prepare (Paton & Johnston, 2006). It is argued that Impact Forecasting and Warning (IFW) Systems may help reduce the effects of these factors, and thus increase warning compliance (e.g., Morss et al., 2018; Otto et al., 2017; Potter et al., 2018; Weyrich et al., 2018).

1.2.2 Impact Forecasting and Warning Systems

Impact Forecasting and Warning (IFW) systems play a key role in resilience to hydrometeorological hazards (Rogers & Tsirkunov, 2013). Identifying the specific social, economic, and environmental impacts of a hazard allows communities to adjust their plans and actions to better adapt to, and cope with, the outcomes of the hazard (WMO, 2015). Rather than preparing for a hazard with no specific knowledge of how they could be affected, people can plan for impacts that are specific to their situation.

A key challenge with implementing IFWs is the lack of supporting data. IFW systems require more than hazard information as they introduce the human element to the warnings (Potter et al., 2021). Impact, vulnerability, and exposure knowledge are also needed to convey the risk accurately and effectively to warning audiences (Poolman, 2014; Sai et al., 2018). Table 1.2 provides the definitions of hazard, impact, vulnerability, and exposure data that are used for this thesis, while Chapter 6 provides further explanation and examples of these four data types. Meteorologists and forecasters have indicated that they do not possess knowledge of impacts, exposure, or vulnerability to effectively incorporate accurate impact information within their messages to suit all warning recipients (Potter et al., 2021).

Table 1.2. The four types of data needed for IFWs.

Hazard	A hazard is "a hydrometeorological-based, geophysical or human-induced element that poses a level of threat to life, property or the environment", such as rainfall, snowfall, high winds, tornado, hail, flood (WMO, 2015, p. 4). In weather forecasting, likelihood is usually combined with hazard (WMO, 2015).
Impact	Impacts are the negative outcomes of an event (Casteel, 2016), and are defined as "a loss of life and injuries, damage to the environment, infrastructure, and private property, often followed by secondary effects like psychological trauma, or disruption of workflow and traffic" (Kox, Lüder, et al., 2018, p. 116). Direct and indirect impacts may be a function of vulnerability and exposure to the hazard (WMO, 2015). Impact data refers to observed post-event impacts and outputs and results from risk/impact models.
Vulnerability	Vulnerability is "the susceptibility of exposed elements, such as human beings and their livelihoods and property, to suffer adverse effects when affected by a hazard" (WMO, 2015, p. 6). Predispositions, sensitivities, fragilities, weaknesses, deficiencies, or lack of capacities that favour adverse effects on exposed elements can increase vulnerability (WMO, 2015). Vulnerability may also be time- and space-dependent.
Exposure	Exposure refers to people, infrastructure, housing, and other tangible human assets that may be affected in an area where hazards may occur (WMO, 2015). Exposure is time- and space-dependent, and it is possible to be exposed to a hazard but not vulnerable.

Beyond IFWs, there is a growing need for effectively collecting and documenting hazard, impact, vulnerability, and exposure data to build more understanding of people's and other assets' risk to natural hazards (i.e., risk assessment) for Disaster Risk Reduction (DRR). This was identified as a priority of the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015b). More details on the Sendai Framework are presented in Chapter Two, Section 2.3. In Aotearoa New

Zealand (NZ), Crawford et al. (2018) found that Civil Defence and Emergency Management (CDEM) agencies and city, district, and regional councils in NZ were not clear on who was responsible for collecting disaster risk-related data, such as impact, vulnerability, and exposure, and thus lacked the data needed for model-based risk assessments.

1.3 Research Problem and Aims

IFW systems are the focus of this study as the World Meteorological Organization (WMO) has encouraged and pushed for National Meteorological and Hydrological Services (NMHSs) to implement IFW systems. A key challenge to implementing an IFW system is the lack of knowledge and data around impact, vulnerability, and exposure from the perspective of the NMHSs (Potter et al., 2021). Knowledge of impacts, vulnerability, and exposure would inform the crafting of more effective warning messages, as called for in the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015b) and the WMO Guidelines (WMO, 2015).

This research aims to support the implementation of an IFW system in Aotearoa New Zealand (NZ) by first exploring the data needs of IFWs and then identifying existing and potential data sources and the processes for collecting, creating, accessing, and using these data (i.e., hazard, impact, vulnerability, and exposure data). This study is based in NZ to support the country's efforts towards improving warnings for hydrometeorological hazards and implementing an IFW system as a member-nation of the WMO. More of the NZ context is provided in Section 2.4.1. The NZ-focus provides a case analysis for international discussions and learnings around IFW system implementation.

This dissertation is written under the 'PhD thesis with publications' format in the Massey University Guidelines (Massey University, n.d.). This study aims to build an understanding of the data gaps and needs for implementing IFWs in a New Zealand context, and to offer avenues for accessing the required data to support IFW implementation.

This doctoral research thus seeks to answer the following research question:

> Which data are needed to support Impact Forecasting and Warning (IFW) systems for hydrometeorological hazards, and how are they currently collected, stored, and shared in New Zealand?

This research question was broken down into five sub-questions and associated objectives in Table 1.3. These research questions and objectives are each addressed by a manuscript or chapter of this thesis. Each manuscript is presented as a thesis chapter. Table 1.3 illustrates the alignment of each manuscript or chapter to the research questions and objectives. Each manuscript can stand alone as an independent research article intended for publication. Due to this format, there will be some level of repetition of ideas, particularly in the introduction and research method sections of the manuscripts.

Table 1.3. Chapter and research alignment.

Research Questions	Objectives	Chapter
1. What are the current and potential uses of Volunteered Geographic Information (VGI) for severe weather warnings?	1.1 To establish VGI as a potential source of impact data for IFWs.	Chapter Five
2. What are the data uses and gaps for impact forecasts and warnings?	2.1 Identify the actors involved in an IFW system and their associated roles. 2.2 Determine how hazard, impact, vulnerability and exposure (HIVE) data are used in an IFW system. 2.3 Identify further data gaps/needs for implementing IFWs.	Chapter Six
3. What are the sources for HIVE data?	3.1 Identify the creators, collectors, and users of HIVE data that is relevant to severe weather IFWs. 3.2 Identify the inhibitors of and facilitators to collecting and using HIVE data to support the implementation of an IFW system in New Zealand for severe weather hazards.	Chapter Seven
4. How can HIVE data governance, access, and sharing be improved for hydrometeorological hazards in New Zealand?	4.1 Identify and understand the governance and access and sharing processes of HIVE data for severe weather hazards in New Zealand. 4.2 To support efforts to fulfil the Sendai Framework priorities around disaster data access. 4.3 To support the implementation of a severe weather IFW system.	Chapter Eight
5. How can partnerships and collaboration better facilitate the collection, creation, and access to HIVE data for IFWs?	5.1 To identify the required partnerships and collaborations required for IFW systems. 5.2 To identify existing partnerships and collaboration in NZ that can support IFW systems. 5.3 To outline a path forward for nurturing partnerships and collaboration for IFW systems.	Chapter Nine

1.4 Thesis Outline

This thesis consists of ten chapters. Several of the chapters have been submitted as journal articles and are formatted as such in this thesis (see Appendix A for Statements of Contribution for each manuscript). In addition, this thesis contains an introductory chapter, a background and context chapter, a research design chapter, a methods results and overarching findings chapter, and finally a discussion and conclusion chapter.

Chapter One introduces the role of the researcher, and the research problem and justification. The intersection of weather and society is provided to 'set the scene' for the rest of this doctoral thesis.

Chapter Two provides a background on EWSs and IFW systems and the associated data needs for IFWs. Further background of the NZ hydrometeorological hazardscape, hydrometeorological warning system, and emergency management sector is provided for context.

Chapter Three presents the research design, which covers the overarching research philosophy and chosen methods used for primary data collection and analysis.

Chapter Four presents the initial results from the data collection methods, and overarching findings from the Grounded Theory analysis, where the key themes and phenomena of this doctoral study are identified.

Chapter Five, the first paper (i.e., journal article), presents a literature review to explore the role of Volunteered Geographic Information (VGI) for EWSs.

Chapter Six, the second paper, investigates the data uses and gaps for IFWs to determine how hazard, impact, vulnerability, and exposure (HIVE) data are used in an IFW system, and to identify gaps in the data that need to be addressed in order to effectively implement an IFW system.

Chapter Seven, the third paper, identifies existing and potential sources of HIVE data in New Zealand that can support IFW systems. Inhibitors and facilitators to collecting these data are also discussed.

Chapter Eight, the fourth paper, delves into issues of data governance and access for HIVE data and identifies opportunities for improving data governance and acquisition.

Chapter Nine integrates the results of each manuscript together around the core category that was identified in the Grounded Theory analysis.

Chapter Ten concludes the thesis by returning to the research questions and objectives of the research and identifying the significance, impacts, limitations of this doctoral research, and areas for future research.

1.5 Chapter Summary

This chapter outlined the research problem and the structure of this doctoral thesis research. It began by introducing the role of the researcher in this study, motivations for the broader body of work, and the research background. From there, the research problem describing the need for Impact Forecasts and Warnings and their supporting data was outlined. The research question was presented, along with objectives for answering the research question. The outline of the thesis was then presented with a summary of each chapter.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Two: **Background and Context**

This chapter provides an overview of severe weather EWSs (Section 2.1), including key concepts of warning thresholds and the inherent uncertainty of forecasting and warning for weather hazards. IFW Systems are then presented in Section 2.2 as a suggested approach by the WMO to address the aforementioned challenges of traditional severe weather EWSs. Section 2.3 provides an overview of the Sendai Framework and its relevance to this doctoral research. This chapter then provides contextual background on the NZ hydrometeorological hazardscape (Section 2.4.1), severe weather warning system (Section 2.4.2), flood warning system (Section 2.4.3), and Emergency Management (EM) sector (Section 2.4.4). The chapter concludes by bringing together the literature gap that this research aims to fill within the NZ context.

2.1 Early Warning Systems

There has been a paradigm shift in Disaster Risk Reduction (DRR) in the last two decades from reactive post-disaster response and recovery to proactive preparedness and mitigation. A key component of better preparedness lies in EWSs (UNDRR, 2015a). Starting in the late 1990s EWSs became the focus of international attention, generating international conferences and experts' symposia, and documents such as the United Nations Global EWS Survey Report (2006), and the World Disaster Report (2009) (Golnaraghi, 2012). In response to this apparent paradigm shift, the second priority of the Hyogo Framework for Action 2005-2015 was made to "identify, assess, and monitor disaster risks and enhance early warning" (UNISDR, 2005, p. 7). EWSs have continued to be a priority for the Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015b).

EWSs have four key operational components: disaster risk knowledge; detection, monitoring, and warning services; communication and dissemination, and response capacity (Figure 2.1) (Basher, 2006). These components are further explained in the literature review within Chapter Five (published as Harrison et al., 2020).

It has been argued that poor linkages between these components have been major causes for EWS failures resulting in disasters (Garcia & Fearnley, 2012). As such, linking these four components into an integrated EWS is critical for their effective performance (Garcia & Fearnley, 2012). Doing so requires coordination and collaboration across agencies and governance levels that have relevant information about the hazards and impacts that threaten people and assets (Garcia & Fearnley, 2012; Golnaraghi, 2012). Such collaborative approaches allow for effective communication networks to be established for integrating research into practice (Garcia & Fearnley, 2012). This can enable the development of effective decision-making processes that include local contexts and define roles and responsibilities (Garcia & Fearnley, 2012).

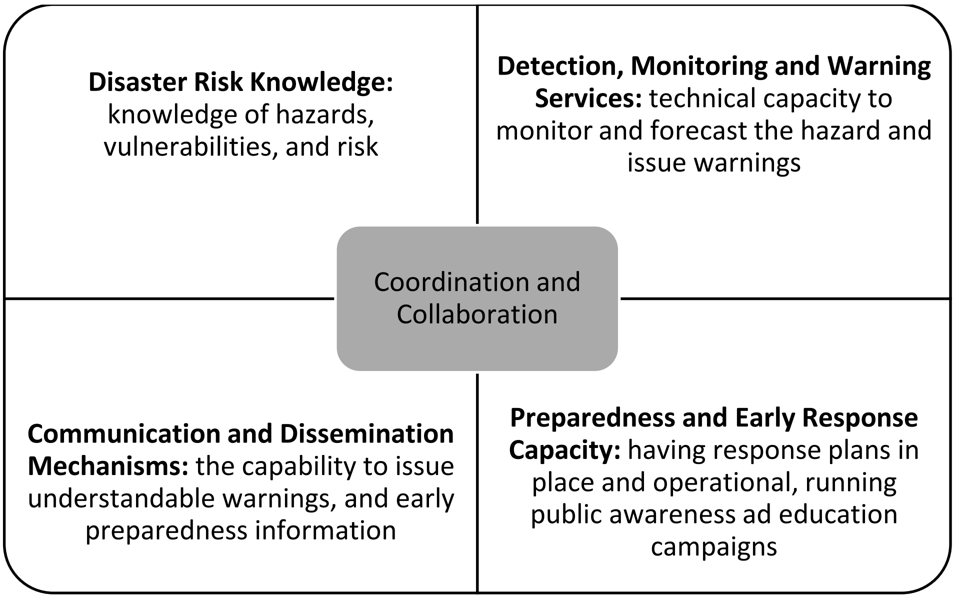


Figure 2.1. Four operational components of an Early Warning System(Harrison et al., 2020 adapted from Basher, 2006; Golnaraghi, 2012; WMO, 2018).

2.1.1 Severe Weather Early Warning Systems

In the context of EWSs for hydrometeorological hazards, National Meteorological and Hydrological Services (NMHSs) are often responsible for monitoring, detecting, and forecasting the hazards (WMO, 2015). In many countries, hydrological services and meteorological services are provided by separate national or regional agencies (Golnaraghi, 2012). Simultaneously, Emergency Management (EM) agencies, or Civil Defence and Emergency Management (CDEM) Groups in NZ, are typically responsible for managing risks and emergency preparedness and response by conducting risk assessments and building mitigation, preparedness and response plans, etc. (Golnaraghi, 2012; WMO, 2015). These agencies and other sector-specific agencies, often monitor and document the impacts of hazards across sectors, such as health, agriculture, infrastructure, water resource management, and transportation (Golnaraghi, 2012).

Golding et al. (2019) outlined the Warning Value Chain concept for representing the information flow amongst actors in the warning chain for designing and operating hydrometeorological warnings. This Warning Value Chain provides a conceptual basis for understanding the flow of information from detection through to warning delivery. The Warning Value Chain consists of six components: (1) Observation, Monitoring, and Detection; (2) Weather Forecasting; (3) Hazard Forecasting; (4) Impact Forecasting; (5) Warning; and (6) Decision/Action. These components are summarised in Table 2.1, and a more detailed description and analysis of the Warning Value Chain is provided in Chapter Six (Harrison et al., 2022).

Table 2.1. Summary of Warning Value Chain components based on the literature review provided in (Harrison et al., 2022).

Warning Value Chain Component	Description
Observation, Monitoring, and Detection	Meteorological and hydrological services routinely monitor and observe atmospheric, meteorological, and hydrological conditions using specialised tools and collect regular observational data. Satellite and radar imagery, weather stations, and rivers gauges are some examples of monitoring and observational tools.
Weather Forecasting	Meteorological services issue frequent weather forecasts of varying time ranges by running Numerical Weather Prediction (NWP) models. Probabilistic forecasts have become the new standard and allow for longer lead times.
Hazard Forecasting	Hazard forecasting occurs when meteorologists and forecasters identify the potential for hazards based on observed and forecasted atmospheric, meteorological, and hydrological conditions. Floods and flash floods, storm surge, droughts, wildfires, snowfall, ice, extreme temperatures, and damaging winds are examples of weather-induced hazards.
Impact Forecasting	Impact forecasting involves identifying the impacts of the hazard, often by combining the hazard forecast with underlying vulnerability and exposure of people and assets.
Warning	Warnings are the end-product of a warning system. Warnings are intended to deliver information about the oncoming hazard such that warning audiences can prepare themselves.
Decision/Action	Recipients of warnings face many decisions with regards to preparing and taking protective action. A warning is considered successful when it is timely, accurate, and incites the appropriate protective actions by warning audiences.

Warning thresholds determine the sensitivity of an EWS and are used to assign warning levels for various hazards (Feinberg, 2009; Stepek et al., 2012). Thresholds are typically pre-defined (Cools et al., 2012), based on ‘trigger points,’ ‘critical amounts,’ or a set of ‘criterion’ by which a given hazard may occur (Frugis & Wasula, 2011; Tiranti & Rabuffetti, 2010). For example, thresholds for landslide warnings can be based on “critical rainfall amounts” (p. 472) that trigger landslides for certain soil types and slopes (Tiranti & Rabuffetti, 2010).

The sensitivity of an EWS can affect its performance (Feinberg, 2009). Thresholds that are too sensitive may result in over-warning while thresholds that are not sensitive enough may result in under-warning (Feinberg, 2009). The consequences of the imbalanced sensitivity can result in false alarms and warning fatigue, or inaction due to a lack of warnings (see Section 2.1.2 for more). Thus, defining warning thresholds, and the sensitivity of the EWS requires finding the right balance between scientific methods of forecasting and assigning thresholds, and the needs of the audiences for which the EWS is designed (Gaztelumendi et al., 2012).

Severe weather warning thresholds are typically based on the physical characteristics of the hazard(s) (WMO, 2015), such as 'x' amount of rainfall over 'y' amount of time. Thresholds can be defined by experiences of damage resulting from hazards of a measured severity (Frugis & Wasula, 2011; Stepek et al., 2012), and through modelling by incorporating multiple physical factors contributing to the hazard trigger point (e.g., Tiranti & Rabuffetti, 2010). National meteorological services (NMSs) typically define the warning thresholds (WMO, 2015), and may also seek consultation with other warning stakeholders to calibrate the thresholds/sensitivity (Frugis & Wasula, 2011). For example, the USA National Weather Service changed the criterion for severe hail based on empirical research and feedback from EM agencies (Frugis & Wasula, 2011).

The likelihood or probability of a hazard occurring at a certain place and time also factors into threshold definition (Gaztelumendi et al., 2012; Tiranti & Rabuffetti, 2010), and in how the forecasts and warnings are communicated (WMO, 2015). Thresholds can also be based on the risk of impact according to the underlying vulnerability and exposure of the people and infrastructure at the place and time of the expected hazard (Gaztelumendi et al., 2012; Potter et al., 2014). This approach is becoming more important with the advent of IFWs (further explained in Section 2.2). The level of uncertainty in a hazard occurring, its severity, and how that uncertainty is communicated to warning audiences, can further affect the warning performance.

Forecasting the weather is prone to uncertainty. Uncertainty in weather forecasts and warnings is introduced from the outset due to the chaotic nature of the atmosphere (National Research Council, 2006). Uncertainty increases when attempts are made to predict or forecast the extreme conditions of the atmospheric system that produce hydrometeorological hazards (Golding et al., 2019). Furthermore, uncertainty is higher in forecasts with longer lead times, and decreases respectively with lead time (Hirschberg et al., 2011). To complicate things further, smaller-scale events such as localised thunderstorms, tornadoes, and flash floods are more difficult to forecast than larger systems such as tropical cyclones due to the spatial resolution of the forecasting models (National Research Council, 2006).

Advancements in technology have allowed meteorologists and forecasters to greatly reduce and quantify uncertainty in their forecast and warning products (Golding et al., 2019). The meteorological forecasting field has shifted from deterministic forecasting to probabilistic forecasting, using ensemble prediction systems (GFDRR, 2016; WMO, 2015). Deterministic forecasts produce just one estimate or outcome of a forecasted phenomenon, while probabilistic forecasts produce a probability distribution of the forecasted hazard from across a range of potential futures (Chen & Yu, 2007). Ensemble prediction systems are one method of supporting probabilistic forecasts by producing multiple modelled outcomes which then provide relevant probability statements (Chen & Yu, 2007). As higher resolution ensemble NWPs become increasingly available, meteorologists can access the 'best available' probabilistic weather prediction guidance (GFDRR, 2016). With probabilistic forecasting, warnings can be issued earlier based upon low probabilities that can increase or decrease as confidence increases (Mason & Senkbeil, 2015; Neal et al., 2014; Rogers & Tsirkunov, 2013).

While probabilistic forecasts are considered an effective tool in uncertain situations, challenges and limitations exist in communicating them. It has been suggested that disaster risk and emergency managers still prefer deterministic information to inform their decisions (WMO, 2017). Kox et al. (2015) found that emergency services tended to exclude low-probability forecasts from their decision-making. However, other work has shown that probabilistic forecasts have improved the decision-making for warning issuance. For example, Pak et al. (2007) concluded that the provision of probabilistic forecasts resulted in participants issuing wind advisories when the probability of strong winds was high, whereas, before the participants received the probabilistic information, they tended to issue too many advisories with low probabilities, and too few advisories with high probabilities. Similarly, LeClerc and Joslyn (2015) suggest, based on their findings, that adding probabilistic uncertainty estimates in forecasts can improve both compliance and decision quality.

This highlights the importance of improving the communication of likelihood, forecasts, or warning messages in uncertain contexts such that the information can be used effectively (Losee et al., 2017). When uncertainty is communicated in a way that is "compatible with both the decision task and cognitive processes of the user" (p. 308), uncertainty information can improve warning recipients' trust and expectations (Joslyn & LeClerc, 2013).

2.1.2 Early Warning Systems Performance

As highlighted in Chapter One, the performance of hydrometeorological EWSs is influenced by factors such as warning fatigue, cry-wolf syndrome, and perceived trustworthiness. Until recently, warning fatigue was dismissed by disaster researchers as a myth (Mileti, 1999; Mileti & Sorensen, 1990), whilst emergency management practitioners perceived it as a "very real problem" (Mackie, 2014, p. 1). Mackie (2014) argued that trust in warnings and warning services, helplessness, false alarms, over-warning, and scepticism in combination can affect warning fatigue of slow-onset bushfire hazards. While Mackie's research is specific to Australian slow-onset bushfire hazards, evidence shows that cry-wolf syndrome and warning fatigue may delay or prevent appropriate response actions to warnings for other events, such as tornadoes (Khan et al., 2017; Ripberger, Silva, Jenkins-Smith, Carlson, et al., 2015). This was found to be a contributing factor in inadequate responses to warnings in the case of the 2011 Joplin tornado described in Table 1.1. Thus, it was suggested that tornado warnings should include simplified and localised information to convey the severity of the storm (Wagenmaker et al., 2011).

Risk communication literature often brings up the concept of trust and how to build trust with the warning audiences (Losee & Joslyn, 2018; Poortinga & Pidgeon, 2003; Sheppard et al., 2012). The broad literature body on trust in DRR, risk communication, and warnings highlights factors that influence trust, which then influences risk perceptions and protective behaviours (Losee & Joslyn, 2018; Poortinga & Pidgeon, 2003). The level of trust is influenced by false alarms and over warning, lack of dialogue between the warning services and the warning recipients, and inconsistent messages and terminology (Losee & Joslyn, 2018; Ripberger, Silva, Jenkins-Smith, Carlson, et al., 2015).

Another contributing factor to the communication gap of EWSs is the terminology used in warning messages and difficulty understanding that terminology. A key factor to an effective EWS is providing warnings in clear, concise, easy-to-understand language (International Network for Multi-Hazard Early Warning Systems, 2017). Paton and Johnston (2006) and Garcia and Fearnley (2012) argue that target audiences must be able to understand the warnings and prepare accordingly, or else the EWS is futile. The cases of Typhoon Haiyan (Yolanda) and the floods in Uttarakhand, India as shown in Table 1.1 highlight the lack of understanding amongst warning recipients of the terminology used in the warnings. In the case of Typhoon Haiyan, a post-event assessment determined that the people in areas at high risk of storm surge hazards who received the warnings did not understand the terminology of the warning, namely the term 'storm surge' (Ching et al., 2015). Supporting literature indicates that many people living in areas where tropical cyclones frequently occur are not aware of, or do not fully understand the risk of storm surge (Morss et al., 2018; Morss, Demuth, et al., 2016; Morss, Mulder, et al., 2016). This may be due to misunderstanding the terminology, as found by Ching et al. (2015), and/or the forecasters and warning services may be unaware of the lack of understanding of technical hazard-related terms. IFWs have been suggested to improve these communication challenges.

2.2 Impact Forecasts and Warning Systems

In the hydrometeorological hazards space, IFW systems are an advancement of traditional EWSs that use thresholds based on physical characteristics of the hazards (i.e., hazard-based thresholds) such as the Saffir-Simpson Hurricane Scale used in the USA to categorise tropical systems based on windspeeds. This scale was designed to predict the expected intensity of wind damage to structures but falls short in accounting for other tropical storm hazards, such as storm surge and impacts (Kantha, 2006).

By nature, these hazard-based warning systems overlook the dynamic exposure and vulnerability of warning recipients (WMO, 2015) such as the low elevation of a coastal area and the capacities of coastal residents to evacuate, as observed in the landfall of Hurricane Katrina (Eisenman et al., 2007). The IFW system was suggested by the WMO to bring in knowledge and understanding of exposure, vulnerability, and historic impacts and build new warning thresholds that better align with the position, needs, and capabilities of target audiences.

The terminology of IFWs varies across the literature. In 2015, the WMO published *"Guidelines on Multi-Hazard Impact-Based Forecast and Warning Services"* (see WMO, 2015) that provided definitions of 'impact warnings', 'impact-based warnings', exposure, vulnerability, and risk. Additionally, Kaltenberger et al. (2020) proposed 'impact-oriented warnings' to refer to warnings that contain impact information and clear protective action advice. The four types of warnings (hazard-based, impact-oriented, impact-based, and impact warning) are summarised in Table 2.2.

Table 2.2. Definitions and examples of hazard-based warnings, impact-oriented warnings, impact-based warnings, and impact warnings (Chapter Six; Harrison et al., Under Review).

Warning Type	Definition	Example	Data Considered
Hazard-based warning	These are traditional warnings, with thresholds based on the physical characteristics of the hazard (WMO, 2015).	"Bora winds are expected tonight with wind speeds of 20 metres per second" (WMO, 2015, p. 6).	Hazard only
Impact-oriented warning	These warnings are independent from the criteria of a warning, which may be hazard-based or impact-based and contain information on impacts and clear protective action advice (Kaltenberger et al., 2020).	"Power and phone distribution networks may be disrupted for relatively long periods. Roofs and chimneys can be damaged…" (Météo-France via Kaltenberger et al., 2020, p. 30).	Any
Impact-based warning	These warnings include hazard and vulnerability and are "designed to express the expected impacts as a result of the weather" (WMO, 2015, p. 6).	"Bora winds are expected tonight which may result in delays or cancellation to ferry services" (WMO, 2015, p. 6).	Hazard and vulnerability
Impact warning	These warnings include hazard, vulnerability, and exposure, and are designed to provide detailed messages down to the individual, activity, or community level (WMO, 2015).	"Ferry services for the island of Brač will most likely be cancelled tonight due to Bora winds" (WMO, 2015, p. 6).	Hazard, vulnerability, and exposure

'Impact-oriented warnings', 'impact-based warnings' and 'impact warnings' broadly differ from traditional hazard-based warnings by communicating what the hazard(s) will do, in addition to what they will be (WMO, 2015). Traditionally, warnings have relied solely on weather-based factors (e.g. wind speeds of a minimum velocity, snowfall of a minimum depth), but IFWs also consider the timing and location of the hazards to identify vulnerable populations and infrastructure (WMO, 2015).

Amongst the three types of impact warnings, 'impact-oriented warnings' may still be based on hazard thresholds as with hazard-based warnings, but include a tangible and understandable description of an expected damage scenario (i.e., impact information) and clear advice on what to do (i.e., instructions/advisories) (Kaltenberger et al., 2020). Thus, impact-oriented warnings are independent of the production process (i.e., the warning thresholds or criteria) used to issue warnings, which may be hazard-based or impact-based. As such, the term impact-oriented warnings may encapsulate impact-based and impact warnings. Impact-based warnings and impact warnings differ based on the production process used to issue them.

For 'impact-based warnings', vulnerability is added to the formula to provide slightly more specific impact information (WMO, 2015). Impact-based warnings are triggered by the likely impacts and their severity from a hazard, and describe the likely impacts based on hazard and vulnerability information (WMO, 2015). 'Impact warnings' are more detailed, and communicate impacts on the individual, activity, or community level (Potter et al., 2018; WMO, 2015). Impact warnings require information on local exposure, which is more difficult to obtain (WMO, 2015).

The goal of the WMO Guidelines is to evolve severe weather warning services into the final 'Impact Forecasting and Warning' form, where vulnerability and exposure are integrated into the thresholds. Herein, I refer to the warning system for which this thesis is intended to support as an IFW system to align with the objectives of the WMO. I use the term 'impact-oriented warnings' to refer to other warnings when it is unclear whether they are impact-based warnings or impact warnings.

2.2.1 Impact Forecasting and Warning System Decision-Making and Communication Processes and Tools

An IFW system requires several streams of information and data to be considered in the decision-making process, beyond hydrometeorological data. Managing all of these data streams that often come from different sources, and formulating effective and efficient decisions, is a key challenge with implementing IFWs (Harrison et al., 2014; Kox & Lüder, 2021). As such, several tools and processes have been discussed in the literature for their potential to support this decision-making process within an IFW system. These tools and processes can broadly be categorised into subjective and objective approaches (WMO, 2015).

Subjective approaches to decision-making typically involve discussions with partners and stakeholders and tools to support those discussions (WMO, 2015). A risk matrix is an example of a tool that can support the decision-making for determining the level of an impact warning. It is a visual tool for estimating risk by combining likelihood and level of impact or severity of the hazard (Hofmann & Schüttrumpf, 2019; Neal et al., 2014). This approach allows for early expressions of likely impacts to be communicated consistently, and for the expressions to progress based on changing expectations of risk (Neal et al., 2014). For example, in the days leading up to an event, the likely impacts are not as well known (i.e., the exact location and timing are uncertain). Thus, early expressions may communicate lower impacts and likelihood (i.e., green or yellow), and as confidence in the likelihood increases as the event nears, the messages can be changed to match the more certain impacts and likelihood (Neal et al., 2014).

Risk matrices have some shortcomings that can limit their effectiveness. Their low resolution (i.e., the small number of colours and rating levels) can result in assigning identical risk ratings to different risks (Cox, 2008, p. 506). For example, a low impact-medium likelihood event may be assigned the same level of risk as a medium impact-low likelihood event using the risk matrix presented by Neal et al. (2014). This can potentially lead audiences to take inadequate protective actions against medium impacts or take overly protective actions against low impacts. Furthermore, the risk matrix is usually built on predefined impact thresholds resulting from a hazard (Neal et al., 2014; Sai et al., 2018), and thus does not include dynamic exposure and vulnerability and may not apply to all audiences (WMO, 2015). It is important to account for dynamic exposure and vulnerability and to design the matrices to suit various audiences to convey the level of risk more accurately. For example, different parts of a country might have different impact thresholds to the same hazard due to underlying vulnerability and exposure (Neal et al., 2014). It is important to consider these underlying conditions and ensure that the risk matrix reflects these different thresholds. Discussions with partners and stakeholders can inform the design of risk matrices and the overall design of an IFW system, to account for these variances in exposure, vulnerability, and warning audiences (WMO, 2015).

As previously described in Section 2.1, interagency communication is critical for integrated EWSs and decision-making in disaster response (Doyle & Paton, 2017; Garcia & Fearnley, 2012; Golnaraghi, 2012). Agencies involved in disaster response require both access to scientific data and a sufficient understanding of these data for rapid decision-making (Paton et al., 1999). Inter-agency networks have proven to fulfil this need (Paton et al., 1999). For example, during the 2012 Tongariro volcanic eruption crisis in NZ, interagency communication was essential for supporting a coordinated response to, and communication process of, the associated hazards and impacts (Leonard et al., 2014). Furthermore, the event revealed a critical communication gap between the health sector and the response and science sectors and provided an opportunity to bridge this gap (Leonard et al., 2014). Learning from events such as this indicate that interagency communication and collaboration supported through developing partnerships are key for hydrometeorological IFW systems such that knowledge of impacts, vulnerability, and exposure can be shared across agencies to inform the warning thresholds, warning messages, and responses (Hemingway & Gunawan, 2018; Kox, Kempf, et al., 2018).

Examples of agencies that possess the information and knowledge needed for IFWs and thus needed to build partnerships and collaborations for IFWs were consolidated from the literature and are summarised in Table 2.3. As mentioned earlier, when meteorologists create forecasts and warnings, they may not possess knowledge of the vulnerable or exposed populations and infrastructure (Hemingway & Gunawan, 2018; Kox, Kempf, et al., 2018). However, insurance/re-insurance companies often systematically collect this information, and EM agencies often conduct hazard and risk assessments to identify areas at risk or exposed to different hazards (Crawford et al., 2018). Working with local communities and economic sectors can help identify the appropriate impact thresholds for the various populations and locations (Neal et al., 2014; Sai et al., 2018). Governments and NGOs can also assist in conducting vulnerability and exposure assessments, as well as identify potential impacts and adequate mitigation actions (GFDRR, 2016). Scientific institutions can help develop and improve observation, forecasting, and modelling tools and processes, as well as share appropriate data sources/datasets (Leonard et al., 2014).

Table 2.3. Examples of sectors and agencies needed for building partnerships to develop IFW systems. Created by the author based on the presented literature review.

Stakeholders	Information/data sharing
Meteorological, Hydrological, and/or hydrometeorological services	Meteorological and hydrological hazard forecasts and observations
Governments, EM agencies (agencies from all levels that are directly responsible for the safety and security of populations)	Evaluate vulnerabilities, identify potential impacts and proper mitigation actions, share expertise
Scientific institutions	Improving and developing technical processes/equipment (e.g., modelling), sharing data sources/datasets, share expertise
Local communities	Identify thresholds, vulnerability, and exposure
Economic sectors (Agriculture, energy, health, transportation, natural resources, tourism, etc.)	Identify thresholds, vulnerability, and exposure
Insurance/Re-insurance	Vulnerability of physical infrastructure
Media	Identify potential impacts, communicate information to and from public
Non-governmental organisations (NGOs)	Vulnerability and exposure assessments, mitigation actions

Quantitative approaches to assessing risk and supporting decision-making for IFWs are also available. Risk modelling is an example of a quantitative tool for assessing risk and associated impacts with hazard intensity. Risk modelling uses fragility functions and vulnerability curves to associate hazard intensity with levels of damage and losses (Martins & Silva, 2020; Schmidt et al., 2011). Fragility curves and vulnerability functions combine hazard intensity with vulnerability (determined by the characteristics of assets such as buildings, road networks, vehicles, etc.) to determine degrees of damage or impact indicators (Martins & Silva, 2020; Schmidt et al., 2011). RiskScape is an example of software under development in NZ to support multi-hazard risk modelling, that is, the

> quantitative estimation of the spatial distributions of potential losses for an area … multiple … natural hazards, multiple … event probabilities … , multiple … human assets, and multiple potential loss components (for each of the assets, e.g. buildings, streets, people, etc.) (Schmidt et al., 2011, p. 1170).

RiskScape operates on a modular framework, where inputs are exchangeable under three modules: the hazard module, the asset module, and the vulnerability module (Schmidt et al., 2011). The hazard module consists of hazard specifications such as hazard type, the hazard model (such as a hydraulic inundation model), and hazard exposures (such as flood inundation depth and velocity), typically in the form of a geospatial layer (Schmidt et al., 2011).

Inputs for the asset module consist of asset types such as buildings, trees, people; asset attributes such as building height, demographics; and asset attribute types (Schmidt et al., 2011). These are all contained in one asset dataset, which can also be geospatial (Schmidt et al., 2011).

The vulnerability module uses a fragility curve or vulnerability function to relate the hazard exposure from the hazard module and the asset data to the resulting potential damage (Schmidt et al., 2011). The output of a model like RiskScape is the quantification of affected assets and losses, which can be provided in tabular and/or geospatial forms for visualisation (Deligne et al., 2017; Schmidt et al., 2011).

Visualisations aid the communication of hydrometeorological warnings, including IFWs. Apart from risk modelling, maps can also be created to convey exposure and vulnerability. Exposure maps are created by overlaying spatial asset layers (e.g., building footprints) with hazard layers (e.g., flood inundation levels), as was done by Bell et al. (2016) and Paulik et al. (2020) to map exposure to floods and sea level rise in NZ. Vulnerability maps can also be created using frameworks to develop social vulnerability indicators using demographic data (e.g., Census population data; Mason et al., 2021). These indicators can then be visualised on maps for further context and planning, as was done by Mason et al. (2021) for Porirua City in New Zealand.

Maps are also the preferred visualisation method using colours to represent warning levels over defined geographic areas (GFDRR, 2016). Amongst others, the UK MetOffice; MeteoAlarm in Europe (Neal et al., 2014); Meteo Shanghai and the Meteorological Administration of Guangdong Province in China; the Philippine Atmospheric, Geophysical and Astronomical Services Administration in the Philippines (Otto et al., 2017); and Instant Weather in Ontario, Canada use this approach to communicate IFWs on maps. These maps can easily communicate impacts to the public, as well as sector-specific impacts to stakeholders (GFDRR, 2016; WMO, 2015)..

2.2.2 Evaluation of Impact Forecasts and Warnings

Warning evaluation has a large body of research that has ultimately led the suggestions for communicating hazards *and* their impacts, as demonstrated by the Joplin Tornado and Typhoon Haiyan examples previously presented in Table 1.1. Since the introduction of IFW systems in the past decade, much of the research has thus focused on evaluating and assessing the performance, effectiveness of, and public response and perceptions to the new warning messages.

Research shows that the public may deem impact-oriented warnings or their sources as less credible. In the USA, Perreault and colleagues (2014) found that 'scary messages' were perceived as less credible than traditional warnings. Similarly, Morss, Demuth, et al. (2016) found that their participants felt that extreme impact messages were 'overblown' and thus rated the source as less reliable. In New Zealand, Potter et al. (2018) found no significant difference in the perceived credibility of impact-oriented warning messages and phenomenon-based messages. The impact-oriented messages increased recipients' understanding of the impacts but did not increase intention to take protective action. In Europe, survey results indicate that the perceived credibility of impact-based warnings that included prescribed behavioural responses or protective actions was higher than that of either impact-based warnings on their own, or simple hazard-based warnings (Weyrich et al., 2018). In a post-event survey following Storm Doris in the UK during which impact-based warnings were issued by the MetOffice, results showed that trust and perceived trustworthiness in the forecasts and warnings increased as the understandability of the warning message increased (Taylor et al., 2019). Findings from most of these studies suggest that when formulating impact-oriented warnings, the language used to communicate the impacts must be carefully considered to ensure accurate understanding of the message and incite desired action, and to avoid or prevent undesired action from being taken by warning audiences. Including protective action guidance in the message in understandable terms can improve warning perception and understanding as well as intended behavioural responses (Weyrich et al., 2018).

Assessments of public response to and perceptions of impact-oriented warnings showed mixed results, and the IFW system seems to work better for some hazards than for others. An overview of these results is presented in the literature review of Chapter Six.

2.2.3 Benefits and Challenges of Implementing Impact Forecasting and Warning Systems

Implementing IFW systems can be costly and difficult, as they require a system overhaul starting with warning thresholds and changing or adding roles and responsibilities (Potter et al., 2021). Existing research around the perceived benefits and challenges of IFWs from the operational perspective is summarised next.

Forecasters and practitioners in Europe perceive the following added value to introducing an impact-focus for communicating hydrometeorological hazards, for building situation awareness, and for planning mitigation and response efforts (Kox, Kempf, Lüder, Hagedorn, & Gerhold, 2018; Kox, Lüder, et al., 2018; Terti et al., 2019). In Germany, emergency managers (EMs), responders, forecasters, and infrastructure managers indicated that receiving IFWs would allow them to better prepare for and adapt to severe weather hazards (Kox, Kempf, et al., 2018; Kox, Lüder, et al., 2018). Furthermore, in a role-playing game study with researchers and practitioners involved in weather communication in Finland and France, Terti et al. (2019) reported that the participants found the additional impact-based information helpful for building situation awareness and thus increased their confidence in decision-making (Terti et al., 2019). However, Terti et al. (2019) further noted that in-game, practitioners appeared to use the impact-based information less than traditional hydrometeorological data. Terti et al. (2019) speculated that this was due to unfamiliarity with the new information, limited understanding of how to use the new impact information, lack of trust in the new developments, and incapability of the new visualisations to convey useful information.

Verification is a standard practice that allows for warning services to measure the quality of their warnings for future improvement. The verification process of traditional hazard-based warnings typically involves measuring the timeliness (e.g., lead time) and accuracy (e.g., hits, misses, false alarms) of the forecast or warning (Wilson & Giles, 2013). These measurements are typically based on observations and reports (or lack thereof) of the physical hazard that was forecasted or warned for. With the advent of IFW systems, there is now a need to verify how well the forecasted or warned event related to the impacts felt on the ground (Robbins & Titley, 2018). As such, forecasters must now develop new verification methodologies to account for the observed impacts in addition to the observed hazard (Robbins & Titley, 2018). This has introduced new challenges. For example, Hemingway and Robbins (2019) questioned how to verify forecasted impacts when impacts stop happening as a result of IFWs. In a NZ-based study involving meteorologists and hydrologists, the participants echoed this concern around verifying warnings and suggested verifying warnings using "dynamic, predetermined hazard-based criteria, even if no impacts occur" (Potter et al., 2021, p. 310).

IFW systems require more than hydrometeorological information. Forecasters and warning services need additional information around historic and potential impacts, and current vulnerability and exposure (Kox, Lüder, et al., 2018; Obermeier & Anderson, 2014; Potter et al., 2021). In developing an impact-based warning system for typhoon gales for the Chinese Meteorological Agency, Wei et al. (2018) noted that accessing sufficient information on hazards, exposure, and vulnerability, and sharing information across disciplines are major challenges to current and future application. Similarly, in developing an impact-forecasting model for vehicles overturning due to high winds in the UK, Hemingway and Robbins (2019) questioned how sufficient and appropriate impact data could be collected. Potter et al. (2021) confirmed these concerns amongst a global sample of meteorological service officials, in addition to NZ-based meteorologists and hydrologists. The findings of Potter et al. (2021) further support the need for collecting and storing impact-related data for hydrometeorological events and point to the need for research into identifying sources of this data.

Researchers and practitioners have indicated the need for more understanding around the decision-making process behind issuing IFWs, and selecting the appropriate warning thresholds for the appropriate audiences (Harrison et al., 2014; Obermeier & Anderson, 2014). This decision-making process requires input from various stakeholders with knowledge from their specialised areas (Harrison et al., 2014; Kox, Kempf, et al., 2018; Potter et al., 2021). For example, forecasters' expertise in weather and atmospheric systems remains foundational to the system (Obermeier & Anderson, 2014), yet linking this information to impacts requires integrating the knowledge and experience of local EM practitioners and responders with the forecasters' expertise (Kox, Kempf, et al., 2018). Furthermore, community involvement and local knowledge of past impacts can help determine impact thresholds for various groups (Kox, Kempf, et al., 2018; Sai et al., 2018).

2.2.4 Crowdsourcing, Social Media, and Volunteered Geographic Information

Crowdsourcing is a potential approach to accessing data for IFW systems. Crowdsourcing has been used by some NMHSs to detect weather hazards and to monitor them (Harrison & Johnson, 2016; Krennert, Kaltenberger, et al., 2018; Krennert, Pistotnik, et al., 2018). The WMO has recognised the need to explore the use of crowdsourcing for severe weather, and researchers in the weather warning space have alluded to its potential for collecting impact-related data (Henriksen et al., 2018; Kox, Kempf, et al., 2018; Marchezini et al., 2018; WMO, 2017).

Crowdsourcing refers to "volunteer-generated decentralised information" contributed online, or by telephone and mail (Harrison & Johnson, 2016, p. 17). Social media, that is, online blogs, micro-blogs, online social networking, and forums that allow sharing of text, audio, photographs, and videos (Alexander, 2014), enables both active and passive crowdsourcing and facilitates multidirectional communication amongst various actors and stakeholders (Alexander, 2014; Harrison & Johnson, 2016; Hong et al., 2018). Active crowdsourcing refers to people proactively contributing to a call for information or tasks through a specialised platform (Loukis &

Charalabidis, 2015). Alternatively, passive crowdsourcing refers to the collection of volunteer-generated information without an active call for contributions; the users may be unaware that they are contributing (Harrison & Johnson, 2016; Loukis & Charalabidis, 2015). Social media platforms are the most accessible resources for passive crowdsourcing from which the information generated by users is harvested by an entity (Loukis & Charalabidis, 2015).

The WMO identified crowdsourcing techniques as an area in which expertise and knowledge is needed for IFW systems (WMO, 2015). In support of this, Krennert, Kaltenberger, et al. (2018) and Krennert, Pistotnik, et al. (2018) surveyed European NMHSs to understand the current state of crowdsourcing practices for severe weather in Europe. Findings showed that nearly all European NMHSs have used crowdsourcing in some way, for updating severe weather warnings in real-time, for verification, and for establishing a climatology of severe weather events (Krennert, Pistotnik, et al., 2018).

Crowdsourcing and social media have the potential to become modern tools for supporting the Sendai Framework objective of making EWSs more people-centred (UNDRR, 2015b). Meissen and Fuchs-Kittowski (2014a, 2014b) developed a conceptual framework which demonstrated that crowdsourced data can theoretically be fully integrated into an existing EWS for severe weather and flood hazards as another dataset to augment or enhance the existing data collection methods. This could be taken a step further by incorporating observed impacts in the data and augmenting warnings with that impact data (Meissen & Fuchs-Kittowski, 2014a, 2014b). Furthermore, Marchezini et al. (2018) completed a literature review to determine the elements involved in bridging crowdsourcing with EWSs and found that more research is needed to examine how crowdsourcing can be mainstreamed in EWSs.

Some agencies have started collecting crowdsourced or social media data for event detection, and some of these agencies also keep track of the impacts recorded. The British Geological Survey began collecting landslide impact data from Twitter and uses text description, photos, and video footage of the resulting impacts (Pennington et al., 2015). This data is integrated into the National Landslide Database and is used to create a Hazard Impact Model as part of the UK's Natural Hazards Partnership (Pennington et al., 2015). In Canada, the National Meteorological Service (NMS) detects weather events such as tornadoes on Twitter and verifies and updates current weather watches and warnings based on verified Twitter posts (Harrison & Johnson, 2016). This is done by using reports posted on Twitter from one location to alert populations further down the storm track to the severe weather that is heading their way (Harrison & Johnson, 2016). These reports are also used to evaluate the service's performance (Harrison & Johnson, 2016).

Volunteered Geographic Information (VGI) offers potential as a collaborative process for collecting vulnerability and exposure data and for creating impact-based thresholds (Fdez-Arroyabe et al., 2018; Harrison et al., 2020; Lavers & Charlesworth, 2018; Sharma et al., 2016). Broadly, VGI is crowdsourced geographic information, or information contributed by volunteers with geographic information associated with it (Harrison et al., 2020). In Australia, Haworth et al. (2018) found that VGI offers a contextual, social aspect of DRR for bushfire hazards. VGI brings members of the public into the DRR process and offers the opportunity for them to share their knowledge about community assets, exposure, vulnerability, impacts, and even 'safer' places for evacuation or sheltering in their local areas (Haworth et al., 2012).

These virtues of VGI make it a sound model for crowdsourcing impact-related data for IFWs as it has the potential to collect the required data whilst also supporting the shift to people-centred EWSs (Marchezini et al., 2018). It is important to collect and create geographically referenced data because disasters are inherently location- and time-dependent: if humans did not reside close to a natural hazard at the time of occurrence, there would be no disaster. Furthermore, visually displaying the impact information for IFWs on maps requires geographic information, thus it is beneficial to begin with collecting geographic information.

A literature review paper was published in the *Australasian Journal of Disaster and Trauma Studies* (Harrison et al., 2020) as part of this PhD study, investigating the role of VGI in severe weather mitigation and preparedness. This is presented in Chapter Five.

2.3 Sendai Framework for Disaster Risk Reduction

The Sendai Framework is built upon decades of international efforts for disaster risk reduction, starting in the 1990s when the UN set-up the International Decade for Natural Disaster Reduction to promote international collaboration towards reducing the effects of disasters (UN Secretary General, 1989). At the end of this decade, the Hyogo Framework for Action 2005-2015 was adopted at the World Conference on Disaster Reduction to further strengthen international cooperation for DRR (UNISDR, 2005). The Sendai Framework for Disaster Risk Reduction 2015-2030 (herein referred to as the Sendai Framework) is the successor of the Hyogo Framework and was developed based on learnings from the Hyogo Framework (UNDRR, 2015b).

The Sendai Framework for Disaster Risk Reduction 2015-2030 is an international agreement between the Member States of the United Nations (UN) to achieve

> the substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries (UNDRR, 2015b, p. 12).

The Sendai Framework is the result of stakeholder consultations and intergovernmental negotiations supported by the UN Office for Disaster Risk Reduction (UNDRR) as requested by the UN General Assembly (UNDRR, 2015b).

The Sendai Framework provides the Member States with measurable actions to achieve the intended outcome cited above. These actions are grouped into four priority areas: (1) Understanding disaster risk; (2) Strengthening disaster risk governance to manage disaster risk; (3) Investing in disaster risk reduction for resilience; and (4) Enhancing disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation, and reconstruction (UNDRR, 2015b). The priorities most relevant to this doctoral research are (1) and (4). This section will focus on these two priorities and their relevance to this research.

The first priority of the Sendai Framework stipulates the need for policies and practices for disaster risk management to be based on understanding all dimensions of disaster risk, including vulnerability, capacity, exposure, hazard characteristics, and the environment (UNDRR, 2015b). This knowledge can be used for risk assessments, prevention and mitigation, and for developing and implementing appropriate preparedness and effective disaster response (UNDRR, 2015b). Actions listed to fulfil this priority centre around collecting, analysing, managing, using, and sharing relevant data, including hazard, impacts/loss, vulnerability, and exposure data (UNDRR, 2015b).

The fourth priority of the Sendai Framework recognises the need for further strengthening of disaster preparedness, taking anticipatory action for events, and integrating DRR with response and preparedness (UNDRR, 2015b). This involves, in part, "investing in, developing, maintaining and strengthening people-centred multi-hazard, multi-sectoral forecasting and Early Warning Systems" (UNDRR, 2015b, p. 21), which are tailored to the needs of the users. IFWs contribute to both of these priorities based on addressing warning audiences' needs for relevant, clear, understandable, and actionable information, and on the basis that IFWs require and make use of the data identified in the Sendai Framework for understanding risk (Harrowsmith et al., 2020).

The Sendai Framework recognises that the State has the primary role for reducing disaster risk and further suggests that responsibilities should be shared with local government, the private sector, and other stakeholders (UNDRR, 2015b). As a Member State, New Zealand is responsible for implementing the Sendai Framework, working towards the priorities and targets, and reporting its progress to the UNDRR (see UNDRR, 2020). To fulfil these tasks, the NZ Government, through the National Emergency Management Agency (NEMA), developed the National Disaster Resilience Strategy 2019 (herein referred to as the Resilience Strategy) (NEMA, 2019). The priorities and activities of the Sendai Framework are mirrored in the Resilience Strategy, particularly for understanding and managing risk, and continuing to increase the availability of and access to multi-hazard EWSs (NEMA, 2019). However, following the nation's 2019 Sendai Framework reporting, key challenges and needs were identified that require more work and attention (UNDRR, 2020). These challenges are around increasing the availability of information and assessments to people and planners across government and improving the availability and quality of information (UNDRR, 2020). As such, there is a primary need in NZ to

> establish a comprehensive Disaster Information Management System [DIMS], combining various existing platforms and databases to harmonize and synergize available information in terms of loss data (for estimating disaster trends), and to support decision-making, prioritization and funding needs projection. This should consider the dimensions of potential climate change impacts as well and be made publicly available to stakeholders and communities. Current, existing systems are maintained by a plethora of actors, and a comprehensive DIMS remains to be established (UNDRR, 2020, p. 28).

This doctoral research is thus focused on New Zealand to support the country's efforts in fulfilling the Sendai Framework priorities by supporting the implementation of hydrometeorological IFWs and by developing more understanding around the data challenges both for IFWs and for general DRR in New Zealand.

2.4 New Zealand Weather Warning System

It is argued that National Meteorological and Hydrological Services (NMHSs) do not carry the full responsibility of obtaining the required data and of fully implementing an IFW system (WMO, 2015). Instead, it is a joint effort between the NMHSs and other stakeholders, particularly EM agencies (WMO, 2015). This varies country by country, as many countries have defined the roles and responsibilities for issuing warnings for different hazards through policies and legislation. Since this study is focused on the implementation of IFWs in New Zealand it is important to understand the hydrometeorological hazards in NZ, and the existing roles and responsibilities for severe weather warnings in New Zealand.

2.4.1 New Zealand's Severe Weather Hazards

> Sometimes it does us a power of good to remind ourselves that we live on two volcanic rocks where two tectonic plates meet, in a somewhat lonely stretch of windswept ocean just above the Roaring Forties. If you want drama – you've come to the right place. – Sir Geoffrey Palmer, Former Prime Minister of New Zealand.

The geographic setting of New Zealand means the country experiences a variety of natural hazards, from earthquakes, volcanic eruptions, to ex-tropical cyclones and floods. As an archipelago located in the mid-latitude zone (Figure 2.2) of westerly winds (i.e., the 'Roaring Forties') and approximately 1,600km away from the nearest land mass (Australia's west coast; Walrond, n.d.), New Zealand is particularly exposed to hazardous weather (DPMC, 2007). Unless otherwise stated the information in the following severe weather hazards profile is sourced from the Natural Hazardscape Report from the Department of the Prime Minister and Cabinet (DPMC, 2007).

Figure 2.2. Global positioning of New Zealand(Maps Open Source, n.d.).

New Zealand experiences a wide range of weather-related hazards. These hazards can produce minor to significant impacts on NZ society. These hazards are organised into six categories: (1) Coastal Hazards, (2) Geophysical Hazards, (3) Floods, (4) Severe Winds and Thunderstorms, (5) Snow, and (6) Droughts and Wildfire. The weather-related hazards that relate to each of these are now discussed. A map of New Zealand is presented in Figure 2.3 to provide context to the locations described in the following text.

Weather-related coastal hazards that NZ experiences are swells and storm surges, with related coastal erosion and inundation. Exposure to these hazards will increase with climate change, thus leading to greater impacts (Spalding et al., 2014). Swells are wind-generated waves with long distances between wave crests that do not lose much energy as they travel thousands of kilometres across the ocean. Southwest swells over 2 metres high regularly affect much of the west coast of the North and South Islands, while the northeast of the North Island can experience occasional northeast 4+ meter-high swells accompanied by storm surge from ex-tropical cyclones. The east of the North and South Islands experiences swells that are more variable in height and direction, with an average of 0.5-2 metres, rising to 4-6 metres on occasion. Significant swell events have caused notable damage and evacuations. For example, on 15 April 2020 large swells recorded at 5.5 metres unexpectedly impacted Wellington's South Coast, resulting in the evacuation of five properties, and property damage and road closures (WREMO, 2020). These swells were driven by a low-pressure system passing near Chatham Island, approximately 770km away. The impacts of this event resulted in the development of a Wave Warning Program with adjusted warning thresholds for swell hazards on the Wellington South Coast due to several recent impactful events on coastal properties and the exposure of these properties to significant swells (WREMO, 2021). This warning system was used a year later on 28 June 2021 where the New Zealand Meteorological Service – Te Ratonga Tirorangi (MetService) issued a heavy swell warning for parts of the Wellington South Coast (Morton, 2021). In preparation for these swells, some residents were told to evacuate and cordons were set up to disallow entry of residents and non-residents (Campbell, 2021).

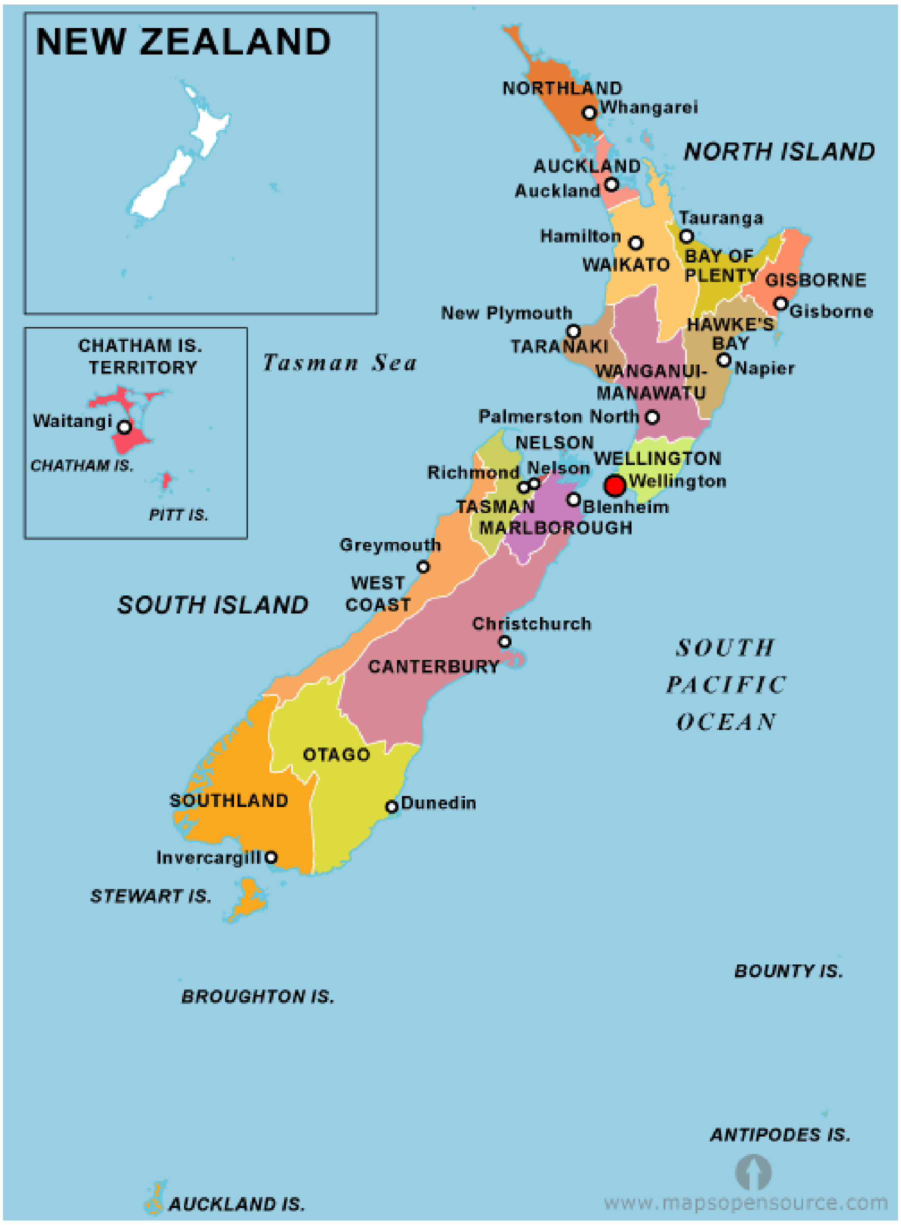


Figure 2.3. New Zealand Regional Map (Maps Open Source, n.d.).

Storm surge is a "temporary elevation in sea level during storm conditions created by … low barometric pressure and wind" (DPMC, 2007, p. 56). A common cause for storm surge is ex-tropical cyclones that approach from the northeast of New Zealand. The most vulnerable areas to storm surge are low-lying coastal areas. Storm surges combined with high tide are likely to cause more damage than storm surge during low tide. As of 2017, 22 billion NZD worth of infrastructure, 4,000 homes, and 13,000 people are situated along the NZ coastline (Bell et al., 2017). Storm surge can cause coastal inundation and erosion, risking damage to infrastructure and further impacts to the communities. For example, in 2018, ex-Tropical Cyclone Fehi made landfall with NZ; the storm's large storm surge, observed at 2.06m (unverified, see Adam et al., 2020) flooded many homes in the Nelson region (Noll, 2018). Rising sea levels and intensification of storm events due to climate change are expected to worsen the impacts of storm surge on the NZ coastline (Adam et al., 2020; Bell et al., 2017).

Land slips and debris flows are geophysical hazards but can be triggered by heavy rainfall. Rainfall-induced land slips and debris flow are influenced by slope angle, vegetation cover, soil depth, drainage patterns, geology/rock type, and the frequency of intense rainstorms. These land slips can damage homes, roads, rail, and farm infrastructure. Past significant rainfall-induced landslides have caused far-reaching impacts including decreases in agricultural productivity due to pasture loss, and degradation of water quality due to silt washing into rivers and streams.

An example of this occurred on 18 May 2005 when heavy rainfall triggered several land slips and debris flows in Matatā, Bay of Plenty (Figure 2.3), destroying 27 homes and damaging 87 properties (McSaveney et al., 2005). One such debris flow occurred at Awatarariki Stream (Massey et al., 2019). Fortunately, no injuries or deaths occurred as most people were inside sheltering from the heavy rainfall that contributed to the debris flow (Massey et al., 2019). However, the results of subsequent risk assessments and the calculated annual individual fatality risk to dwelling occupants (Tonkin & Taylor Ltd, 2013, 2015) led the Whakatāne District Council to deem the risk assessment as "intolerable" (Massey et al., 2019, p. 1), thus requiring mitigative action. In response, an evaluation of a potential debris flow EWS was launched and concluded that a multi-staged debris flow EWS would be unlikely to allow all potential people in the hazard zone to evacuate safely and thus would not be an effective mitigative approach (Massey et al., 2019).

Floods are the most frequent and costly natural hazard in NZ, aside from earthquakes, causing millions of dollars' worth of damage (Rouse, 2011). *Floods* can be a result of widespread heavy rain and/or localised rain. *Heavy rainfall* can occur anytime and anywhere in NZ but is most common in the west and south of the South Island where moist air arriving from the west is forced upwards over the Southern Alps, and the air cooling produces precipitation in the form of heavy rainfall. Heavy rainfall in the North Island and northeast of the South Island is typically caused by ex-tropical cyclones moving over or past NZ from the north. In the southeast of the South Island, mid-latitude *cyclones* to the east can also produce heavy rainfall. In early April 2017, ex-Tropical Cyclone Debbie brought heavy rainfall to New Zealand (Cullen et al., 2017). This rainfall, combined with saturated soil from a wet month in March resulted in very high river levels in both the Whakatāne and Rangitāiki Rivers in the Bay of Plenty (Cullen et al., 2017). These high water levels resulted in stop bank breaches, causing widespread, devastating flooding in the town of Edgecumbe (Cullen et al., 2017). Consequently, Edgecumbe was entirely evacuated due to flooding, leaving some residents unable to return to their homes (Cullen et al., 2017).

Localised rain is typically associated with **thunderstorms**, which can produce intense *rain, damaging winds, hail,* and *lightning*. They are difficult to forecast accurately due to the rapid speed at which they develop. Thunderstorms can last from minutes to several hours producing intense rain which can lead to flash flooding and sometimes hail. Flash floods pose a threat to life and can cause significant damage due to fast-moving debris flows. Over six weeks in March and April 2017, Auckland (Figure 2.3) was hit by six localised storms that brought heavy rainfall leading to flooding and landslips (Golubiewski, 2019). The suburb of New Lynn was particularly affected by the third storm, during which heavy rainfall exceeded the capacity of the stormwater network, leading to widespread road flooding that was exacerbated by a partial culvert collapse (Golubiewski, 2019). Fortunately, no injuries or deaths occurred from this event, but 69 buildings were affected, roads were closed for up to four weeks, 23 people were rescued, and 12 residents were evacuated from a multi-dwelling residential block (Golubiewski, 2019).

Lightning and *hail* are additional **thunderstorm**-related hazards that threaten New Zealanders. NZ experiences more than 50,000 *lightning* strikes per year, with one death reported every five to ten years (MCDEM, 2010). *Hailstorms* pose the greatest meteorological risk to the agricultural sector and buildings and infrastructure, by damaging crops and buildings respectively. Hailstorms account for some of the costliest weather events in NZ; the Timaru Hailstorm of 20 November 2019 ranks as the costliest meteorological event in NZ at over 170 million NZD (ICNZ, 2021), where golf ball-sized hail stones heavily damaged buildings, caused business closures and hazardous driving conditions (stuff, 2019). This is followed by the Marlborough-Nelson Hailstorm which occurred a year later, on 26 December 2020, costing over 50 million NZD, and causing widespread damage to fruit crops, agricultural infrastructure, and buildings (Neal, 2020).

Considering the **severe winds** category, New Zealand lies in the path of the 'Roaring Forties' (mid-latitude westerly winds) which produce strong and damaging winds. *Windstorms, tornadoes*, and *ex-tropical cyclones* pose the most significant wind hazards. In September and October 2013, windstorms heavily impacted the agriculture sector in Canterbury, costing millions of NZ dollars in direct and indirect impacts to farmers (Safa & Birendra, 2015). On 10 April 2018, Auckland was impacted by a windstorm that caused widespread power outages lasting several days due to downed trees and power distribution networks (Smol, 2018). The extended power outage in conjunction with cold weather led to increased welfare impacts and increased vulnerabilities of people depending on power supplies for medical support (Smol, 2018). As such, a significant welfare response ensued to distribute portable toilets, potable water, and power generators (Smol, 2018).

Tornadoes produced by **thunderstorms** are relatively small and short-lived in New Zealand but still threaten life and property. Between 20-30 tornadoes are observed in NZ annually, leaving 10-20-meter-wide and up to 5-kilometre-long damage paths. Tornadoes can happen anywhere in the country, and several have resulted in unfortunate fatalities. On 6 December 2021, an EF1 tornado struck the Whenuapai and Hobsonville suburbs in Auckland, resulting in the deaths of three construction workers on-site, seven injuries, and 10 million NZD worth of damage (Turner et al., 2013). More recently, another EF1 (1 News, 2021) tornado struck the Auckland suburb of Papatoetoe on 18 June 2021, unfortunately killing one person, injuring two people, and damaging 60 houses (Franks, 2021)

In addition to meteorological hazards presented by thunderstorms such as extreme wind, tornadoes, heavy rainfall, and lightning, thunderstorms have also recently been found to pose *health risks* in NZ relating to asthma attacks and allergens. On 2 December 2017, thunderstorm-induced asthma attacks were detected by an increase in asthma presentations at the Waikato Hospital in Hamilton (Sabih et al., 2020), (Figure 2.3). This event highlighted a need to develop response plans for paramedics and emergency facilities in NZ in the event of a large-scale thunderstorm, like the outbreak that occurred in Melbourne, Australia in 2016 (Thien et al., 2018).

Ex-tropical cyclones are the most common source of widespread high wind in Northland, Auckland, and the Bay of Plenty. They are also usually accompanied by heavy rainfall causing flooding. Tropical cyclones form over the warm tropical waters north of New Zealand. Typically, they tend to weaken as they move south to cooler waters. However, some ex-tropical cyclones heading south towards New Zealand can form into large mid-latitude storms infused with colder air; these storms can create widespread impacts on New Zealand's coastal communities. The ex-tropical cyclone cases previously presented (e.g., ex-Tropical Cyclones Fehi and Debbie) exemplify the risks posed by these systems to New Zealand. Both storms contributed to power outages and travel disruptions (i.e., road closures, flight cancellations, rail service cancellations) due to high winds (Noll, 2018).

The higher altitude areas of New Zealand commonly experience winter **snowfall**, while altitudes below 1000 metres experience winter snowfall less frequently. *Snowstorms* caused by cold southerlies or warm advection can disrupt electricity, telecommunications, and transportation, and can damage buildings and infrastructure. On 18 September 2010, heavy snowfall resulted in the collapse of a sports stadium in Southland (Department of Building and Housing, 2012). Snowstorms can also result in significant agricultural losses through lack of access to water supplies and lack of feed. In June 2006, heavy snowfall damaged power and telecommunication networks and closed roads for several days in South Canterbury (Kelly & Smith, 2012). Farmers experienced both *physical* and *mental health impacts* due to physical exhaustion from clearing snow and the added stress of the threat of another snowstorm (Kelly & Smith, 2012). Additionally, *snow avalanches* in New Zealand's alpine areas threaten the lives of people working in the mining industry and of people involved in mountaineering, skiing, or snowboarding. From 1999 to 2018, there were 742 reported avalanche incidents and 27 fatalities; averaging out to 37 annual reported incidents, and 1.35 annual fatalities (NZ Mountain Safety Council, 2021).

Droughts are caused by prolonged periods of below-average rainfall resulting in reduced soil moisture levels for extended periods of time. Droughts can cause widespread *economic, environmental, and public health* and *safety impacts* (e.g., food supply, water supply) (Centre for Public Health Research, 2014; Hendy et al., 2018), as well as *acute mental health impacts* on farmers (Goffin & ACC Policy Team, 2014). This makes droughts one of the costliest hazards in New Zealand. The estimated economic losses from droughts between mid-2007 and mid-2017 were estimated at 720 million NZD (Frame et al., 2018). These costs are expected to increase due to climate change (Frame et al., 2018; Mullan et al., 2005); eastern regions of NZ were found to experience more dry periods from 2004-2013 (Centre for Public Health Research, 2014).

Each year, New Zealand experiences 4,100 wildfires that burn around 4,170 hectares of forest and rural land annually (Langer & Wegner, 2018). Meteorological conditions such as strong winds, low humidity, and seasonal drought can lead to favourable conditions for dangerous fire weather (Pearce & Clifford, 2008). These conditions, combined with human activity such as arson, escaped burns, forestry operations, vehicle operation, and campfires (Cameron et al., 2007), produce most of the wildfire hazards in NZ (Hart & Langer, 2011; Pearce et al., 2008). Furthermore, with human development into rural lands and climate change, the risk of wildfires impacting humans is increasing and has already resulted in some of NZ’s worst wildfire events at the rural-urban interface (Huggins et al., 2020; Pearce, 2018). In February 2017, the Port Hills wildfire impacted the southern boundary of Christchurch, burning 1,661 hectares, destroying nine houses, and damaging five other houses (Langer & Wegner, 2018). The fire led to the evacuation of over 450 homes, between 1,400 and 2,800 residents for three to nine days (Langer & Wegner, 2018), and cost nearly 18 million NZD (ICNZ, 2021). Two years later the Pigeon Valley fire impacted Nelson and became NZ’s costliest wildfire disaster and the most destructive wildfire in 60 years (Dudfield et al., 2020). In February 2019 the Pigeon Valley fire burned more than 2,300 hectares of land southwest of Nelson and caused the evacuation of more than 2,500 residents (Dudfield et al., 2020). An investigation concluded the cause of the Pigeon Valley fire to be an accidental spark from agricultural equipment (Cowan, 2019).

New Zealand is prone to, and experiences, a wide range of hydrometeorological hazards, many of which require an EWS to alert people to their dangers. This thesis will focus on the severe weather warning and flood warning systems in New Zealand as opposed to EWSs for droughts and wildfires, as these were determined to be the most relevant warning systems for IFW systems based on discussions with experts and stakeholders both within and outside of New Zealand. For example, informal discussions with wildfire communications experts in NZ and Australia indicated that IFWs were not fully conceptualised for wildfires at the outset of this thesis, and it was unclear whether IFWs would be effective for these hazards. Alternatively, warnings for droughts require a different context from severe weather and flood warnings due to the longer onset of droughts as opposed to shorter lead times for severe weather and floods.

2.4.2 Severe Weather Warnings

The Meteorological Services Act 1990 of New Zealand ensures the provision of meteorological services in the country and holds the Minister of Transport responsible for ensuring the provision of meteorological warning services (Ministry of Transport, 1990). As such, the Minister of Transport is responsible for arranging for the making and issuing of forecasts of the weather, and the collection and recording of meteorological information (Ministry of Transport, 1990). In line with this mandate, and under the State Owned Enterprises Act 1986, the Minister of Transport entered into a commercial contract with the Meteorological Service of New Zealand Limited – Te Ratonga Tirorangi (MetService) (a State Owned Enterprise or SOE) in 1992 (referred to as the Meteorological Services Contract) for the provision of these meteorological services (Williamson, 1998). Thus, the MetService is the appointed National Meteorological Service (NMS) of New Zealand. This is stipulated in the National Civil Defence Emergency Management Plan Order 2015, where:

> 1) Monitoring, identification, and analysis of geological and meteorological hazards and threats and subsequent issuing of hazard information is to be undertaken at all times by the following agencies:
>   a. the Meteorological Service of New Zealand Limited (severe weather); and
>   b. GNS Science (earthquake, volcanic activity, and landslides); and
>   c. the NEMA (tsunamis).
> 2) Relevant government agencies, CDEM Groups, local authorities, and lifeline utilities are to maintain arrangements to receive and respond to hazard information. (New Zealand Government, 2015b, cl 119)

The Meteorological Services Contract specifies the services that the MetService must provide. These services consist of three primary tasks: making and issuing warnings and forecasts, acquiring meteorological data, and providing emergency advice (Williamson, 1998). The MetService is responsible for providing basic public forecasts and issuing warnings of hazardous weather affecting land areas, issuing marine forecasts and warnings (Williamson, 1998). The explicit requirements for each of these services are provided in Table 2.4 based on the Meteorological Services Contract (Williamson, 1998). For land-based hazards, the MetService is responsible for issuing warnings where the hazard meets a set of predefined physical thresholds: widespread heavy rainfall, widespread heavy snowfalls, widespread severe gales, heavy coastal swells, and severe thunderstorms. The MetService must also provide regular forecasts daily: four short forecasts issued daily covering the next two days, two extended forecasts covering the following three days, and two brief forecasts for the mountainous regions. Marine forecasts and warnings issued by the MetService include warnings of gales, storms, and hurricanes for the Tasman Sea and a large part of the South Pacific Ocean, as well as a series of regular forecasts described in Table 2.4.

Table 2.4. Meteorological Forecast and Warning Services provided by the MetService , taken directly from the Meteorological Services Contract (Williamson, 1998. paras. 5-7)[2].

Service	Requirements & Responsibilities
Warnings of hazardous weather affecting land areas	• Widespread heavy rain, exceeding 50 mm in 6 hours or 100 mm in 24 hours • Widespread heavy snowfalls below 1000 metres [above sea level] on the North Island and 500 metres [above sea level] on the South Island, exceeding a depth of 10 cm in 6 hours or 25 cm in 24 hours • Widespread severe gales with a sustained wind speed of 90 km/hr or more, or frequent gusts of 110 km/hr or more • Heavy coastal swells, according to agreed criteria for certain regional authorities
Basic public forecasts	• Four short forecasts are issued daily, covering the next two days, for all of New Zealand • Two extended short forecasts are issued daily, covering the following three days • Two brief forecasts are issued daily for the mountain areas of New Zealand
Marine forecasts and warnings	• Warnings of gales, storms, and hurricanes are issued as required for the Tasman Sea and a large part of the South Pacific Ocean, extending halfway to South America, and from latitude 25ºS to 55ºS (roughly 6% of the world's oceans) • Twice daily synopses and forecasts are issued for the same area • Four times daily detailed marine warnings and forecasts are issued for the coastal waters of New Zealand (up to 100 km from the coast) and the Chatham Islands (the precise areas covered for these coastal services are as specified in the New Zealand Nautical Almanac) • Warnings of near gales (25 to 33 knots) are issued as required for the Auckland marine area - Manukau and Waitemata harbours and the Hauraki Gulf south of a line from Cape Colville to Bream Head. • Four times daily, marine forecasts are issued for the Auckland marine area, Wellington Harbour and south coast, for inshore waters from Waitarere to Pukerua Bay, and for Pegasus Bay from the mouth of the Waimakariri River to Lyttelton Harbour • MetService operates a radio-facsimile service broadcasting marine weather charts over the Pacific Ocean south of the equator

[2] Over the last 20 years since signing the Meteorological Services Contract, the requirements in this contract have been expanded. However, the current Commercial Contract cannot be shared publicly. Examples of such expansions are the introduction of thunderstorm warnings, and an increase in the number of inshore marine forecasts.

In times of emergency, the contract ensures that the MetService will make urgent meteorological advice available. The contract defines emergencies as

> the need for weather information for national and international search and rescue operations, a fruit fly or a foot and mouth disease outbreak, volcanic eruptions and marine pollution incidents (Williamson, 1998, para. 8).

The creation and issuance of forecasts and warnings requires extensive meteorological observations to ensure the services are as accurate as possible.

In addition to creating and issuing meteorological forecasts and warnings, the MetService is responsible for acquiring the appropriate data to support these services, as outlined in the Contract (Williamson, 1998). To meet this requirement, the MetService maintains a data network in compliance with standards prescribed by the WMO. The data collected comes from observations across New Zealand, upper air observations, weather surveillance radar, ships, a buoy network in the Tasman Sea, and aircraft (e.g., Aircraft Meteorological Data Relay or AMDAR) (Williamson, 1998). The MetService makes a selection of its data available nationally and internationally in accordance with WMO regulations for the exchange of data. The MetService provides free public access to a particular set of observational data through its official website, and distributes observational data from the Regional Basic Synoptic Network through the WMO communications for unrestricted use (Williamson, 1998). The MetService passes all observational data in direct support of forecast services to the National Institute of Water and Atmospheric Research (NIWA) for archiving in the National Climate Database (Williamson, 1998). Additional tasks outlined in the Meteorological Services Contract include providing support services to the Pacific, representing New Zealand to the WMO, and maintaining quality assurance and performance standards (see Williamson, 1998).

The severe weather warning service provided by the NZ MetService includes Outlooks, Watches, and Warnings. An Outlook is defined as a “heads up” that bad weather may occur in the next 3-5 days (MetService, 2019b). By issuing an Outlook, the MetService aims to increase recipients’ awareness of potential severe weather (MetService, 2019b). Following an outlook, if hazardous weather is expected, the MetService can issue a Watch or Warning, as listed in Table 2.5 with their respective thresholds.

A Severe Weather Watch is typically issued within 1-3 days of potential severe weather with additional details around timing, location, and intensity (MetService, 2019b). The MetService issues a Watch either when they expect severe weather will occur but has not reached warning criteria, or when uncertainty is significant (MetService, 2019b). The MetService instructs Watch recipients to remain alert and prepared (MetService, 2019b).

Table 2.5. The thresholds as defined by the MetService for its Severe Weather Watches, Severe Weather Warnings, Severe Thunderstorm Warnings, Road Snowfall Warnings, and Heavy Swell Warnings (taken directly from MetService, 2021c).

Watch or Warning	Thresholds
Severe Weather Watch	• After the next 24 hours but within 48-72 hours, or • If there is a high level of uncertainty within the next 24 hours.
Severe Weather Warning	• Widespread[3] rainfall greater than 50 mm within 6 hours or 100 mm within 24 hours; • Widespread snowfall below 1000 m [above sea level]on the North Island, South Canterbury or Otago - or below 500 m [above sea level] elsewhere on the South Island with a snow depth of 10 cm within 6 hours or 25 cm within 24 hours; • Widespread severe gales with a minimum mean speed of 90 km/h or frequent gusts exceeding 110km/h.
Severe Thunderstorm Warning	• Heavy rain from thunderstorms of 25mm/h or more. • Large hail of 20mm diameter or more. • Strong wind gusts from thunderstorms of 110km/h (60 knots) or more. • Damaging tornadoes with wind speeds more than 116 km/h (63 knots) (i.e., Fujita F1 or stronger).
Road Snowfall Warning	• For Napier-Taupo Road (SH5), Desert Road (SH1), Remutaka Hill Road (SH2), Lewis Pass (SH7), Arthur's Pass (SH73), Porters Pass (SH73), Haast Pass (SH6), Lindis Pass (SH8), Crown Range Road, Milford Road (SH94) or Dunedin to Waitati Highway (SH1). • Whenever there is a likelihood of snow settling on one or more of those roads within the next 24 hours.
Heavy Swell Warning	• The Wellington South Coast: • Swell height of 4 m or more from the S or SE with a long period of 14 seconds or more • Combined waves of 6m or more from the S or SE with a long period of 14 seconds or more

A Warning is issued when MetService forecasters are confident about what will happen and where, and that any of the thresholds listed in Table 2.5 will be met by the weather conditions in the next 24 hours (MetService, 2021c). Warnings are usually issued within 1-2 days of the potential severe weather (MetService, 2019b). When a Warning is issued, the MetService instructs recipients to act, prepare for disruptions, and follow the advice of local authorities if the impacts are expected to be significant.

The MetService issues a Severe Thunderstorm Warning when one or more of the Severe Thunderstorm Warning criteria listed in Table 2.5 are met (MetService, 2021c) (MetService, 2021c). The MetService further notes that tornadic systems such as funnel clouds, waterspouts, and land-based tornadoes are possible with thunderstorms that they have not classified as severe. The MetService does not currently issue any specific tornado warnings due to difficulties in detecting and forecasting for them (e.g., Franks, 2021), however tornadoes may be signalled as a threat in a Thunderstorm Warning issued for other phenomena including heavy rain, damaging winds or large hail.

[3] "Widespread" means over an area of 1,000 square kilometres or more (MetService, 2021c).

Road Snowfall Warnings are issued for specific state highways listed in Table 2.5 when snowfall is expected (MetService, 2021c). An additional disclaimer stipulates that the MetService does not provide information about road conditions or the amount of snow currently on the roads (MetService, 2021c). Heavy Swell Warnings are issued publicly for the Wellington South Coast whenever it is expected that the conditions listed in Table 2.5 will occur in the next 24-48 hours (MetService, 2021c). The MetService notes that arrangements exist with Regional Councils along other parts of the NZ coast for Swell Warnings for those areas, but those are not currently published on the MetService website.

In 2019 the MetService instituted changes to their warnings such that a differentiation can be made for events that are expected to produce significant impacts (MetService, 2019a). The new warnings are categorised by colour to correlate with the level of expected severity and impacts, as shown in Figure 2.4. Severe Weather Watches are Yellow (Figure 2.4a) for possible severe weather (MetService, 2019a). Severe Weather Warnings can be either Orange (Figure 2.4b) or Red (Figure 2.4c). An Orange Warning is issued when the forecast indicates incoming severe weather as per the thresholds in Table 2.5. A Red Warning is reserved for the "most extreme" weather events, where they can expect significant impacts and disruptions, and immediate action is required (MetService, 2019a).

Figure 2.4. The MetService's colour-coded Severe Weather Watches and Warnings. a) Yellow Watch for recipients to "Stay Alert". b) Orange Warning for people to "Take Action". c) Red Warning reserved for events to produce to significant impacts, instructing recipients to "Take immediate action, act now!" (MetService, 2019a).

At the time of thesis submission (October 2021), the MetService has issued four Red Warnings since the implementation of the new warning system, three for heavy rainfall (e.g., Forrester & Daly, 2021; Gabel, 2021; SMC, 2020), and one for severe gales (e.g., Tan, 2021). The first Red Warning was issued on 3 February 2020 (Figure 2.5) for heavy rainfall in parts of Southland and West Coast Regions on the South Island of NZ after receiving 350 mm of rain in 24 hours, and surface flooding and land slips were observed, with more rain forecasted for the next two days (SMC, 2020). A state of emergency was declared after floods occurred in Southland, resulting in road closures due to land slips and the evacuation of over 5,000 people (Emergency Management Southland, 2020). The second Red Warning was issued over a year later on 28 May 2021 for heavy rain in Canterbury. In response to the event, a state of emergency was declared for the entire region of Canterbury; impacts included 50 school closures, over 300 homes evacuated, 4 bridges washed away, and 20 road closures (Quinlivan et al., 2021). The third Red Warning was issued on 15 July 2021 for heavy rain, upon expectation of flooding and slips in Westland and Buller (Gabel, 2021). Buller District Council pre-emptively declared a state of emergency stating an expectation that houses were likely to flood overnight; the state of emergency declaration allowed emergency services to activate and plan for evacuations (Gabel, 2021). The flood impacts resulted in evacuations of more than 800 people in Westport (RNZ, 2021).

As shown in these three Red Warning examples, severe weather hazards such as rainfall can introduce secondary hazards, such as floods, which can result in their own impacts. In New Zealand, floods resulting from severe weather hazards such as ex-tropical cyclones and heavy rainfall have resulted in significant impacts. As such, an overview of the flood forecasting and warning system is provided next.

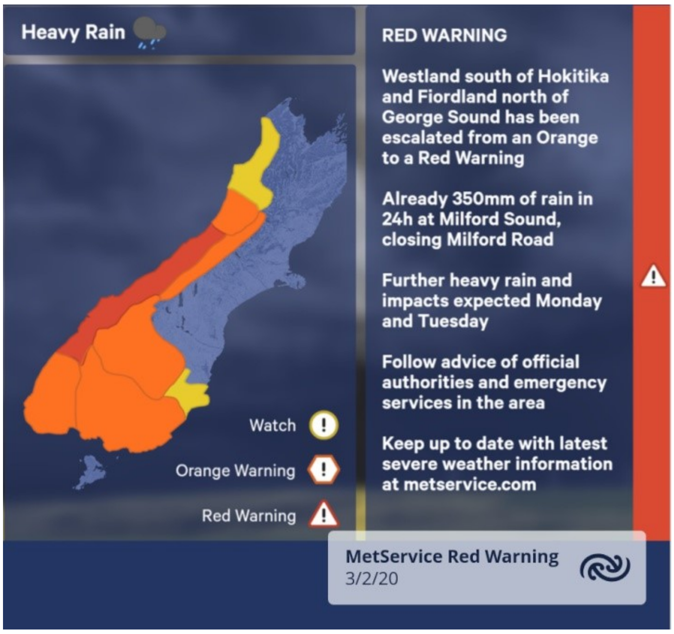


Figure 2.5. Image release of the first Red Warning issued by the MetService on 3 February 2020for parts of West Coast and Southland regions on New Zealand's South Island (source: MetService).

2.4.3 Flood Warnings

Flood warnings do not fall under the jurisdiction of the MetService in New Zealand. Flood risk communication (specifically forecasts and warnings) in New Zealand is more complex and layered than severe weather communication as it is tied into flood risk management practices, which are multi-layered and 'hierarchical' (Rouse, 2011). Three pieces of legislation outline the responsibilities for natural hazard management, including floods: the Resource Management Act 1991, the Civil Defence and Emergency Management Act 2002, and the Local Government

Amendment Act 2012. Under the Resource Management Act 1991 (the RMA), sixteen regional councils or unitary authorities hold the responsibility for water management (Ministry for the Environment, 1991; Rouse, 2011). Furthermore, the RMA assigns natural hazard mitigation responsibilities to territorial authorities, such as district and city councils (Ministry for the Environment, 1991; Rouse, 2011). This includes flood risk management (Ministry for the Environment, 1991; Rouse, 2011).

The Civil Defence and Emergency Management Act 2002 (the CDEM Act) is another piece of legislation which clarifies more specific roles and responsibilities for hazard management and mitigation (Rouse, 2011). The CDEM Act stipulates local authorities must create and become members of the Regional Civil Defence and Emergency Management Groups, who then write Civil Defence and Emergency Management Plans (MCDEM, 2016; Rouse, 2011). These plans support the coordination and planning for reduction, readiness, response, and recovery for all hazards, including floods (MCDEM, 2016; Rouse, 2011).

Finally, the Local Government Amendment Act 2012 (the LGA) ensures that local authorities take a sustainable development approach to promote social, economic, environmental, and cultural wellbeing (Department of Internal Affairs, 2012; Rouse, 2011). The LGA empowers local authorities to decide which activities to undertake and how it will be done (MCDEM, 2016; Rouse, 2011). As such, if flood hazard management is deemed key to the communities' well-being, the council is responsible for arranging funding and planning of these management efforts (MCDEM, 2016; Rouse, 2011).

Local and Regional Councils hold the bulk of responsibility for flood monitoring, forecasting, and warning, with support from NIWA, the MetService, and CDEM Groups (Ministry for the Environment & The Flood Risk Management and River Control Review Steering Group, 2008). The Local and Regional Councils carry out flood forecasts and create flood warnings which they disseminate through their own networks (such as their official websites) and via CDEM Groups (Ministry for the Environment & The Flood Risk Management and River Control Review Steering Group, 2008).

Reports on flood risk management have noted the need for greater collaboration between organisations and increased data and information sharing not only for improving flood warning systems, but also for improving greater flood risk management efforts (e.g., Cullen et al., 2017; Ministry for the Environment & The Flood Risk Management and River Control Review Steering Group, 2008; Rouse, 2011). One suggestion is for NIWA to take on the role of aggregating and sharing flood data (Ministry for the Environment & The Flood Risk Management and River Control Review Steering Group, 2008; Rouse, 2011).

Severe weather warnings and flood warnings require actions from the New Zealand Emergency Management (EM) sector for dissemination and response. Thus, the NZ EM structure is presented next.

2.4.4 The New Zealand Emergency Management Sector

When a severe weather warning and/or flood warning is issued, the Emergency Management (EM) sector in New Zealand has a role to play in the dissemination of and response to the warning messages. The EM sector in New Zealand is governed by the Civil Defence Emergency Management (CDEM) Act 2002.

The National Emergency Management Agency (NEMA) is the lead agency under the CDEM Act, as described in the *Guide to the National CDEM Plan 2015* (New Zealand Government, 2015a). The objective of NEMA is to provide leadership, strategic guidance, national co-ordination, and facilitate and promote key activities for reduction, readiness, response, and recovery (New Zealand Government, 2015a). The recipients of NEMA's leadership and guidance are primarily CDEM Groups (New Zealand Government, 2015a).

Under the CDEM Act, local authorities must form and maintain CDEM Groups, usually at the regional level (NEMA, 2021a). CDEM Groups are responsible for implementing local CDEM plans efficiently and effectively (New Zealand Government, 2015a). CDEM Groups provide leadership and co-ordination amongst member local authorities, partner agencies, clusters, and communities within their jurisdiction (New Zealand Government, 2015a).

Sixteen CDEM Groups exist in New Zealand, as shown in Figure 2.6. CDEM Group members can consist of regional councils and territorial authorities (i.e., city and district councils). For example, the members of the CDEM Group for the Southland Region of NZ (known as Emergency Management Southland), consist of Gore District Council, Invercargill City Council, Southland District Council, Southland Regional Council. Each CDEM Group outlines their own tasks and associated roles and responsibilities in their Group Plan, which they make publicly available through their websites[4].

Amongst their designated responsibilities under the CDEM Act, CDEM Groups are responsible for two tasks relevant to this research: emergency information dissemination, and response. While the MetService is the designated authority for issuing severe weather warnings and regional councils are responsible for issuing local flood warnings, CDEM Groups act to respond to and disseminate these warnings across their jurisdictions. For example, within the Southland Regional Group Plan, it is stipulated that in addition to responding to relevant warnings, the Southland EM Group "operates a 24-hour, 365-day-a-year, point of contact to receive and disseminate all warnings to the appropriate key stakeholders" (Emergency Management Southland, 2017, p. 34).

[4] For example (accessed 4 July 2021): Southland EM Group Plan, https://www.es.govt.nz/about-us/meetings?item=id:28zrwy7e21cxbynl4xbc

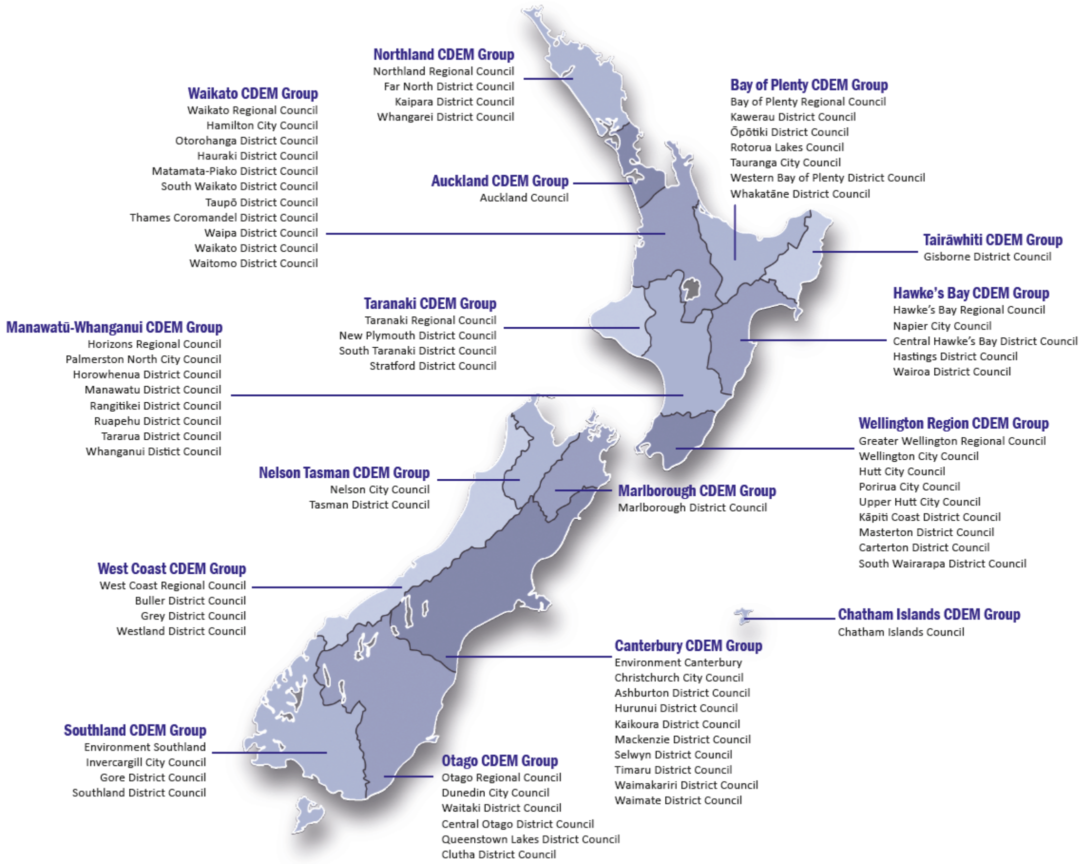


Figure 2.6 Map of the 16 CDEM Groups in New Zealand with their respective group members, which consist of regional, city, and district councils. Source: NEMA.

During emergency response, the CDEM Group is primarily responsible for coordinating response activities. One key task to support this role is collecting, analysing, and disseminating information to the public and stakeholders (e.g., Auckland Emergency Management, 2016; Emergency Management Southland, 2017). This facilitates effective leadership and decision-making, efficient and accurate communication with the public and stakeholders, and situational awareness for response personnel (e.g., Auckland Emergency Management, 2016; Emergency Management Southland, 2017).

2.5 Chapter Summary

This chapter provided (1) a literature review of hydrometeorological EWSs and their associated challenges and shortcomings, IFW systems and how they have been proposed to address the shortcomings of traditional hydrometeorological EWSs, (2) the relevance of this research to the Sendai Framework, and (3) the context of NZ hydrometeorological hazards, EWSs, and emergency management.

The literature review indicates that IFWs may improve the communication of hydrometeorological hazards and their impacts, and thus may allow warning audiences to make informed decisions and take appropriate protective action. IFWs differ from traditional hydrometeorological warnings by incorporating knowledge of impacts, vulnerability, and exposure into the decision-making process for issuing warnings. However, a key challenge was identified in the literature review around implementing IFWs: meteorological and hydrological services that issue warnings do not have the required knowledge and data relating to impacts, vulnerability, and exposure. Thus, there is a need to explore how these services can obtain and use this information to support the development and design of IFWs.

It was then argued that as a member nation of the UN and the WMO, New Zealand is responsible for implementing effective and user-friendly EWSs for its various natural hazards and is duty-bound to report its progress towards achieving the priorities and objectives of the Sendai Framework. Two such priorities were identified to be relevant to this doctoral thesis: those of understanding disaster risk; and of enhancing disaster preparedness for effective response. IFWs align with these Sendai Framework priorities, and thus have been identified as an opportunity for this doctoral research which aims to support NZ's goals of meeting these priorities. This will be achieved by exploring the data needs of IFWs in the NZ context and investigating how these data can be accessed and used by stakeholders involved in an IFW system for hydrometeorological hazards in NZ.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Three: **Research Design**

The research question guiding this PhD study is

> Which data are needed to support Impact Forecasting and Warning (IFW) systems for hydrometeorological hazards, and how are they currently collected, stored, and shared in New Zealand?

Based on the overview and definition of an EWS, provided in Chapter Two, it can be argued that an EWS/IFW system is a "central component and output" of a larger information system involving risk assessments, communication, and decision support (Pulwarty & Sivakumar, 2014, p. 15). Since data sources and information needed to support severe weather IFW systems are the focus of this study, it is logical to conduct this research through an Information Systems lens. Information Systems (IS) research investigates the use and impacts of information technology development through understanding "communication and collaboration between people and organisations, inter-organisational systems, electronic commerce and the Internet" (Myers & Avison, 2002, p. 2).

The IS lens applied to this research informed the research design, which consists of two major components, the research paradigm and the research methodology (Al Kilani & Kobziev, 2016), as shown in Figure 3.1. The research paradigm consists of the researcher's ontological and epistemological views (i.e., how the researcher views and interprets the world) (Morgan, 2007; Scotland, 2012). The research methodology is comprised of the research approach (e.g., qualitative, quantitative, or mixed methods approach), the research strategy (e.g., Grounded Theory, Case Study research, Design Science Research), the data collection methods (e.g., interviews, workshops, surveys), and the analytical tools and techniques (e.g., constant comparison, statistical analysis techniques) (Al Kilani & Kobziev, 2016). These components and sub-components will be defined in the following sections, and the overall design of the research will be provided.

This chapter presents the chosen design for this doctoral research, consisting of the research paradigm (Section 3.1), the methodology (Section 3.2), the data collection methods (Section 3.3), the analytical techniques and tools (Section 3.4), and the ethical considerations (Section 3.5). The chapter then concludes with a chapter summary (Section 3.6). Results of these methods, including the number of participants, and themes and codes identified from the analytical techniques and tools are provided in Chapter Four.

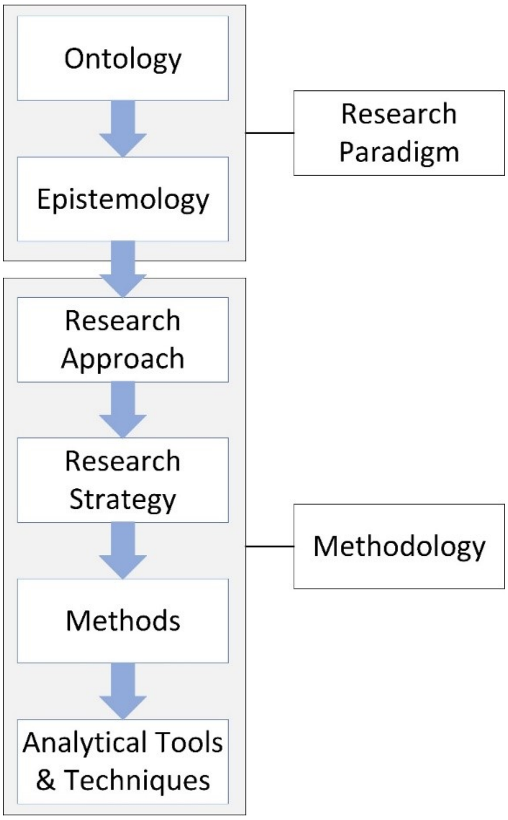


Figure 3.1. Conceptual framework of the research design (based on Al Kilani & Kobziev, 2016).

3.1 The Research Paradigm

There is the ontological question, 'What is the form and nature of reality and, therefore, what is there that can be known about it?'; the epistemological question, 'What is the relationship between the knower or would-be knower and what can be known'; and the methodological question, 'How can the inquirer ... go about finding out whatever he or she believes can be known about?' (Heron & Reason, 1997, p. 276).

Within social science research, the research design is guided by an overarching paradigm, which encapsulates a researcher's beliefs and view of the world (Morgan, 2007). Ontology (Figure 3.1) is "the study of being" (Crotty, 1998, p. 10), and refers to the 'nature of reality'. In conducting research, ontology refers to the researcher's beliefs of the world and reality (Lee, 2004). Epistemology (Figure 3.1) refers to the theory of knowledge (Cardinal et al., 2004), and is "concerned with how knowledge can be created, acquired and communicated" (Scotland, 2012, p. 9). The epistemological approach of a researcher describes how they understand, interpret, and develop their knowledge of the world, guiding their methodology (Gray, 2014). An understanding of a researcher's ontological and epistemological approaches offers insights into the researcher's chosen methodology (Gray, 2014).

Based on the IS literature, there are five commonly used research paradigms within IS research: Positivism/Post-positivism, Interpretivism, Critical Theory, Pragmatism, and Participatory Inquiry. A deeper understanding of each paradigm supported by references to the literature is presented in Appendix B, and a summary is presented in Table 3.1.

As summarised in Table 3.1, *Positivist/Post-positivist researchers* see one reality, and gain knowledge of this reality through experimentation and measurements to investigate, determine, and predict the causal relationships (i.e., the 'how' and 'why') and theories developed from the data deductively (Creswell, 2014; Scotland, 2012). Deduction involves using a pre-existing theory or set of rules to examine the data and determine how the data support or disconfirm the theory or rules (Kennedy, 2018).

The Interpretivist research paradigm proposes that reality is relative, formed by the social actors and their social structure and culture (Guba & Lincoln, 1994; Lee, 2004; Scotland, 2012). Knowledge is gained through transactions and dialogue with social actors, such as interviews, and is based on personal experience (Guba & Lincoln, 1994; Mertens, 2015; Scotland, 2012). The researcher employs methods that require interaction with the participant(s) to understand their perspective and build context (Scotland, 2012). Theories are drawn from the data through induction, rather than deduction (Morgan, 2007). Induction occurs when the researcher identifies patterns through empirical cases and creates a general statement based on this evidence (Kennedy, 2018).

The Participatory Inquiry paradigm proposes that a world exists outside of the observer, but the observer perceives and understands the world based on their own experiences and interactions with the world (Breu & Peppard, 2001; Heron & Reason, 1997). Participatory Inquiry research is designed for intervention and action and emphasises the importance of conducting research with the participants, rather than on the participants (Breu & Peppard, 2001; Heron & Reason, 1997). Participatory Inquiry is a cyclical process in which all the people involved in the research continuously engage in defining the problem, applying the methodology, and communicating the results. This cyclical approach ensures the practice of critical subjectivity (Heron & Reason, 1997).

Critical Theory holds that multiple realities exist and are shaped over time and history, with power dynamics at play (Guba & Lincoln, 1994; Mackenzie & Knipe, 2006; Mertens, 2015). The epistemological approach under this paradigm is similar to that of the Interpretivist, with the added dimension of applying a cultural lens and maintaining awareness of power issues (Mertens, 2015). The Critical Theory researcher gains knowledge through similar methods used in Interpretivist research but maintains awareness of power dynamics and ensures that diverse, marginalised groups are included (Mertens, 2015).

Table 3.1. Summary of paradigms used in IS research.

	Positivism/Post-positivism	Interpretivism	Critical Theory	Pragmatism	Participatory Inquiry
Ontological approach	Realist. Reality is real and independent of the knower.	Relativist. Reality is formed by the social actors and their social structure and culture.	Historical realism. Human experiences and cultures shape reality over time and there are multiple versions of reality based on social positioning.	Less emphasis is placed on ontology. Pragmatism recognises the value of the former paradigms, namely Positivism/Post-positivism and Interpretivism, in conducting social research.	Subjective-objective and participative. A world exists outside of the observer, but the observer perceives and understands the world based on their own experiences and interactions with the world.
Epistemological Approach	Objectivist. In positivist research, the researcher and subject are independent. Under post-positivism the researcher approaches the subject objectively to prevent the researcher's biases from influencing the outcomes.	Transactional and subjectivist. Knowledge is gained through interactions; knowledge is subjective because it is based on personal experience.	Transaction and subjectivist with a cultural lens applied to maintain awareness of power dynamics.	Experiential - Pragmatists gain knowledge from inquiries and actions.	Four forms of 'knowing': experiential, presentational, propositional, and practical. The researcher practices critical subjectivity to maintain awareness of the four ways of knowing and of how they are interacting.
Research Approach	Experimental and manipulative. Typically, quantitative, guided by hypotheses that are empirically tested and verified; theories are developed deductively.	Hermeneutical and dialectical. Research is built on discussions and interpretation; typically, qualitative; theories are developed inductively.	Dialogic and dialectical. The researcher and subject must develop a transactional dialogue to exchange and develop ideas, and to transform ignorance and misapprehensions.	Mixed methods to use both quantitative and qualitative research to develop and test theories through abductive reasoning.	Participatory and collaborative - research is done with the people, rather than on them.
Methods	Experiments, quasi-experiments, tests, surveys, scales.	Interviews, observations, document reviews, visual data analysis.	Similar to methods used in Interpretivist research, but especially designed to include diverse, marginalised groups and allow them to participate in the research.	The researcher chooses the most appropriate methods in answering the research question(s).	Similar to mixed methods with emphasis placed on participation.

Pragmatic researchers recognise the importance and value of the Positivist/Post-positivist and Interpretivist epistemologies, and believe that there is a single and measurable 'real world,' but human experiences also help to build knowledge and understanding of the world in which we live (Goldkuhl, 2004). Under the Pragmatism paradigm, knowledge is gained through experience and action (Goldkuhl, 2004; Morgan, 2014). The Pragmatic paradigm offers flexibility for the researcher to draw from other paradigms and methodologies for obtaining 'useful answers' (Johnson & Onwuegbuzie, 2004; Mertens, 2015).

3.1.1 A Pragmatic Choice

Severe weather IFWs bring together the measurable world of meteorology and its associated hazards (e.g., floods) and the various experiences (or realities) of people exposed to the hydrometeorological hazards (i.e., impacts). As such, it is not adequate to approach this research problem from just a Positivist/Post-positivist or Interpretivist perspective. Doing so risks excluding either the objective nature of meteorology or the subjective experiences of the impacts.

The participatory nature of Participatory Inquiry in every stage of the research introduces practical challenges to a PhD study. The participation may be limited to interviews, workshops, focus groups, and discussions at limited times that are best-suited for the 'co-researchers' and 'co-subjects' (Heron & Reason, 1997). This can introduce delays in the various stages of the research, which were deemed less than ideal for the time-limited duration of a PhD study.

The Critical Theory paradigm introduces challenges like those of the Participatory Inquiry paradigm. The need for a transactional dialogue to exchange and develop ideas may also be limited to interviews, workshops, focus groups, and discussions. Furthermore, Critical Theory researchers direct their efforts towards politics and social oppression in research (Mertens, 2015). While these issues are relevant to this research, for example for marginalised groups, it is not the sole objective to address them in this study. Thus, the Critical Theory paradigm was also not fully suited for this study.

Under a Pragmatic paradigm, the researcher recognises the importance and value of the Positivist/Post-positivist and Interpretive epistemologies and believes that there is a single and measurable 'real world,' but is aware that human experiences also help to build knowledge and understanding of the world in which we live (Goldkuhl, 2004). This is an appropriate approach for severe weather impact forecasting and warning research as it recognises both the measurable world of meteorology and the less measurable, more subjective impacts that various people experience from those hazards. Furthermore, this research is looking at what information is available and how it can be used for IFWs. Pragmatist researchers recognise the value and importance of information and go beyond this by exploring how the information is used for decision-making (Ansell & Boin, 2017). This aligns well with the scope of this research.

Furthermore, a pragmatic (i.e., 'what works') approach is appropriate for meteorological and emergency/crisis/disaster management operations and practice, where it is important to find the most effective, efficient, and usually affordable approach to achieving the immediate task (Ansell & Boin, 2017; Theis et al., 2005). For this reason, the Pragmatist research paradigm has been argued for and employed in relevant research. For example, Ansell and Boin (2017) argued that the analytical and prescriptive approach of Pragmatism provides "a way of thinking that will help practitioners prepare for, and deal with, emerging risks, crises, and disasters" (p. 1079). Additionally, Theis et al. (2005) presented a "pragmatic, low-budget postprocessing procedure" (p. 266) for probabilistic precipitation forecasts to overcome cost barriers. Thus, Pragmatism was the chosen paradigm to guide this doctoral research.

3.2 Methodology

Methodology refers to the combination of the chosen research approach (e.g., qualitative, quantitative, or mixed methods), research strategy, data collection methods, and analytical tools and techniques used to create and build knowledge and understanding of that knowledge, as shown in Figure 3.1 (Al Kilani & Kobziev, 2016; Kothari, 2004). When designing the methodology, the researcher must evaluate which research approach, strategy, and methods will be most effective in answering the research questions.

3.2.1 Research Approach

The Pragmatist research paradigm is typically associated with a mixed methods approach (Mertens, 2015). However, it is also argued that mixed methods is not the only suitable approach for Pragmatist research (Feilzer, 2010; Mertens, 2015). The Pragmatist researcher can decide on the most appropriate and effective approach to answer their research question (Feilzer, 2010; Mertens, 2015). Along with assessing the effectiveness, the researcher also seeks the most appropriate methods based on consensus from the research community (Mertens, 2015).

A qualitative research approach was deemed as the most suitable research approach for this study due to its exploratory nature of investigating an area (i.e., IFW system implementation) that has had very little research conducted on New Zealand[5]. Exploratory research is "a flexible procedure in which the scholar shifts from one to another line of inquiry, adopts new points of observation as [their] study progresses, moves in new directions previously unthought of, and changes [their] recognition of what are relevant data as [they acquire] more information and better understanding" (Blumer, 1969, p. 40). The objectives of this research reiterated from Chapter One are:

- Objective 1.1: To establish VGI as a potential source of impact data for IFWs.
- Objective 2.1: Identify the actors involved in an IFW system and their associated roles.
- Objective 2.2: Determine how HIVE data are used in an IFW system.

[5] See Potter et al., 2018; 2021 for New Zealand-specific IFW research.

- Objective 2.3: Identify further data gaps/needs for implementing IFWs.
- Objective 3.1: Identify the creators, collectors, and users of HIVE data that are relevant to severe weather IFWs.
- Objective 3.2: Identify the inhibitors and facilitators to collecting and using these data, to support the implementation of an IFW system in New Zealand for severe weather hazards.
- Objective 4.1: Identify and understand the governance and acquisition process for HIVE data for severe weather hazards in New Zealand.
- Objective 4.2: To support efforts to fulfil the Sendai Framework priorities around disaster data access.
- Objective 4.3: To support the implementation of a severe weather IFW system.
- Objective 5.1: To identify the required partnerships and collaborations required for IFW systems.
- Objective 5.2: To identify existing partnerships and collaboration in NZ that can support IFW systems.
- Objective 5.3: To outline a path forward for nurturing partnerships and collaboration for IFW systems.

Achieving these objectives involved identifying and interacting with the creators, users, sharers, and custodians of these data for the purpose of understanding current challenges with first collecting, using, sharing, and maintaining the data, and second, using it for an IFW system in New Zealand. A qualitative research approach was chosen for this study as it met the needs of this research by allowing for the development of a deeper understanding of the reasons behind processes leading to data collection, use, sharing, maintenance, and its applicability for IFW systems (Creswell, 2003). Qualitative research in IS employs several research strategies which will be described next. The most suitable research strategy for this study is also selected.

3.2.2 Research Strategy

Meeting the research objectives required engaging with the issuers of severe weather warnings, and the users of hazard, impact, vulnerability, and exposure data. The most suitable research strategies for this kind of engagement in Pragmatic IS research for this study were Action Research, Design Science Research, Practical Inquiry, Case Study, and Grounded Theory (Darke, Shanks, Broadbent, Gartner, & Pacific, 1998; Goldkuhl, 2008a, 2008b; Iivari & Venable, 2009; Peffers, Tuunanen, Rothenberger, & Chatterjee, 2007). These research strategies are summarised in Table 3.2. For a more in-depth description of the research strategies with references to the supporting literature, please see Appendix C. The following section provides an analysis of the benefits and limitations of each strategy in the context of this research, from which the most suitable strategy is selected.

Table 3.2. Summary of common research strategies used in IS research. These were identified from a review of the literature.

	Action Research (AR)	Practical Inquiry	Design Science Research (DSR)	Case Study	Grounded Theory Methodology (GT)
Description	AR is "grounded in practical action, aimed at solving an immediate problem situation while carefully informing theory" (Baskerville, 1999, p. 3).	Practical Inquiry is rooted in the Pragmatic paradigm and is focused on generating knowledge for general practice.	DSR "creates and evaluates [information technology] artefacts intended to solve identified organisational problems" (Hevner et al., 2004, p. 77).	In-depth investigation into a unit of analysis (i.e., the case).	GT is the process of building a theory by systematically gathering and analysing data through the lens of the researcher (Chun Tie et al., 2019).
Key Objective(s)	To simultaneously inform practice and research to create change.	To generate knowledge for general practice, rather than local practice as is done through AR.	To produce an artefact to address a problem. Artifacts include constructs, models, methods, instantiation, social innovations, or new resource properties.	To develop an understanding of the interactions between information technology innovations and organisational contexts.	To generate conceptual insights from empirical evidence in a systematic and rigorous way (Bryant, 2009; Chun Tie et al., 2019).
Key Characteristics	Context-dependent, heavy involvement of participants. An iterative process involving collaboration between the researcher and participants through five phases. True AR research requires that phases be completed, but variations in AR exist for varying degrees of intervention and phase completion.	Possess similar characteristics as AR, but is concerned with creating knowledge for general, practical use outside of the local practice, which also contributes to the scientific body of knowledge.	The artefact is built by drawing from existing theories and knowledge. There is no specific client or collaboration between the researcher and client, but the artefact is developed and designed for a generalised class of clients (people or organisations).	Most associated with qualitative research but is not tied to one fixed paradigm, and is flexible in ontology, epistemology, and methodology. No specific requirements guide it, which allows for tailored research design. The Case Study can be single- or multi-case (Darke et al., 1998).	Several methodological genres exist: classic-Glaserian GT , evolved-Straussian GT, and constructivist GT (Chun Tie et al., 2019). The constant comparative method offers a process for organising and analysis qualitative data (Chun Tie et al., 2019). Theoretical sampling guides data collection (Chun Tie et al., 2019). Memo writing facilitates interpretation of data.

Action Research (AR) is an applicable research strategy for this study. However, true AR with the completion of all phases was not feasible due to time and funding constraints that come with a PhD study. These limitations also apply to *Practical Inquiry Research*. It may also be difficult to apply the knowledge generated from Practical Inquiry to general practice across NZ, and outside of NZ. This is because, as was discovered in the preliminary interviews with EM officials across NZ, the warning system is not consistent across the country, and each CDEM Group has their own approach to issuing warnings (Ministry of Civil Defence and Emergency Management, n.d.). Thus, the knowledge contribution will likely be to local practice, rather than general practice. As such, it was determined that Action Research and Practical Inquiry were not suitable for this research.

The key objective of Design Science Research (DSR) is to develop an artefact to solve organisational problems (Hevner et al., 2004). Artifacts include constructs, models, methods, instantiation, social innovations, or new resource properties (Aken, 2004; Hevner et al., 2004). The objective of this study was not to design an artefact, thus DSR was deemed not suitable for this study.

The Case Study research strategy offers flexibility whilst also enabling in-depth understanding of the study case. Traditional case studies have been limited by geography and time, such as an event that occurred, or an agency/agencies (e.g., Ehnis, 2018; Yates & Paquette, 2011) The Case Study research strategy was not the most appropriate strategy for this PhD research because of the wide range of actors and organisations involved in hydrometeorological warnings and HIVE data collection in New Zealand. HIVE data are collected and used by various stakeholders, such as meteorological services, emergency management groups, risk modellers, researchers, etc. Case studies would not have captured a wide enough range of perspectives for this study.

Grounded Theory (GT), the process of building a theory by systematically gathering and analysing data through the lens of the researcher (Chun Tie et al., 2019), has become a widely used research strategy in IS research (Urquhart & Fernández, 2016; Wiesche et al., 2017). As an exploratory strategy, GT is particularly useful for research on areas with little to no prior research and where theory building is needed or desired (Fernandez, 2005; Lehmann, 2010). The field of IS research has been criticised for lacking theories developed within the IS context (Weber, 1987, 2003), due to the rapid development and evolution of information technologies (Weber, 1987, 2003). As such, GT has been identified as a viable approach for developing IS-based theories (Urquhart et al., 2010). Yet, while many IS research studies have claimed to use GT, they have been criticised for incorrectly labelling the study as a GT study when the GT was not fully utilised, and for failing to develop any theories (Urquhart & Fernández, 2016; Wiesche et al., 2017). Therefore, when GT is said to be applied for IS research, the researcher must ensure that they explicitly state how they used GT, whether for data analysis (in which case, the full methodology is not applied), or for data planning, collection, and analysis (i.e., the full GT is used) (Urquhart et al., 2010).

There is little empirical research on the data needs for IFWs. As such, GT was chosen as the research approach for this study to enable an exploration of the data needs and opportunities for IFWs, with a particular focus on New Zealand while simultaneously integrating international perspectives and experiences. Furthermore, the sampling technique commonly employed in GT (i.e. Theoretical Sampling) allows for, and encourages, a wide range of perspectives and participants to be included in the study.

The next section provides a brief history of GT and the three common branches: classic (or 'Glaserian') Grounded Theory, evolved (or 'Straussian') Grounded Theory, and Constructivist Grounded Theory. Rationale for choosing the Evolved-Straussian GT for this doctoral research is provided, followed by the research methods and tools used to conduct the research.

3.2.2.1 Grounded Theory Research Strategy

In 1967, sociologists Barney Glaser and Anselm Strauss published their seminal book titled *"The Discovery of Grounded Theory: Strategies for Qualitative Research"* (Glaser & Strauss, 1967) in an attempt to address a need for more systematic data collection and analysis methods for generating theory in social science and qualitative research. In their book, Glaser and Strauss identified concerns with an overemphasis on traditional theory testing and verification through fact-gathering (1967). They indicated that until their "discovery" of Grounded Theory, the field of sociology lacked theory development from empirical data which could then provide "relevant predictions, explanations, interpretations, and applications" (Glaser & Strauss, 1967, p. 1).

The novelties of GT lie in the fact that the concepts constructing the theory are derived directly from the data collected during the research, rather than being chosen before the research starts; and in the interrelatedness of data collection and analysis (Corbin & Strauss, 2015). Three basic principles form the foundation of the GT: (1) *emergence*, (2) *comparative analysis*, and 3) *theoretical sampling*.

The term "*emergence*" has been described as a "metaphor" (Seidel & Urquhart, 2016, p. 158) for the key principle of GT whereby categories and concepts 'emerge' (or are 'discovered') from the data through comparative analysis (Glaser & Strauss, 1967; Kelle, 2005; Seidel & Urquhart, 2016). Glaser and Strauss argued that, while GT researchers can borrow categories from existing theory (as long as the researcher continuously studies the data to ensure the categories fit), emergent conceptualisation of categories is the preferred approach to generating theory (Glaser & Strauss, 1967). This is because selecting data for a pre-existing category hinders the generation of new categories, and pre-existing categories are less relevant to the data in question, thus not the "best fitted" to the data (Glaser & Strauss, 1967, p. 37). Furthermore, trying to fit a category of another theory to the current data introduces the risk of 'forcing' the data into inappropriate categories (Glaser & Strauss, 1967). This reduces the credibility of the research (Glaser & Strauss, 1967). To facilitate the emergence of categories, Glaser and Strauss suggested the GT researcher "at first, literally to ignore the literature of theory and focus on the area under study" to ensure that emerging categories are not "contaminated" by external concepts (Glaser & Strauss, 1967, p. 37). This suggestion has been widely criticised and debated in the literature and is discussed further in Section 3.2.2.2.

Comparative analysis, the second basic principle of GT, is a commonly used term in sociology and anthropology with several different meanings (Glaser & Strauss, 1967). Comparative analysis is useful for fact checking the evidence gathered; for establishing boundaries for where to apply categories and concepts derived from the evidence (i.e., making the theory generalisable); for specifying the unit of analysis for a one-case study by comparing other possible cases; for verifying theory; and for generating theory (Glaser & Strauss, 1967). Glaser and Strauss coined the term 'Constant Comparative Method,' which encapsulates four stages: "(1) Comparing incidents applicable to each category, (2) Integrating categories and their properties, (3) Delimiting the theory, and (4) Writing the theory" (Glaser & Strauss, 1967, p. 105).

Constant comparison is an iterative process whereby the researcher breaks the data down into pieces and compares each piece against the other. For example, the researcher may start by comparing incident to incident while coding. Through this process, the researcher will start thinking about the category, its dimensions, the conditions leading to it, the consequences of it, and how it relates to other categories (Glaser & Strauss, 1967). Once codes have been categorised they can be compared to other codes in other categories, categories compared to each other, and new data compared to earlier data (Glaser & Strauss, 1967). The stages do not have to be done consecutively; the researcher can transition between stages as the research and theory development progresses (Glaser & Strauss, 1967). Through this process, the researcher will identify clues, gaps, and uncertainties that future data collection can target (Chun Tie et al., 2019). This process is termed 'theoretical sampling' (Glaser & Strauss, 1967).

Theoretical sampling is the third basic principle of GT. Glaser and Strauss defined theoretical sampling as "the process of data collection for generating theory whereby the analyst jointly collects, codes, and analyses [their] data and decides what data to collect next, and where to find them, in order to develop [their] theory as it emerges" (1967, p. 45). Initial data collection may start with a "general sociological perspective" (Glaser & Strauss, 1967, p. 45) on a subject or problem area, but these decisions are not based on a preconceived theoretical framework (Glaser & Strauss, 1967). The researcher should employ 'theoretical sensitivity' to conceptualise the theory as it 'emerges' from the data during the concurrent data collection and analysis process (Glaser & Strauss, 1967).

Theoretical sensitivity is developed by asking questions of the data and the theory, such as "What does the theory do? How is it conceived? What is its general position? What kinds of models does it use?" (Glaser & Strauss, 1967, p. 46). Theoretical sensitivity is also developed from the researcher's experiences, and their theoretical insight into their field of research (Glaser & Strauss, 1967). Through the iterative process of constant comparison through writing memos and remaining theoretically sensitive, theoretical sampling is used for data collection until 'theoretical saturation' is reached (Glaser & Strauss, 1967).

GT researchers complete the data collection phase of their research once they have reached '*theoretical saturation*'; when no new properties or insights are obtained from new data (Glaser & Strauss, 1967). An indication of theoretical saturation is when the researcher observes repetitive instances in the data and "becomes empirically confident that a category is saturated" (Glaser & Strauss, 1967, p. 61). The researcher should collect a diverse range of data to ensure that they have reached saturation; this means gathering as many differences in the data as possible and comparing them (Glaser & Strauss, 1967). Saturation is met with the combined process of data collection and analysis. Furthermore, saturation is reached category by category. As such, when saturation is met in one category, the researcher continues data collection until saturation is met for all categories. At this point, the researcher may find that gaps in their theory have been filled (Glaser & Strauss, 1967).

3.2.2.2 The Three Main Strands of Grounded Theory

Since the release of Glaser and Strauss' seminal book, *"The Discovery of Grounded Theory"* (1967), the methodology has evolved to account for apparent contradictions in the book and different interpretations of the book. A key contradiction in the book is the concepts of emergence and theoretical sensitivity (Kelle, 2005). The GT literature has documented questions, debates, and criticisms of how researchers can allow for emergence, while also practicing theoretical sensitivity. In other words, how can a researcher know what to look for in the emerging categories and concepts without drawing from their own existing theoretical knowledge or practical experience? And how can researchers ensure that they are enabling emergence, rather than forcing, if they are to be theoretically sensitive?

In their book, Glaser and Strauss indicated that they were aware of this conflict, by writing "Of course, the researcher does not approach reality as a tabula rasa. [They] must have a perspective that will help [them] see relevant data and abstract significant categories from [their] scrutiny of the data" (Glaser & Strauss, 1967, p. 3). Yet, it was still identified as a conflict or contradiction by the wider research community. In response, Glaser and Strauss each developed their own approaches to attempt to reconcile this conflict, which consequently resulted in two different strands of GT. The first strand is considered closest to the initial idea of GT and is often referred to as 'Classic Grounded Theory' or 'Glaserian Grounded Theory'. Strauss developed his own approach, referred to as 'Evolved Grounded Theory' or 'Straussian Grounded Theory'. Finally, 'Constructivist Grounded Theory' is a third strand of GT that was developed more recently by Kathy Charmaz. These three strands of GT are summarised in Table 3.3.

Table 3.3. Summary of the three main strands of Grounded Theory Methodology: Classic-Glaserian, Evolved-Straussian, and Constructivist.

	Classic-Glaserian GT	Evolved-Straussian GT	Constructivist GT
Philosophical perspective	Positivist realist ontology or postpositivist critical realist ontology, objectivist epistemology (Rieger, 2019).	Pragmatism and symbolic interactionism (Rieger, 2019).	Constructivist stance with relativist ontology and subjective epistemology (Rieger, 2019).
Coding procedures	Substantive coding Open coding Selective coding Theoretical coding	Open coding Axial coding Selective coding	Initial coding Focused coding Axial coding Theoretical coding
Analytical Tools	13-23 Coding Families. Memo writing. Constant Comparison.	The Coding Paradigm (optional). Memo writing. Constant Comparison.	The researcher can employ analytical tools developed by other grounded theorists if they are appropriate for the emerging analysis (Rieger, 2019). Memo writing. Constant Comparison.
A priori literature review	Does not encourage a priori literature review. Compromises the researcher's ability to keep the tenets of classic GT (Rieger, 2019). May waste researcher's time reviewing literature that is not significant to the core variable that eventually emerges from the data (Matavire & Brown, 2013). Danger of researcher using literature to deductively verify reviewed theoretical concepts (Matavire & Brown, 2013).	Allows for the potential of a priori literature review. Provides context and justification for the study (Rieger, 2019). Informs research questions (Rieger, 2019). Provides basis for demonstrating the appropriateness of GT for the study (Matavire & Brown, 2013). Increases theoretical sensitivity (Rieger, 2019). Satisfies institutional requirements for literature review (Matavire & Brown, 2013).	Allows for a priori literature review, which helps to orient the research(er) (Charmaz, 2014).
Research question or problem	Does not start with a research question or problem, but investigates area (Matavire & Brown, 2013).	Researcher starts with a research question as a statement about the phenomenon (Matavire & Brown, 2013).	A research question is developed before beginning the research (Charmaz, 2014).

3.2.2.3 Evolved-Straussian Grounded Theory Methodology for this study

Evolved-Straussian GT (ES-GT) was chosen for this PhD study. The primary reasons for this choice are: (1) ease of use for novice researchers (Charmaz, 2006; Kelle, 2005), (2) the allowance for a priori literature review (Hughes & Jones, 2003; Matavire & Brown, 2013), and (3) its wide use in IS research (Matavire & Brown, 2013; Urquhart et al., 2010).

ES-GT is considered the more appropriate strand of GT for novice researchers to learn as it provides clear guidelines and frameworks for data collection and analysis via the coding paradigm (Kelle, 2005). The coding paradigm used in ES-GT is said to provide novice researchers with structure and a starting point in generating categories (Charmaz, 2006; Seidel & Urquhart, 2016; Strauss, 1987). See Section 3.4.2 for more on the coding paradigm.

Despite these perceived benefits of the coding paradigm for novice researchers, the coding paradigm has received much criticism. The most notable concern with the coding paradigm is around the risks of 'forcing' versus emergence (Glaser, 1992). As Glaser and Strauss described, "to preconceive relevance is to force data, not to discover from data what really works as a relevant explanation" (1967, pp. 142-143).

Concerns of forcing by using the coding paradigm are valid because the coding paradigm stems from Pragmatist social theory (Kelle, 2005, para. 21). Thus, if the coding paradigm is applied in the wrong context, a risk of forcing exists. However, Kelle argued that upon a closer look of the conceptual design of the coding paradigm, the underlying theory of action is compatible with various sociological theories (Kelle, 2005). Furthermore, the coding paradigm appears to represent everyday human action (Kelle, 2005). While Strauss and Corbin initially viewed the coding paradigm as a mandatory tool in their methodology (1990), they have since indicated in more recent works that the paradigm is not mandatory but can be used as a 'springboard' to guide the analysis (Corbin & Strauss, 2008). The 1990 version (see Strauss & Corbin, 1990) of the coding paradigm was deemed a good fit for the data in this doctoral research, and thus was used in the analysis for this research. More on the analysis process and results for this doctoral thesis are presented in Chapter Four.

ES-GT allows for a literature review to be completed before the research is undertaken. The benefits of completing an a priori literature review, as listed in Table 3.3, are that a literature review provides context and justification for the study (Rieger, 2019); it can inform research questions (Rieger, 2019); it provides a basis for demonstrating the appropriateness of GT for the study (Rieger, 2019); it increases theoretical sensitivity (Rieger, 2019); and it satisfies institutional requirements for a literature review (Matavire & Brown, 2013). Furthermore, a literature review is expected for the completion of a PhD study, which is presented in Chapter Two and Chapter Five.

ES-GT has become a widely accepted research method in the field of IS research (Matavire & Brown, 2013; Urquhart et al., 2010). The coding paradigm is particularly useful for identifying and explaining causal relationships (Seidel & Urquhart, 2016). Axial coding and the coding paradigm from the ES-GT may provide "potential devices" for understanding causal and intervening conditions (2016, p. 191). In terms of the quality of the theories developed from ES-GT, the resultant theories may be classed as 'explaining' theory (i.e., explaining how and why things happen), as defined by Gregor (2006), because studies that applied the coding paradigm tended to produce causal relationships (Seidel & Urquhart, 2016). For example, Day et al. (2009) used ES-GT and applied the Strauss and Corbin coding paradigm to identify impediments to the flow of information in disaster relief supply chains. They found that the paradigm 'fit the data' well, and only had to alter one category, that of intervening conditions, as it was "too broadly defined" for their purposes (p. 642). Through this paradigm, they identified the causes of information flow impediments during disaster response and proposed recommendations to overcome these impediments based on the experiences of their interviewees.

Urquhart and colleagues (2010) and Seidel and Urquhart (2016) developed recommendations for researchers looking to apply ES-GT, and by extension, the coding paradigm. The recommendations from Seidel and Urquhart are summarised in Table 3.4. These recommendations were kept in mind throughout the data collection and analysis for this doctoral thesis.

3.3 Data Collection Methods

This study used a qualitative research approach. Qualitative data collection methods have been commonly used in both IS and warnings research (e.g., Potter, 2014; Prasanna, 2010). In the first phase of this doctoral research, interviews were the primary data collection method. The purpose of the interviews was to develop an understanding of the current perspectives on IFW systems in New Zealand and the associated data needs for the warning system. From these interviews, following ES-GT, a conceptual framework was developed around the data needs, sources, and uses of impact, vulnerability, and exposure data for IFW systems in New Zealand. More details on the conceptualisation of the framework are provided in Chapter Four.

The second phase of the research involved running workshops whereby the resulting framework developed from the interviews was presented to further New Zealand participants for verification and triangulation. More detail around the design and process of conducting the interviews and workshops is provided in the following sections.

Table 3.4. Summary of recommendations for IS researchers using Evolved Straussian Grounded Theory presented by Seidel and Urquhart (2016).

Recommendation	Summary
Flexible use of axial coding.	IS researchers should flexibly use axial coding "as a stage, where relationships between categories are identified" (Seidel & Urquhart, 2016, p. 190). If IS researchers apply axial coding as suggested in Strauss and Corbin (1990) they may limit themselves and risk hindering theoretical sensitivity and result in forcing of data.
A rationale for adaptations.	IS researchers should provide clear rationale for any adaptations they make to using the coding paradigm to ensure the integrity of the method.
Awareness of 'forcing' issues.	Researchers can use the paradigm as a "jumping-off point" (Seidel & Urquhart, 2016, p. 185) as opposed to rigidly using it, to avoid 'forcing.' Jointly using the coding paradigm with other coding families can enhance theoretical sensitivity. Many IS researchers that have used ES-GT opted out of using the coding paradigm, thus treating it as an option as suggested by Corbin and Strauss (2008).
Theoretical sensitivity towards causality.	IS researchers can use the coding paradigm as a "sensitizing device" (Klein & Myers, 1999; Seidel & Urquhart, 2016, p. 190). This can help the researcher think about causal relationships, which can lead to the development of a 'theory to explain' (Gregor, 2006).
Contextualisation.	Context is a feature of the paradigm. As such, IS researchers should consider using the paradigm specifically in studies seeking to uncover the context leading to the occurrence of a phenomenon. It is helpful for IS researchers to view "technology as being enmeshed with the conditions of its development and use" (Seidel & Urquhart, 2016, p. 190).

3.3.1 Interviews

A purposive sampling method (Chun Tie et al., 2019) was initially used to target and recruit interviewees based on their roles in severe weather risk communication, response, and use of impact, vulnerability, and exposure data. Recruitment was targeted towards individuals or organisations that issue hydrometeorological warnings, and/or collect, create, share, manage, maintain, and/or use hazard, impact, vulnerability, and exposure data for severe weather hazard and risk management. Potential participants were identified through networks and contacted directly via e-mail. After the initial interviews were conducted, theoretical sampling guided the rest of the data collection process for this research whereby recruitment targeted participants who were knowledgeable or experienced with themes that emerged from previous interviews (see Section 3.2.2.1).

Data collection took place from November 2018 to May 2021. The purpose of the interviews was to supplement the gaps in the literature around the data needs and potential sources for IFW systems. The interview script was semi-structured to allow for follow-up questions to be asked based on interviewees' responses, and to follow-up on emerging themes in the interview (Patton, 2015). Questions were asked regarding the participants' thoughts on IFWs (e.g. what they know about it, perceived challenges and benefits, requirements for implementation); what kind of impact, vulnerability, and/or exposure data they use, why, and how; the life path of the data (e.g. how it is obtained, used, stored, what happens to it after its intended use), experienced and/or perceived challenges with obtaining the required data for IFWs and other uses; thoughts on collecting and using alternative data sources (e.g. social media and crowdsourcing) to address their challenges (if they identified any). See Appendix D for the interview questions. The interviews were transcribed verbatim for subsequent analysis.

3.3.2 Workshops

Workshops were conducted in the second stage of data collection to diversify the qualitative dataset and to triangulate the research findings (Corbin & Strauss, 2015; Gibson, 2007). Workshops were chosen to capture a wider coverage of participants with diverse perspective for facilitating co-creation of knowledge (e.g., Belanger, 2012; Henriksen et al., 2018; Potter et al., 2021). Furthermore, nurturing partnerships and engaging with stakeholders is an important process for the successful implementation of IFWs (Hemingway & Gunawan, 2018; WMO, 2015), and workshops were deemed an effective method for stakeholder engagement and nurturing partnerships.

3.3.2.1 Virtual Workshop Methods

The workshops were held virtually due to COVID-19 concerns. From 12 to 30 August 2020, Auckland went into Alert Level 3[6] (partial lockdown), and the rest of the country moved from Alert Level 1 to Alert Level 2, introducing physical distancing measures. From 30 August to 7 October 2020 Auckland was in Alert Level 2, while the rest of the country moved back to Alert Level 1 on 21 September 2020. On 7 October 2020, Auckland moved back to Alert Level 1 with the rest of the country. Due to the uncertainty around the changing COVID-19 Alert Levels and concerns with traveling across the country, the workshops were held virtually over Microsoft Teams.

The web-based whiteboarding platform, Mural[7], was used to facilitate the workshop. A virtual whiteboard was mapped out with specific questions and activities for the participants to navigate and interact with. Prior to the day of the workshop, participants were provided with training resources to become familiar with the Mural platform. Workshop questions and activities are available in Appendix E.

Participants were asked to provide feedback on the impact, vulnerability, and exposure data framework that resulted from the interviews. They were then asked to identify data requirements and sources for IFWs from the perspective of their roles and agencies. The third activity requested the participants to identify 1-2 datasets/data sources that are important and outline the life track of the data, and to

[6] The New Zealand government implemented a 4-level COVID-19 alert level system to inform the population on what measures are needed to reduce the spread of the virus (https://covid19.govt.nz/about-our-covid-19-response/history-of-the-covid-19-alert-system/).
[7] https://www.mural.co/

describe how they understand what impacts are occurring or could occur from a severe weather hazard. The fourth activity looked at identifying alternative uses for the datasets/data sources that they identified, beyond IFWs. Finally, the last activity investigated the application of the framework: whether the participants would use it, why or why not, and how. The workshops were audio recorded through Microsoft Teams, and data from the virtual sticky notes were entered into a spreadsheet for further analysis. More detail on the workshop results and the number of participants is provided in the next chapter, Chapter Four.

3.4 Analytical Techniques and Tools

Data collection and analysis occur concurrently in GT to facilitate theoretical sampling. Data collection and analysis are complete when saturation has been met and the core category/ies has/have been identified (Strauss & Corbin, 1990). Analysis for this doctoral thesis occurred in the form of constant comparison, memo writing and diagramming, and coding. Nvivo 12, a qualitative data analysis software package, was used to support the transcribing, coding, and memo writing. Nvivo 12 is an industry-standard and facilitates data management, idea management, data querying, graphical modelling of ideas and concepts, and data reporting (Bergin, 2011).

3.4.1 Memo Writing and Diagramming

Memos are "written records of analysis" (Corbin & Strauss, 2015, p. 57). Memo writing allows the researcher to document the constant comparison analysis, and to formulate and deepen their thoughts (Corbin & Strauss, 2015). The GT researcher should continuously write memos and draw diagrams to track their analytical process and draw out conceptual connections between categories (Strauss & Corbin, 1990). As such, GT researchers are encouraged to "stop coding and record a memo on your ideas" (Glaser & Strauss, 1967, p. 113). Memo writing and diagramming were carried out in this study throughout the data collection and analysis process. Evidence of this is presented in Chapter Four.

3.4.2 Coding

Coding is described as "denoting concepts to stand for meaning" (Corbin & Strauss, 2015, p. 57). Coding in ES-GT takes place in three stages: open coding, axial coding, and selective coding. Figure 3.2 provides a visualisation of the ES-GT data collection and analysis process employed in this doctoral research.

When open coding the researcher codes the data by line, sentence, or paragraph (Charmaz, 2006). Axial coding investigates the relationships between concepts and categories resulting from the open coding process (Strauss & Corbin, 1990). When axial coding, the researcher can employ Strauss and Corbin's coding paradigm for guidance (Strauss & Corbin, 1990). Selective coding, also referred to as theoretical integration in Corbin and Strauss' 2008 and 2015 texts, involves relating all categories to the core category/ies and to each other to develop the Grounded Theory. A core category is one which is central, where all major categories relate to it (Matavire & Brown, 2013). Multiple core categories may be identified (Strauss &

Corbin, 1990). Open coding, axial coding, and selective were conducted in this research until the core category/ies were identified and integrated.

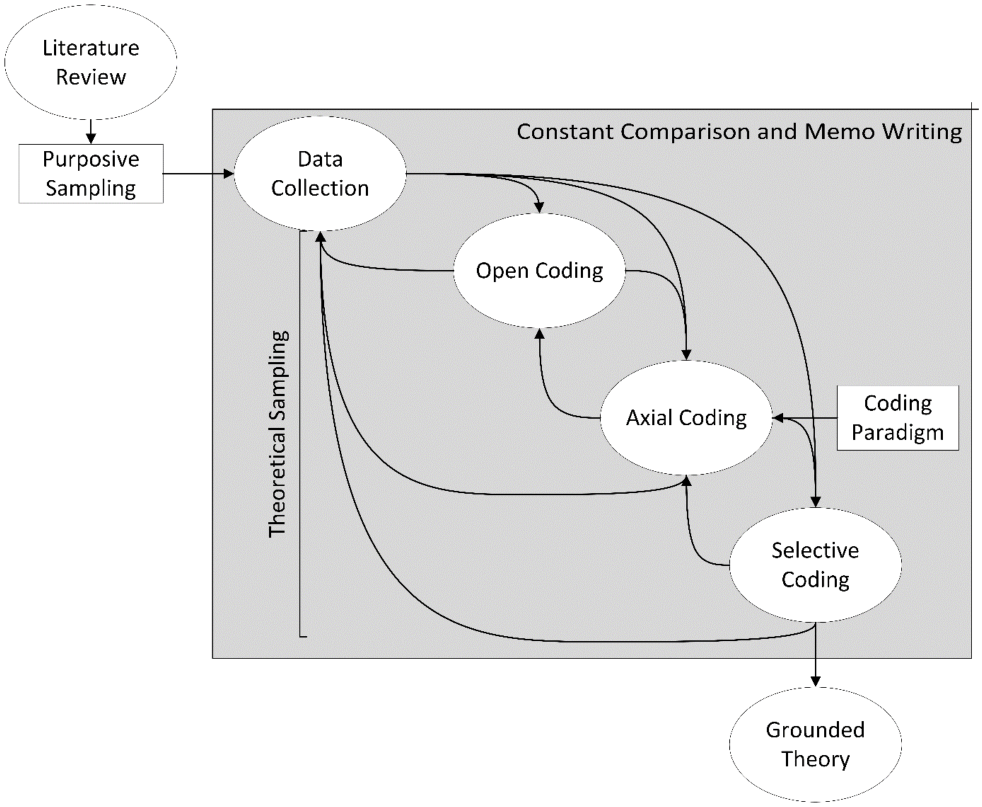


Figure 3.2. Conceptual framework of the ES-GT analytical process employed in this research. Figure created by S. Harrison based on interpretations of Corbin and Strauss (2015), Corbin and Strauss (2008), Charmaz (2006), and Glaser and Strauss (1967).

Open coding, typically the first step in analysing the data in ES-GT, was carried out by conceptualising and categorising the data piece by piece and constantly comparing the data (Vollstedt & Rezat, 2019). Open codes were created to describe the core idea of concepts (Vollstedt & Rezat, 2019). Data that are categorised and conceptualised into one code is called a 'concept', and concepts that are related to each other to form a concept of a higher order are called categories (Strauss & Corbin, 1990). The goal of open coding is to develop rich analytical codes to describe the data (Vollstedt & Rezat, 2019). Theoretical sensitivity was applied throughout the coding process, which is developed from the researcher's expertise, experience, and knowledge of the literature (Vollstedt & Rezat, 2019).

Axial coding, the second phase of coding in ES-GT, was used in this research to investigate the relationships between concepts and categories resulting from the open coding process (Strauss & Corbin, 1990). After the data were broken up into pieces (concepts and categories), axial coding was used to piece the data back together to form higher conceptual codes (Vollstedt & Rezat, 2019).

The coding paradigm, a tool introduced by Strauss and Corbin (1990) to aid in the axial coding process, was used in this research as it was found to fit well with the data. The coding paradigm focuses on phenomena, causal conditions, contextual conditions, intervening conditions, action/interaction strategies, and consequences (see Table 3.5). By using the coding paradigm, open codes were linked back to these five dimensions for increased density and precision in the resulting theory (Strauss & Corbin, 1990). Axial coding was completed by relating each code and category to the coding paradigm dimensions presented in Table 3.5. Upon completing the axial coding phase selective coding was conducted as the final stage of analysis.

Table 3.5. Coding paradigm summary (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).

Coding Paradigm Dimension	Description
Causal Conditions	A set of events that influence the phenomena or result in the appearance or development of a phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Phenomenon	The subject or object under study (Strauss & Corbin, 1990).
Contextual Conditions	The specific set of conditions and characteristics surrounding the phenomena and resulting in action/interaction strategies taken to address the phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Intervening Conditions	Unexpected events or factors leading to action/interaction strategies (e.g., time, space, culture, socioeconomic status, technological status, history) (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Action/Interaction Strategies	Purposeful and deliberate acts taken to address the phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Consequences	Predictable or unpredictable, intended or unintended outcomes of the action/interaction strategies (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).

Selective coding in this doctoral thesis involved relating all categories to the core category/ies to develop the Grounded Theory. The core category/ies are categories that "incorporates or supersedes other categories in explanatory importance and hence is 'elevated' to the status of an important concept" (Timonen et al., 2018, p. 7). The goal of selective coding is to integrate all of the different categories resulting from axial coding into one cohesive theory (Vollstedt & Rezat, 2019). Selective coding aims to answer the questions "*What is the research all about?*" and "*What seems to be going on here?*" by relating the core category to all of the other categories (Corbin & Strauss, 2008, p. 14). In this stage, relations were validated, and categories were refined and further elaborated (Vollstedt & Rezat, 2019).

Once the relationships between codes were established through axial coding, supported by the coding paradigm, selective coding commenced to unify the resulting categories around a core category (Corbin & Strauss, 2008). Through continuous reflection, constant comparison between codes and categories, re-assignment of codes and categories, memo-writing, and diagramming, the core category was established. The last three interviews were conducted to explore any unclear aspects or outstanding questions of the core category to confirm or negate propositions made around the core category based on previous coding analysis.

3.5 Ethical considerations

A 'low risk' ethics notification was lodged with the Massey University Human Ethics Committee prior to data collection in 2018 (see Appendix F). Participants received information sheets and consent forms which they signed and returned. All interviewees remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by area of expertise and/or practice (e.g., Meteorology, Emergency Management, Data Management), industry (e.g., Private, Governance), location (e.g., NZ or International), or governance level (e.g., National, Regional, Local) (Table 3.6). The acronyms and abbreviations in Table 3.6 are as follow: Meteorology (Met.), Emergency Management (EM), New Zealand (NZ), Geographic Information Systems (GIS), Regional (Reg), Government (Gov.), Early Warning System (EWS), International (Int.).

Table 3.6. Interviewee codes.

Interviewee Code	Position	Classification	Location	Government Level
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ	National
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ	National
Data Management Private NZ. B	Geospatial Specialist	Data Management	NZ	
Data Management Research NZ. C	GIS Specialist	Data Management	NZ	
Data Management Private NZ. D	GIS Specialist	Data Management	NZ	
Data Management Gov. NZ. Nat. E	Head of Data	Data Management; Governance	NZ	National
EM. NZ. Reg. A	Director	Emergency Management	NZ	Regional
EM. NZ. Reg. B	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. C	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ	Regional
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ	Regional
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ	National
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Nat. I	First Responder	Emergency Management	NZ	National
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ	National
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ	Regional
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ	Regional
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ	Regional

Interviewee Code	Position	Classification	Location	Government Level
Hyd. Gov. NZ. Reg. A	Flood EWS Programme manager	Hydrology; Governance	NZ	Regional
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ	Regional
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ	
Met. Int. A	Science Manager	Meteorology	International	National
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	International	National
Met. Int. C	Senior Policy Officer	Meteorology	International	National
Met. Int. D	Senior Social Scientist	Meteorology	International	National
Met. Int. E	Consultant Meteorologist	Meteorology	International	National
Met. NZ. F	Senior Meteorologist	Meteorology	NZ	National
Met. NZ. G	Communications	Meteorology	NZ	National
Met. NZ. H	Public Relations	Meteorology	NZ	National
Met. Int. I	Division Chief/Meteorologist	Meteorology	International	National
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ	National
Met. NZ. K	Senior Meteorologist	Meteorology	NZ	National
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ	
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ	National

3.6 Evaluation of Rigour and Credibility

Ensuring credibility and rigour in Grounded Theory research involves several measures of evaluation similar to those of other qualitative research methods. Corbin and Strauss (2008) provided a set of evaluation criteria which were used to ensure the credibility and rigour of this research, presented in Table 3.7.

Table 3.7. Criteria for evaluating qualitative research (Corbin & Strauss, 2008).

Criteria	Description
Fit	Do the findings resonate/fit with the experience of both the professionals for whom the research was intended and the participants who took part in the study?
Applicability	The usefulness of the findings. Do the findings offer new explanations or insights? Can they be used to develop policy, change practice, and add to the knowledge base of a profession?
Logic	Is there a logical flow of ideas? Do the findings "make sense"? Or are there gaps or missing links in the logic that leave the reader confused and with a sense that something is not quite right? Are methodological decisions made clear so that the reader can judge their appropriateness for gathering data and doing analysis?
Depth	Are the descriptive details rich and varied, and do they lift the findings out of the realm of the ordinary?
Variation	Has variation been built into the findings, meaning are there examples of cases that don't fit the pattern or that show differences along certain dimensions or properties?
Creativity	Are the findings presented in an innovative manner? Does it say something new or put a twist on an old idea?
Sensitivity	Did the researcher demonstrate sensitivity towards the participants and to the data? Did the analysis drive the research or was the research driven by preconceived ideas?
Evidence of Memos	Since a researcher cannot possibly recall all the insights that go on during analysis, memos are among the most necessary of all procedures. Thus, there should be some evidence or discussion of memos in the final report.
Concepts	Concepts are necessary for developing common understandings and for professionals to talk among themselves, therefore one would expect that findings would be organized around concepts/themes.
Contextualisation of Concepts	Without the context of the concepts, the reader cannot fully understand why events occurred and ascertain the meaning of the experiences being described

Triangulation and member-checking were carried out to ensure the fit and applicability of the findings. Triangulation is the use of multiple approaches to increase the credibility and validity of a study. Interviews, workshops, and document analysis were employed in this study (Creswell, 2003; Patton, 2002). First, three workshops were conducted after most interviews were conducted to collect diverse perspectives and receive feedback on the resulting HIVE data framework that was developed from the interviews (e.g., Figure 4.9). In these workshops, the data framework was presented to workshop participants who were asked to provide feedback through a set of pre-determined questions and activities. Document analysis provided further validation against participants' statements and the researcher's own understanding of the DRR and EWS processes in NZ. For example, when participants referred to specific events like the 2017 Edgecumbe flood and the 2010-2011 Canterbury earthquake sequence, further documentation of these events was tracked down to verify the claims made by participants and to fill in any outstanding gaps from those discussions. In another example, documentation from LINZ (e.g., LINZ, 2014a, 2014b) and NEMA (e.g., NEMA, 2020a; NEMA, 2020c) were sought and used to clarify processes of data collection and management.

Member-checking tests the accuracy of research findings by presenting the findings to the participants for feedback (Stake, 1995). Member-checking was done by providing the results chapters to the participants for feedback on how their words were interpreted and presented. The participants were asked to return their feedback within two weeks and were informed that if they did not return feedback by the specified deadline, it was assumed that they had no feedback. Most of the participants who replied were pleased with how their words were interpreted and presented. Seven participants returned feedback which consisted of slight changes to their direct quotes, further elaboration or clarification on their quotes, re-interpretation of their words, and suggestions for terminology and literature references. All these suggestions were adopted into the final doctoral thesis.

Logic was ensured by requesting feedback from the supervisory team throughout the data collection, analysis, and writing phases. This provided supervisors with regular opportunities to identify critical gaps in data collection, analysis, and reporting that required further investigation and/or clarification. Furthermore, when 'new' ideas and concepts were identified from the analysis, the researcher consulted with the literature to provide clarity and additional understanding of these ideas. For example, when the concept of 'Individual and Community leadership' was found to be an action/interaction strategy for overcoming misdirected management priorities and lack of motivation or interest, the literature was consulted to verify this finding with existing theories; it was found that the Policy Capacity Framework provided a fitting explanation for this concept, as reported in Chapter Seven.

Variation was achieved through theoretical sampling and constant comparison such that the data and resulting codes were constantly compared against each other and against new data pieces (Strauss & Corbin, 1998). For example, in the early stages of conducting interviews, participants from meteorological services pointed to EM services for collecting impact data. Thus, EM agencies were targeted for subsequent interview recruitment to verify these suggestions and gain further understanding of EM agencies' data collection practices. EM agencies and meteorological services also pointed to regional councils and hydrologists for knowing more about flood impacts and warnings. As such, regional councils and flood hydrologists were recruited for further verification and validation. Cases that varied from the trend or pattern were picked up and investigated further. For example, while most participants were found to support the concept and goals of IFWs, one participant varied from this trend. This participant offered a different perspective of IFWs and provided their reasons for this variation. This variation was compared against the trend and further explanation was sought from the literature, as reported in Chapter Six.

The researcher strived to maintain sensitivity to the participants and to the data at every point in the research process. In the early stages of the research, when the researcher felt that a particular research solution was being forced without the strong presence of a research problem, the researcher made the critical decision to pivot the focus of the research to address a problem that was being identified by the research participants. Thus, the researcher practiced sensitivity to the participants and their contexts from this pivotal point until conclusion of this research.

Memos were written during initial research problem definition, data collection, and data analysis. These memos played a critical role in the researcher's reflections and explorations of emerging themes, concepts, and relationships.

The presentation of the findings is organised by phenomena and core category in the first order (i.e., research paper topic). In the second order, the findings pertaining to each phenomenon are organised and presented by theme and/or concept. Further context of these themes and concepts is provided in the reporting of the findings. Thus, this ensures that concepts and contextualisation of concepts are presented and discussed in detail.

3.7 Chapter Summary

This chapter described the overall design of the research by first justifying the choice of the Pragmatic paradigm to guide this doctoral research, followed by the methodology, which consists of the research approach, research strategy, data collection methods, and analytical techniques. A qualitative research approach was chosen for this exploratory study, using the Evolved-Straussian Grounded Theory research strategy. The next chapter presents the results of the data collection methods and overarching findings from the analysis.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight Data Governance and Access for Severe Weather Hazards and Impacts
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Four: **Data Collection, Analysis, and Overarching Findings**

This chapter presents the results of the data collection methods, and the overarching findings from the Evolved-Straussian Grounded Theory (ES-GT; Strauss & Corbin, 1990) analytical techniques employed in this PhD study. The purpose of this chapter is to demonstrate the use of the ES-GT data collection methods and analytical techniques in more depth than could be provided in the resulting manuscript chapters (Chapter Six, Chapter Seven, Chapter Eight, and Chapter Nine). The chapter first describes the process of collecting the data by conducting a series of interviews (Section 4.1) and workshops (Section 4.2) followed by presenting the results obtained after analysing the data collected from the interviews and workshops (Section 4.2.3). The chapter then introduces the two phenomena under study in this PhD research along with an elaboration of how they were identified through the axial coding process (Strauss & Corbin, 1990). Finally, the chapter presents the identified core category that resulted from the selective coding process (Corbin & Strauss, 2015). A chapter summary (Section 4.4) concludes this chapter.

4.1 Data Collection: Interviews

In this study thirty-nine (n=39) individuals were interviewed. The interview participants were recruited based on their roles and interactions with severe weather risk communication and hazard, impact, vulnerability, and exposure data, as shown in Table 4.1. Meteorological experts (e.g., Senior, consultant, and communication meteorologists, social scientists, senior policy advisors, and public safety managers) from National Meteorological Services (NMS) both inside and outside of New Zealand (NZ) were recruited. Officials from agencies outside of NZ were sought to understand international perspectives that may help implementation efforts in NZ. NZ-based leaders, chief operators, communications specialists, data specialists, and hydrologists were sought from the NZ Civil Defence and Emergency Management (CDEM) sector to understand local and regional practices in collecting and using hazard, impact, exposure, and vulnerability information. NZ-based experts in data creation, management, standards, and custodianship, and experts in risk and loss modelling were also sought. Furthermore, the theoretical sampling resulted in additional recruitment of one public health worker, one Lifelines group manager, and one agriculture policy coordinator.

The interviews ranged in length from 45 minutes to 1.5 hours. Interviews were audio-recorded and transcribed verbatim for further analysis. Due to the COVID-19 pandemic and the nature of the targeted participants, recruitment was limited towards the final months of data collection as many of the target participants were responding to COVID-19. Interviews were conducted both in person and virtually. Prior to COVID-19, in-person interviews were conducted with participants located in the same vicinity as the researcher (i.e., in Wellington, NZ), and virtual interviews were conducted with participants outside of Wellington using either the telephone or Zoom, depending on the participant's preference.

Table 4.1. Summary of targeted and recruited interview participants.

Category	n	General Roles	Representation
Hydro-meteorological Experts	6	Senior, consultant, and communication meteorologists, social scientists, operational manager, senior policy advisors, and public safety managers	International: Argentina, Australia, Austria, United Kingdom, USA
	6	Meteorologists, operational manager, communication meteorologist, senior policy advisor, Weather analyst	New Zealand: MetService, NIWA, Weather Watch
	1	Regional flood specialist	New Zealand: Greater Wellington Regional Council
Emergency Management and Response Sector	3	First responder, Senior Hazard Risk Management Advisor	New Zealand National Level: National Emergency Management Agency (NEMA), Fire and Emergency New Zealand (FENZ)
	9	Chief operators, communications specialists	New Zealand Regional Level: Auckland, Bay of Plenty, Canterbury, West Coast, Northland
Data Creation, Management, Standards, Custodianship	2	Geographic Information Systems (GIS) specialists	Private Industry: Eagle Technology, Independent
	3	GIS specialists, Statistical Analysis specialist	Public Sector: Land Information New Zealand, Stats NZ/DataVentures, West Coast
	1	GIS specialist	Research: Massey University
Risk and Loss Modelling	4	Risk modellers	Research and policy: GNS Science, NIWA
	1	Loss modeller	Research and policy: Victoria University of Wellington
Other	1	Public health worker	Practice: Regional hospital
	1	Civil Engineer	Practice: Wellington Region Lifelines Group
	1	Agriculture policy coordinator	Practice: Federated Farmers
Total	39		

During the NZ COVID-19 lockdown (Alert Level 4) from 25 March 2020 to 27 April 2020, and during Alert Level 3 (27 April 2020 to 11 May 2020) and Alert Level 2 (11 May 2020 to 8 June 2020; 12 August 2020 to 30 August 2020), all interviews were conducted virtually using either telephone, Microsoft Teams, or Zoom, depending on the participant's preference. During Alert Level 1 (8 June 2020 to 12 August 2020; 20 August to present), interviews were conducted according to the participants' location and preference (i.e., in person or virtually). From these interviews, following ES-GT, a theoretical framework was developed around the data needs, sources, and uses of impact, vulnerability, and exposure data for IFW systems in New Zealand. This framework was then verified through the workshops.

4.2 Data Collection: Workshops

Three workshops were held in the final stages of the research. EM officials and MetService staff participated in two regional workshops for Auckland and Southland. A third workshop was conducted with researchers and scientists from GNS Science who are involved in hazard and risk management in NZ. Workshop participants were recruited via email using existing connections from previous interviews and the research team's network. The processes and results of the workshops are described next. All three workshops were conducted virtually due to uncertainty around changing COVID-19 restrictions. The virtual whiteboard platform, Mural, was used to facilitate all three workshops and capture participants' response.

4.2.1 Auckland Region Workshop

The first workshop was held with Auckland Council and Civil Defence on 12 October 2020. Auckland is the largest urban centre in NZ, located in the north of the North Island (Figure 2.6). More information on the hydrometeorological hazard profile of Auckland is provided in Appendix G. Auckland Council was chosen for the first workshop due to their experience with notable hydrometeorological events, such as the 2017 New Lynn storms and consequent flood, and the 2018 windstorm (Golubiewski, 2019; Smol, 2018). Furthermore, as a large metropolitan city, Auckland offers an urban context to this PhD study.

Four people attended the Auckland workshop, representing Auckland Civil Defence, the MetService, and Auckland Council from the Planning Department and the Healthy Waters Department. Every participant joined Mural individually while being connected through Microsoft Teams. This allowed for each participant to enter their own virtual sticky notes and contributions into the Mural 'whiteboard'. The participants were asked to assign a unique colour to their sticky notes and keep that colour for the duration of the workshop for ease of tracking responses, as shown in Figure 4.1. With each activity, participants were given time to enter their responses and share them with the group.

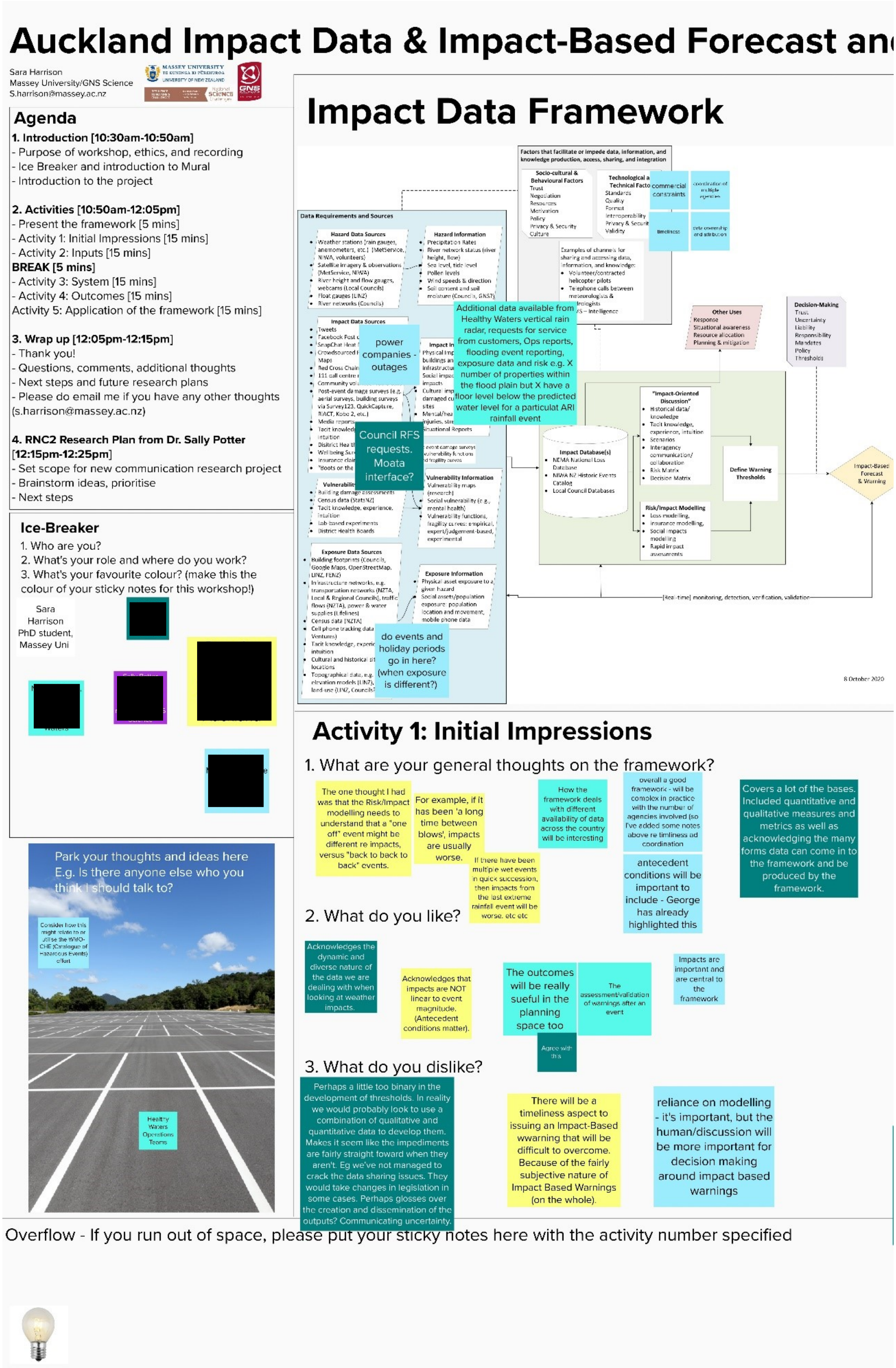


Figure 4.1. Final image of the populated Mural whiteboard from the Auckland Workshop on

12 October 2020.

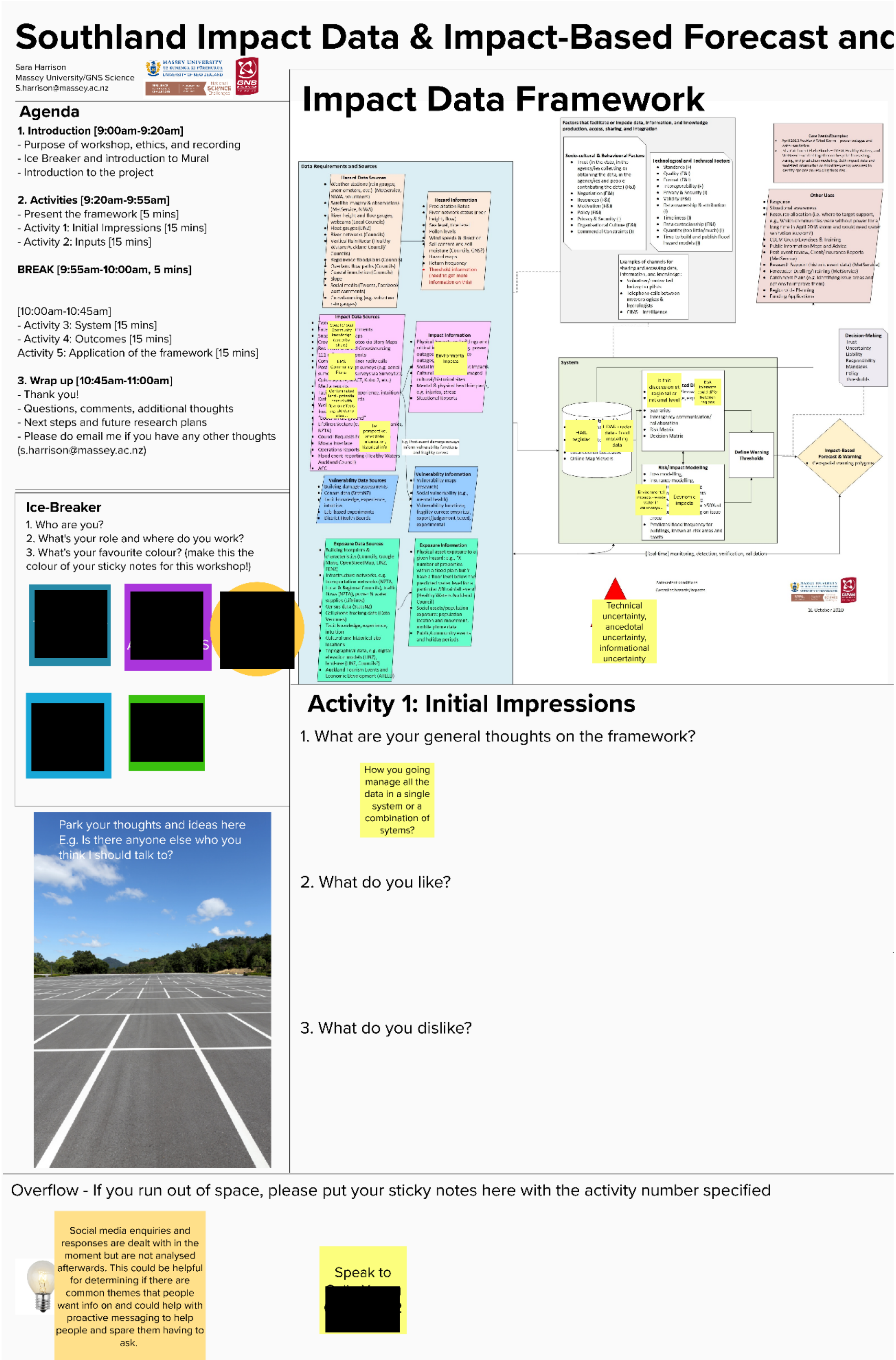
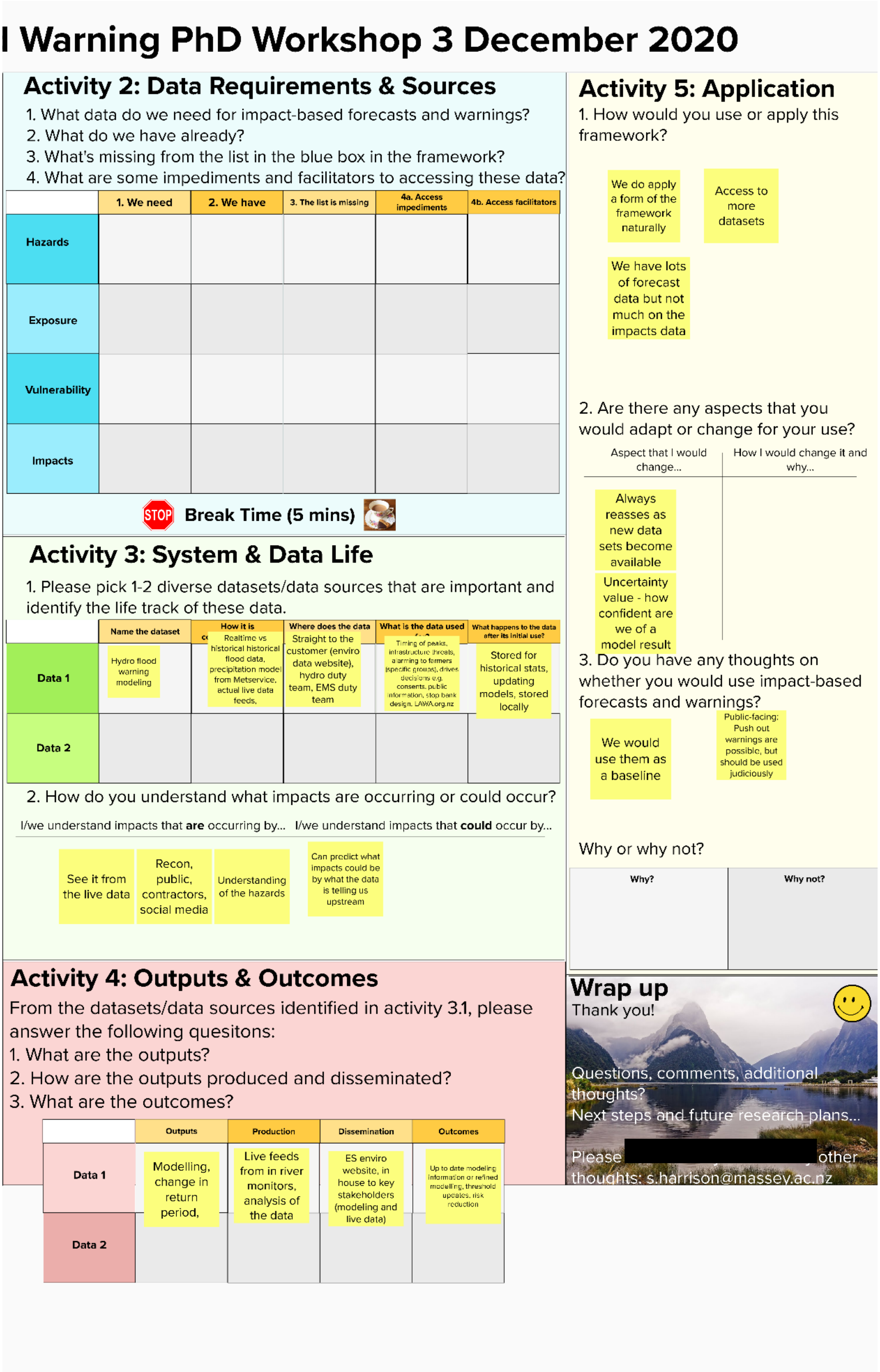


Figure 4.2. Final image of the populated Mural whiteboard from the Southland Workshop on



3 December 2020.

4.2.2 Southland Region Workshop

The second workshop was held with Southland Council and Civil Defence on 3 December 2020. Southland is the southernmost region of NZ, located on the southwestern portion of NZ's South Island. Southland is considered a remote region, and thus provides a rural context. In February 2020, Southland experienced heavy rainfall, floods, and landslides. Southland Region was selected for the second regional workshop because of this event which resulted in the NZ MetService issuing its first Red Warning since the implementation of the new warning system (see Chapter Two). Furthermore, Southland is the southernmost region of NZ, located on the southwestern portion of NZ's South Island, providing a geographic spread for these regional workshops and a rural context. See Appendix G for more on the hazard profile of Southland.

Five people attended the Southland workshop, representing Southland Regional Council from the Geographical Information Systems (GIS) team, the Hydrology team, Communications and Engagement team, and Emergency Management Southland. All Southland participants coordinated with each other and joined the Microsoft Teams meeting from the same physical meeting room, sharing one keyboard between five participants. This was an unexpected outcome and made it difficult to record each participants' responses onto virtual sticky notes as the keyboard had to be shared until one person was anointed scribe to record the responses. While this resulted in less detailed responses on the Mural (see Figure 4.2), the discussion was found to be richer than that from the completely virtual Auckland workshop.

4.2.3 Community of Research Workshop

A third virtual workshop was conducted with a portion of the risk and hazards research community in New Zealand. Researchers and scientists from GNS Science were invited to participate in a virtual workshop to understand the organisation's current position and plans around IFWs. GNS Science is a Crown Research Institute (CRI) of New Zealand. The agency is heavily involved in the management of natural hazards risks across New Zealand by providing scientific evidence for response, planning, and policy (GNS Science, n.d.; Woods et al., 2017). The workshop was organised by Dr. Sally Potter and Dr. Danielle Charlton from GNS Science, and myself. The workshop design included a data collection activity for this PhD study where the participants were asked to share their feedback on the data process framework that resulted from previous interviews and workshops (see Section 4.3.1 for more). Eleven people from GNS Science attended the virtual community of research workshop

4.3 Data Analysis and Key Findings

Various tools and techniques were used following the ES-GT research strategy to guide the analysis of this PhD study, as outlined in Chapter Three. The following sections provide further details of the analytical process and key findings, including the ensuing codes, categories, phenomena, and core category. Integration of these analytical findings with literature is provided in the resulting manuscripts and chapters (Chapter Six to Chapter Nine).

4.3.1 Memo writing and diagramming

Memo writing and diagramming were two techniques regularly used throughout the data collection and analysis for this study. When the researcher noticed common themes emerging from the interviews, a memo was written to identify the theme and begin to understand the potential significance of the theme. For example, on 4 November 2019, a memo was created regarding the emergence of exposure:

Memo: Emergence of Exposure, Harrison, S., 4 November 2019

Interviewee 12 has a clear bias towards exposure for risk/impact modelling because they are working on a project to develop a population exposure model. However, I think this bias is not undue, and is valid because the literature around impact-based warnings lists exposure as one of the factors for impact-based warnings, and exposure is an important piece of the risk modelling puzzle. Fragility functions or vulnerability curves are based on asset exposure, be it buildings, infrastructure, or people.

From the discussion with my first participant, it has become clear that exposure, particularly exposure of people, is important yet difficult to capture. I think this is an important, and interesting area to explore.

Until this point in the data collection and parallel analysis, exposure and vulnerability were not considered within the scope of this research, with impact data being the sole focus. However, after writing this memo, returning to the literature for further verification, and discussing with supervisors, it was decided to expand the focus of this research onto exposure and vulnerability data. Following this decision, after more data was collected regarding exposure, another memo was written:

Memo: Emergence of Exposure, Harrison, S., 5 January 2021:

Since [4 November 2019], the concept of "dynamic exposure" has come up. I haven't been able to find a definition of it, but my guess is that it's the changing of exposure over space and time. We already know that exposure changes over space and time, so the term "dynamic exposure" might be a bit redundant. But this term seems to be used mostly in the risk modelling space, so perhaps the idea is to bring attention to the need for capturing the dynamic nature of exposure, and how to capture that? This is a challenge that has already been identified in the literature. Some ideas for capturing "dynamic exposure" *are using mobile phones for population movement, social media, crowdsourcing. Data Ventures, a branch of Stats NZ, is playing with mobile phone data for COVID-19 analysis. There is potential to use this data for early warning systems as well.*

Exposure is a tricky factor for IFWs. It is (arguably) an important factor for defining warning thresholds. But as my MetService forecaster participant described, exposure is different at all scales, and the warnings are not currently issued at all scales. So which scale do we pick for the warning thresholds? And how can we justify excluding people who may be exposed but don't meet the warning criteria, and thus do not receive a warning?

Upon identifying the theme of exposure, the researcher then compared physical and social impacts and exposure, which became another memo:

Memo: Physical vs. Social/Human Impacts and Exposure, Harrison, S., 4 November 2019:

As I discovered in my first interview, there's a clear emphasis on the physical world when talking about risk and impact data and assessments. The focus in New Zealand, to date, has been on capturing the physical impacts of hazards, such as earthquakes. This means a lot of emphasis on capturing the physical damage to buildings, service utility networks, and key infrastructure. There has been minimal attention paid to social impacts, aside from counting deaths and injuries. What about traffic delays? Evacuation routes and delays? Service outages?

When talking about data, for the past two interviews, much of the focus was on assets of buildings, service utilities networks, and key infrastructure. Discussion about population exposure is cropping up, though, and there's a clear emerging shift in the direction of risk and impact modelling towards modelling social impacts. But what are social impacts? It could be service outages and their effect on how people live their day-to-day lives, it could be evacuation routes and behaviours, traffic delays, etc.

What kind of impacts are we interested in for impact-based warnings? Just physical? or social as well?

This led the researcher to attempt to identify sources of social/human impacts and exposure in subsequent interviews, whereby Wellbeing surveys/welfare assessments were identified as a potential source for capturing social/human impacts:

Memo: Physical vs. Social/Human Impacts and Exposure, Harrison, S., 21 February 2020:

Welfare assessments that take place during an event, as mentioned by the participant in Interview 15, are a potential data source for social impacts. However, this data contains a lot of personally identifiable information (PII), that it is next to impossible to obtain this data. The most that could be obtained from this kind of information is a high-level summary of the results of the assessments, *as mentioned by participant from Interview 14 (from MCDEM/NEMA), and participant from Interview 15 (regional CDEM).*

In line with these memos, interview questions specifically asked meteorologists and emergency management officials about using exposure and vulnerability for warnings and collecting exposure and vulnerability data.

Following interviews with CDEM Groups and meteorologists, diagrams were drawn to visualise the warning and data collection processes described by interviewees. For example, Figure 4.3 and Figure 4.4 are diagrams that were drawn following interviews with the West Coast CDEM Group and Emergency Management Bay of Plenty, respectively, to visualise and understand the severe weather warning processes within those groups. Similar diagrams were drawn following interviews with the other participating CDEM Groups and meteorological services. These diagrams were compared and digitised into a more generalised diagram of the severe weather warning chain, shown in Figure 4.5.

Diagramming was also performed to represent the data collection and use process in the context of IFWs based on interviews. This resulted in several iterations of an impact data framework. For example, Figure 4.6 shows the first iteration of the framework drawn on 8 October 2019. At this point, hazard, vulnerability, and exposure data were considered out of the scope of this research. Following the emergence of the exposure theme as documented in the memo writing, exposure data sets began to be identified, as shown in Figure 4.7. In October 2020 after a year of data collection via interviews, the framework became more filled in as shown in Figure 4.8.

The diagram in Figure 4.8 was presented to the workshop participants for feedback and validation. Based on feedback from the workshops and additional interviews, the framework was updated again and presented to the GNS workshop participants as shown in Figure 4.9. At this point, uncertainty about forecasting impacts was identified in interviews and workshops as a concern for IFWs. It was drawn in as an increasing wedge to represent the compounding uncertainty that begins from hazard forecast through to the warning. The diagram was also simplified to allow workshop participants to focus on key gaps in the framework which were represented as dashed lines, where the link from risk modelling to warning remained unclear.

Further memo writing and comparisons between the warning chain diagram and the data framework process diagram were conducted to determine how these two frameworks/concepts could be integrated. It was found that the impact data process framework focused heavily on the process for collecting and using impact, vulnerability, and exposure data for IFWs but excluded the initial stages of the process where the hazard is first detected, monitored, and forecasted. However, this hazard forecasting component was captured in the warning chain diagrams. Thus, integrating the warning chain diagram and the data process framework allowed for representation of the hazard forecasting component. This was done using the Warning Value Chain concept presented by Golding et al. (2019) as a guiding framework. These results are presented in Chapter Six (Harrison et al., 2022).

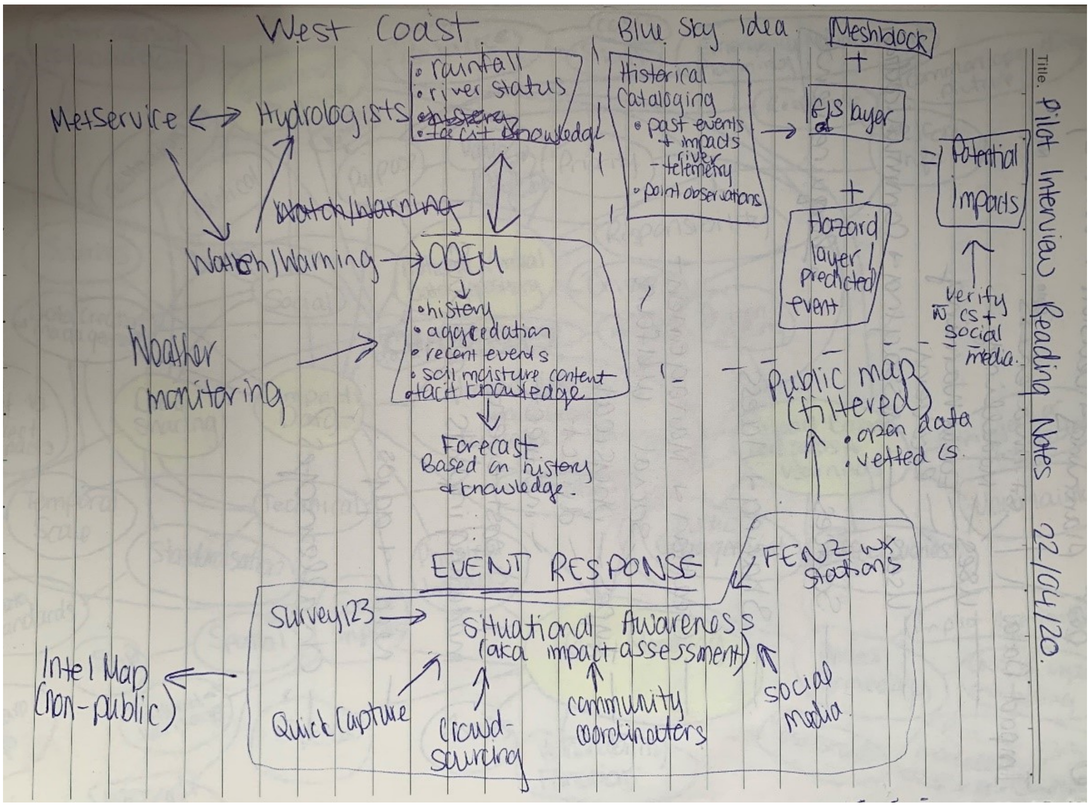


Figure 4.3. Diagram of West Coast warning process following an interview with the West Coast CDEM Groupon 22 April 2020.

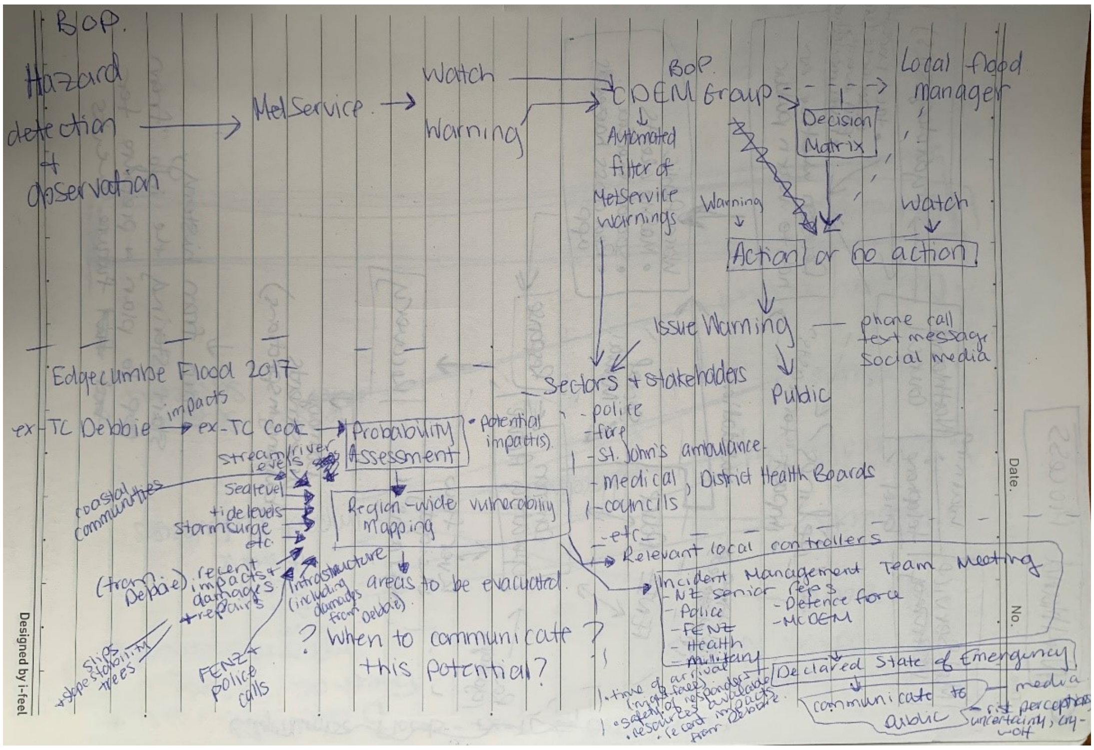


Figure 4.4. Diagram of the Bay of Plenty severe weather warning processfollowing an interview with Emergency Management Bay of Plenty.

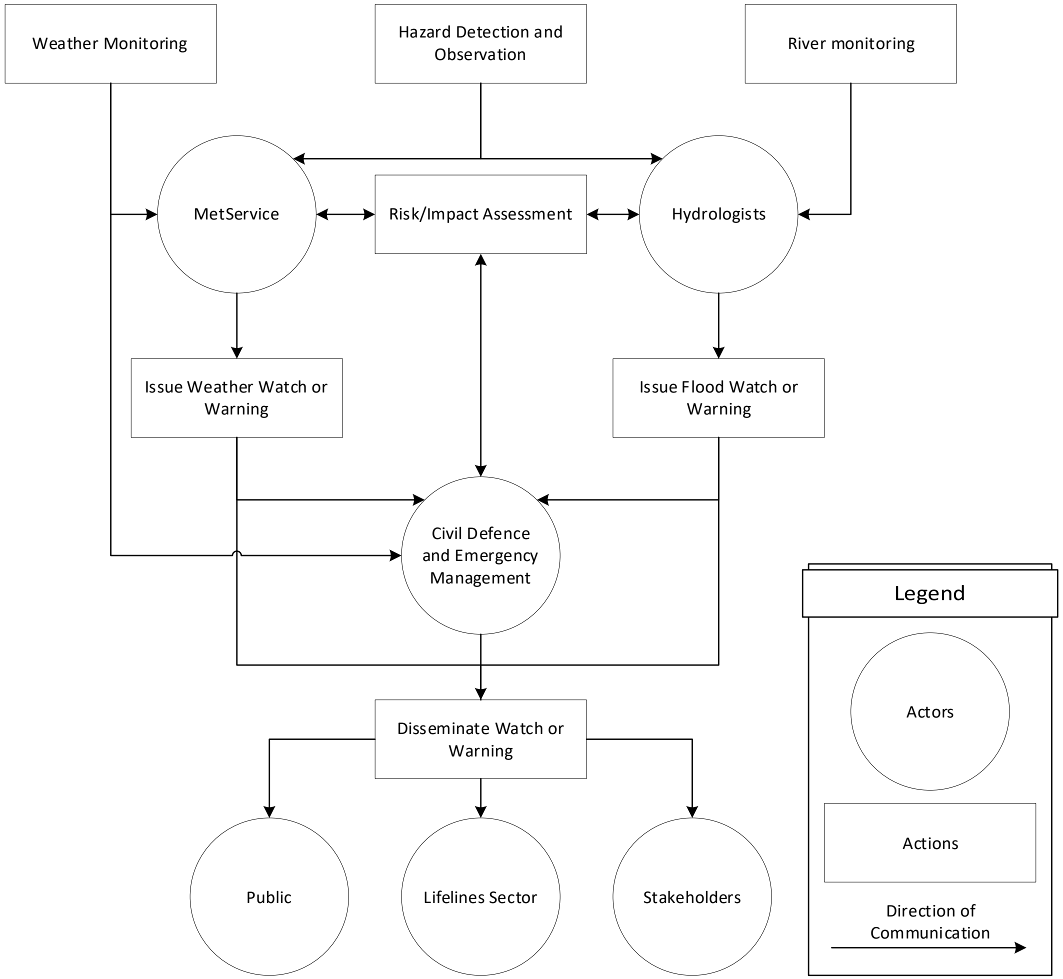


Figure 4.5. Diagram of severe weather warning chain based on interviewswith NZ CDEM Groups and the MetService.

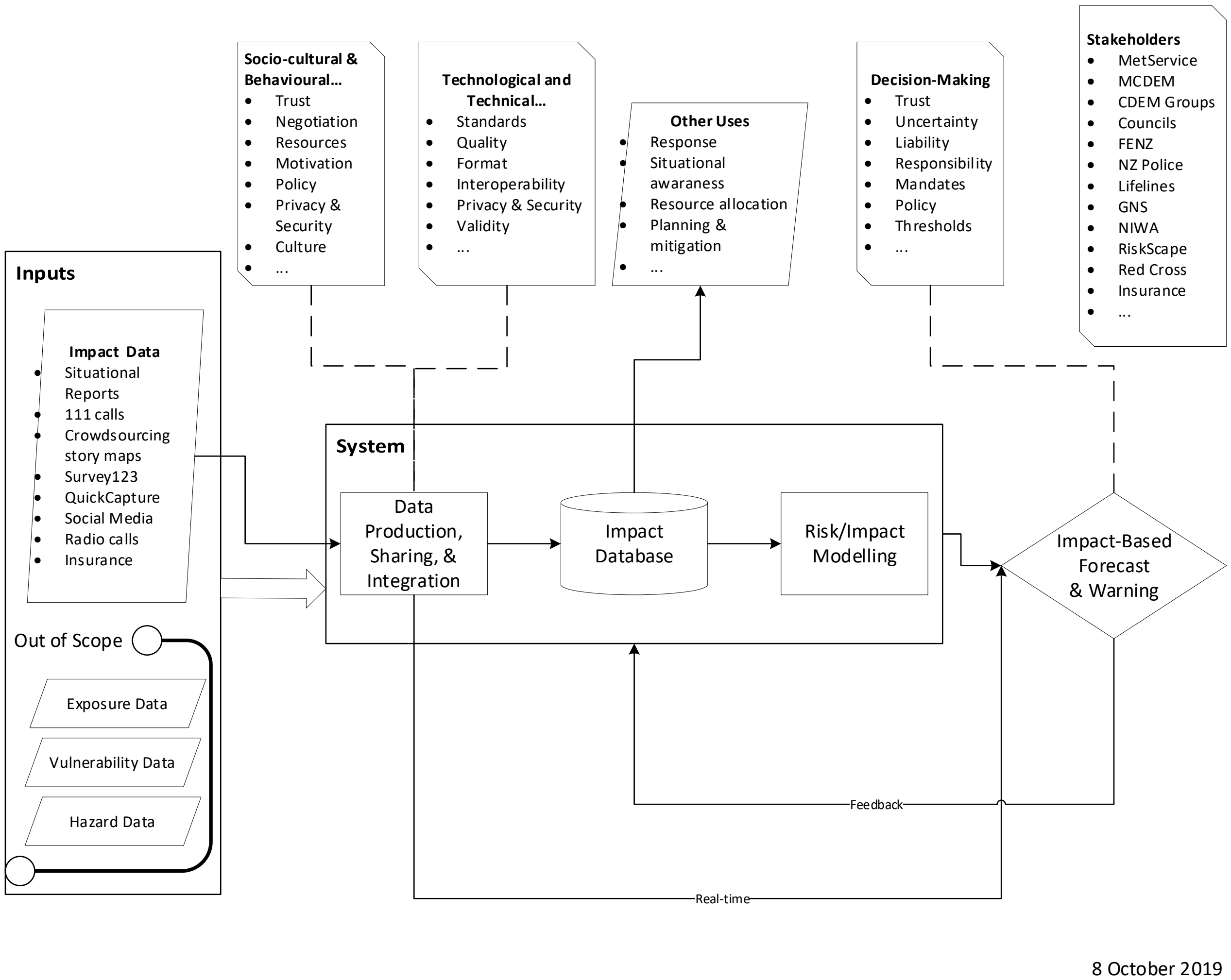


Figure 4.6. First iteration of the impact data frameworkdrawn on 8 October 2019

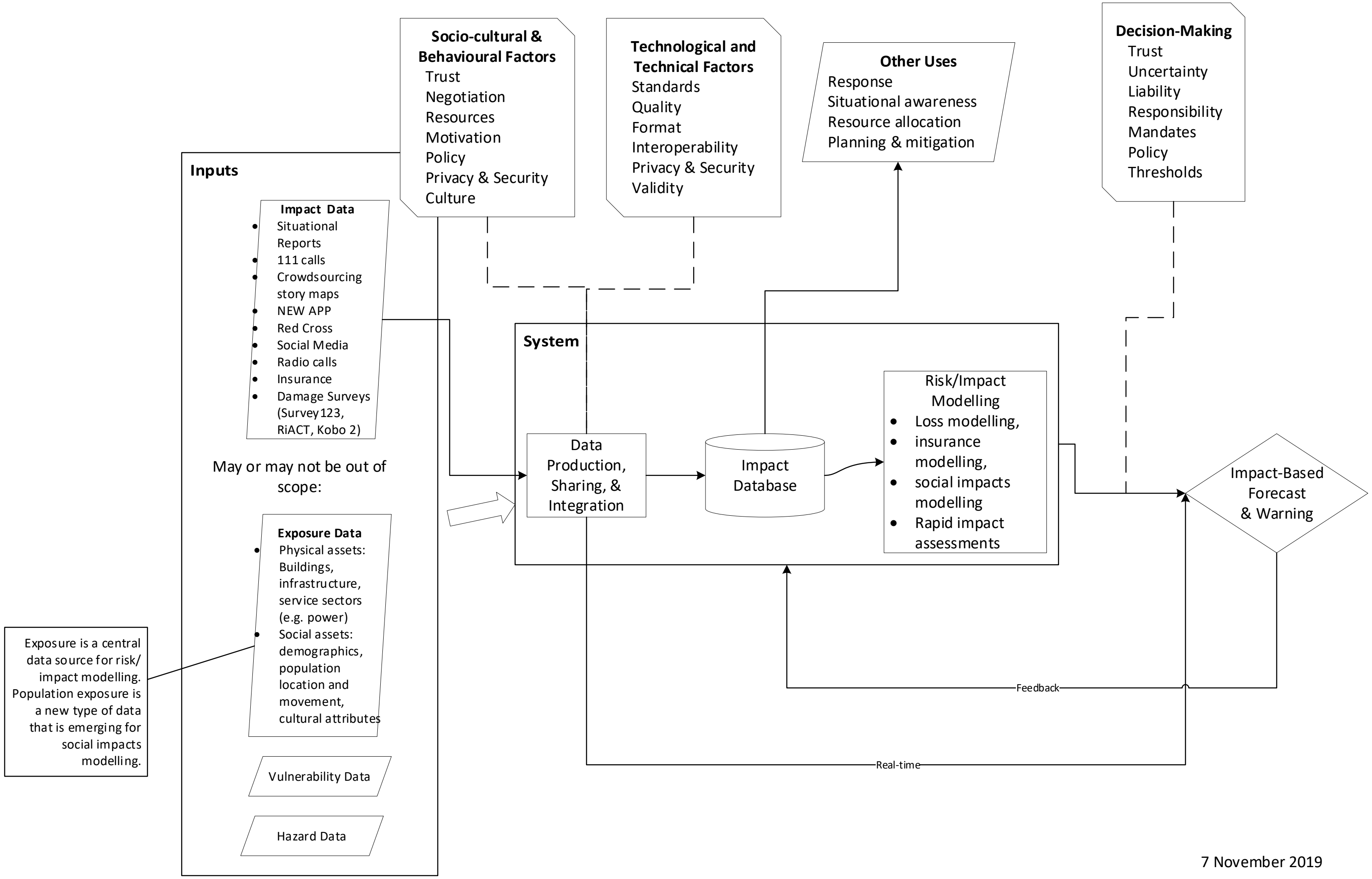


Figure 4.7. Second iteration of the impact data framework following the emergence of the exposure theme, drawn on 7 November 2019.

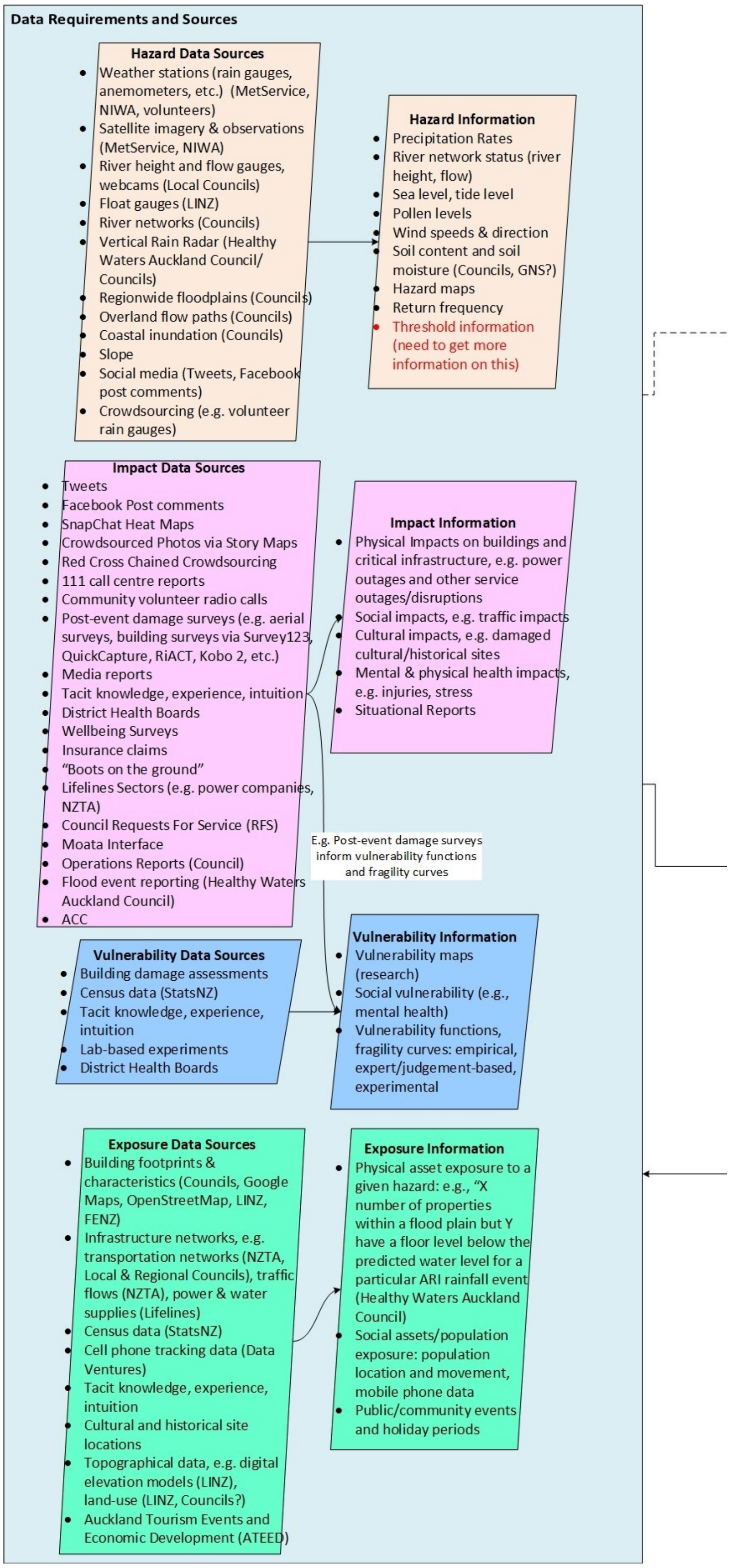
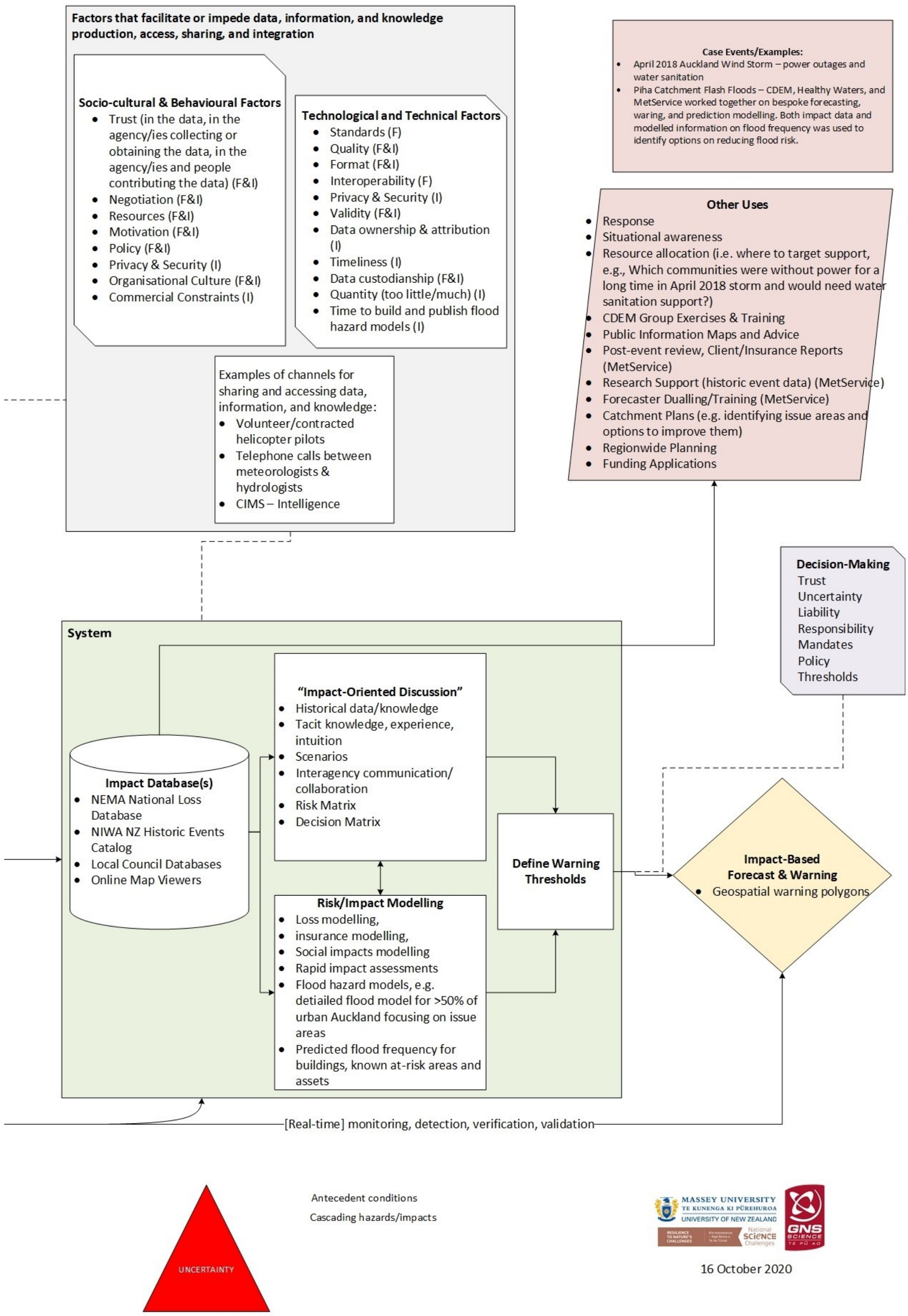


Figure 4.8. Data process framework resulting from the Auckland workshop in October 2020.



and used in the Southland workshop in December 2020.

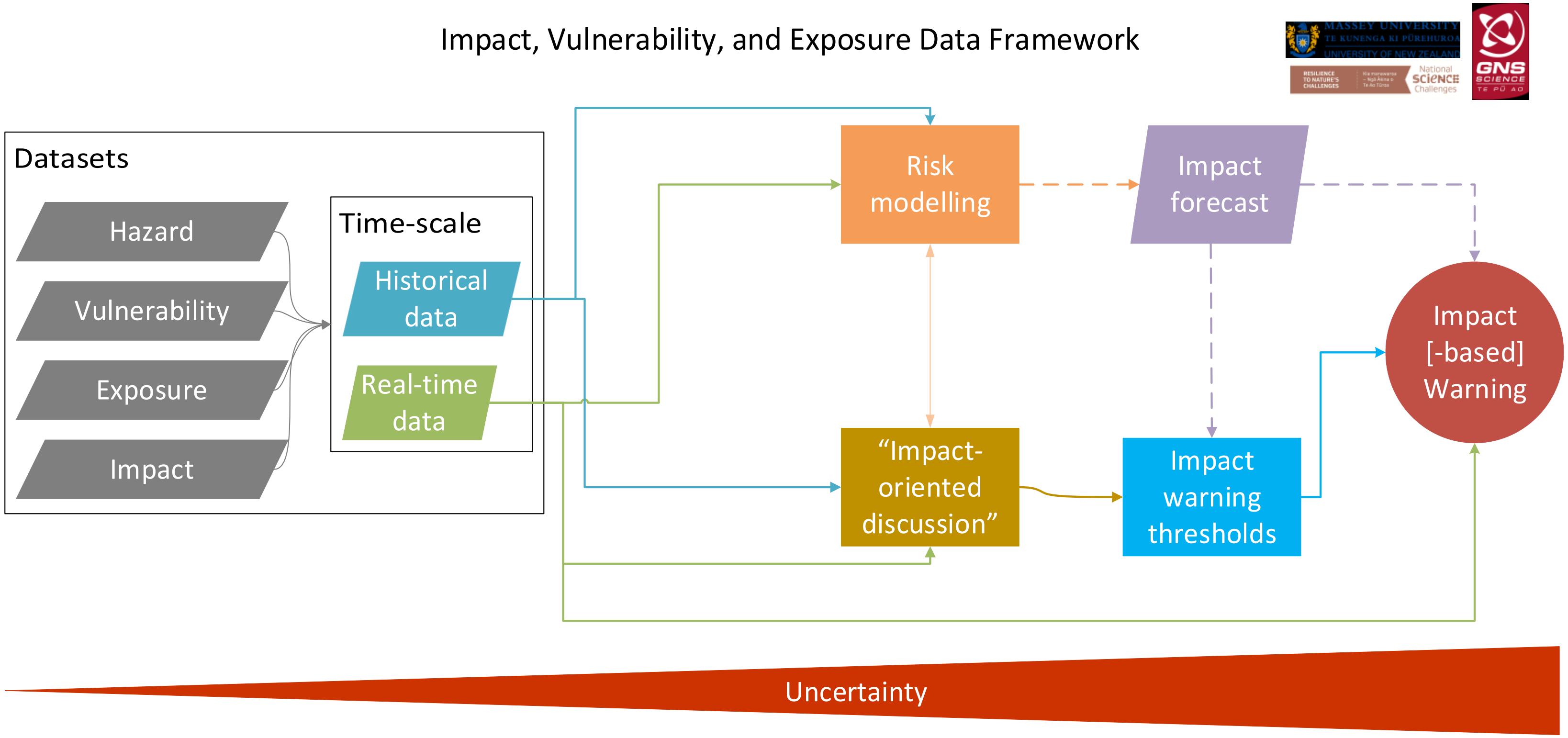


Figure 4.9. Impact data process framework presented to GNS workshop participants in February 2021.

4.3.2 Coding

The coding process of the ES-GT research strategy guided the analysis for this study. Results of the three coding phases (open, axial, and selective coding) are presented next.

4.3.2.1 Open coding

Open codes were developed directly from the data (i.e., in vivo), and with reference to literature and theories (Vollstedt & Rezat, 2019). For example, during the pilot interviews, open codes were created to classify the different sources of impact data, such as Twitter posts (i.e., Tweets), Facebook posts and Facebook comments, SnapChat posts, etc. Constant comparison took place by comparing the data pieces (e.g., sentences, paragraphs) for similarities and differences; similar parts were assigned the same code and different parts were assigned a different code (Vollstedt & Rezat, 2019).

The open coding process was documented with theoretical memos and in the code descriptions (Corbin & Strauss, 2015). For example, in the following memo trust in the data was identified as a key theme for being able to use data for IFWs:

Memo: High level data needs for IFWs, Harrison S., 6 January 2021:

The first round of interviews … explored two things. The first was identifying the data needs for IFWs, and the second thing was exploring whether or not VGI (in the form of geo-located social media posts, geo-located crowdsourcing, and participatory mapping) would be useful for addressing these data needs.

During these interviews, a number of needs were identified for IFWs, but they were not specifically linked to particular datasets or data sources. They were more general data needs. The data needs are listed here …

- *the importance of and need for official data*
- *the need for quality control*
- *the need for real-time impact data*
- *the need to be able to trust the data*
- *the need for up-to-date information*

These data needs are at a much higher level than I expected them to be, and they do not delve into the specific needs for exposure and vulnerability data. Perhaps because I did not specifically ask about vulnerability and exposure, although I know that I asked about it with my [redacted] participants. This tended to link more into the "data uses" theme, which draws out what the data are actually used for.

These needs are intrinsically linked to the socio-technical data challenges. Official data must be standardised and interoperable to enable the technical sharing and use of the data. But we also need agencies and organisations to trust each other so that they can build partnerships and share the data with each *other. Quality control is supported by standardised and systematic data collection, and validation measures. Real-time impact data can potentially be collected via social media, crowdsourcing, media reports, but these data must be perceived as trustworthy. Trusting these datasets requires a cultural shift in the agencies, as I found in my Masters thesis (Harrison & Johnson, 2019). The need for up-to-date information is closely linked to the need for real-time impact data, and the need for quality control, and for official data. Official data is not very useful if it is not up-to-date or of a high quality. This is a big problem for the census data in Argentina and New Zealand.*

From this memo, open codes of trust, official data, unofficial data, standardised data collection, systematic data collection, and real-time data were formed. A full list of open codes is provided in Appendix H.

These open codes were further grouped into categories using constant comparison and memo writing. For example, posts from the various social media platforms identified were grouped into a 'Social Media' category. The 'Social Media' and 'Crowdsourcing' categories were then grouped into 'Alternative or unofficial data sources', while another category was created for 'Official and Trusted Data Sources' to capture the data sources that interviewees deemed as such (e.g., CDEM-led damage surveys and impact assessments, emergency calls, and media reports). This relational process allowed for different dimensions of categories to be described (Vollstedt & Rezat, 2019), such as trustworthiness of the data.

4.3.2.2 Axial coding

The coding paradigm is a tool specific to the ES-GT research strategy intended to guide the researcher in the axial coding process (see Section 3.2.2.3). The coding paradigm provided by Strauss and Corbin (1990) and summarised in Table 3.5 was found to better fit the data than more recent variations of the coding paradigm. For example, this 1990 coding paradigm includes "Causal", "Intervening", and "Contextual Conditions" (Strauss & Corbin, 1990, p. 99), while the most recent variation of the coding paradigm only provides "Conditions" (Corbin & Strauss, 2015, p. 158). Causal, Intervening, and Contextual Conditions were found to better explain the data by allowing for drivers (i.e., causal conditions) for the phenomena (e.g., IFW systems and HIVE data) to be identified, along with challenges in progressing the phenomena (e.g., barriers to IFW implementation, challenges with collecting data). For example, past disaster events such as the 2010-2011 Canterbury earthquake sequence were identified in interviews as a driver (i.e., causal condition) for improving data collection and management within the NZ CDEM Sector. Contextual conditions were determined to be high level influences of overall practice, particularly governance and cultural conditions in NZ. The initial results of this process are presented in Figure 4.10.

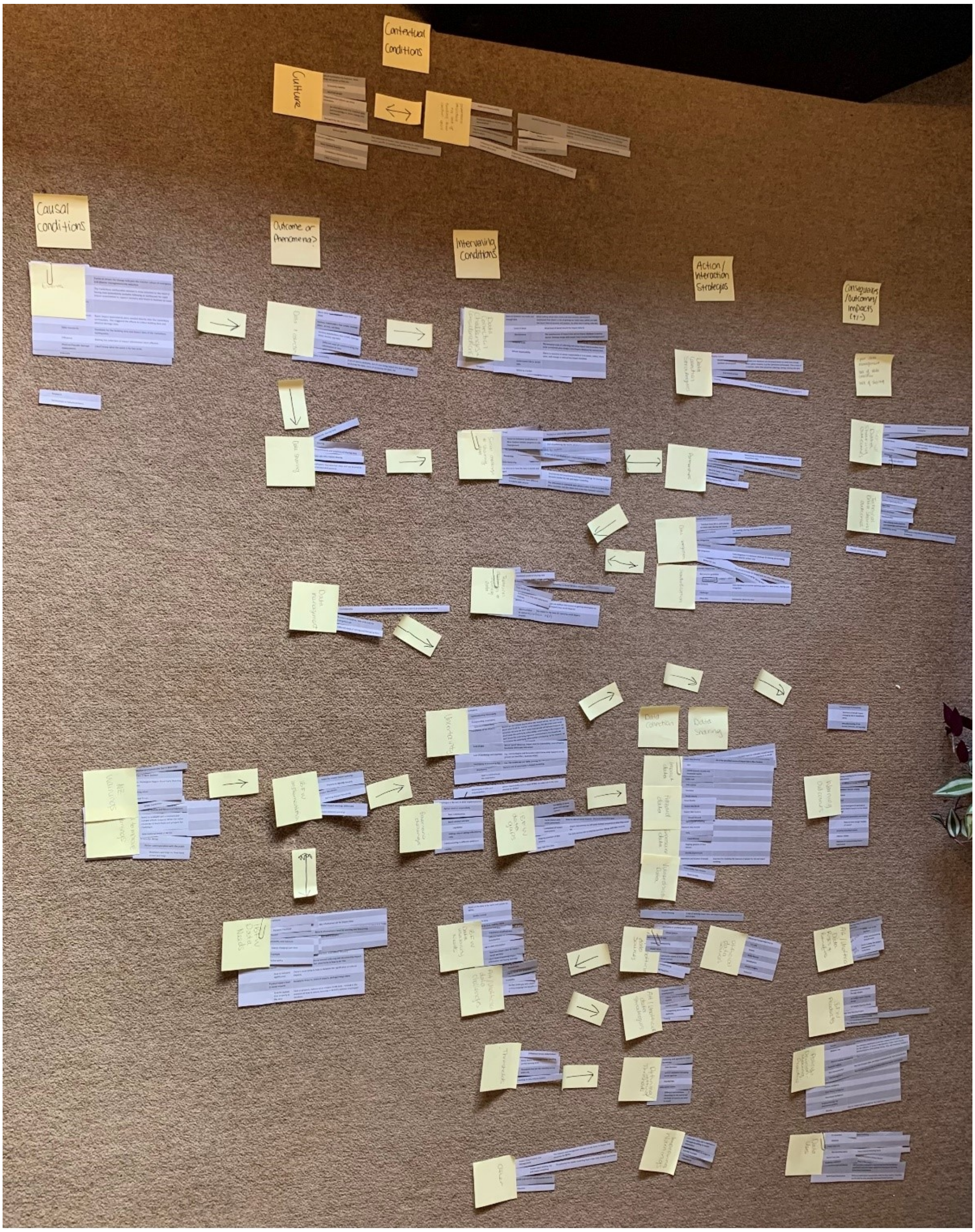


Figure 4.10. Axial coding processwhere codes were grouped into categories and related to the coding paradigm dimensions on 16 April 2021 (Image Source: S. Harrison).

Results from the axial coding process were digitised into an Excel spreadsheet where further aggregation and shifting of codes and categories was completed and significant themes were highlighted for reporting. These initial results from 16 April 2021 are provided in Appendix I. Note that further memo writing, results writing, and analysis led to the refinement of these initial results (Corbin & Strauss, 2013), likely causing variation from the results in Appendix I and the results forthwith. Results of the axial coding process are presented next according to each dimension of the coding paradigm: Phenomena, causal conditions, contextual conditions, intervening conditions, action/interaction strategies, and consequences.

Phenomena

Phenomena are the subjects or objects under study (Strauss & Corbin, 1990). Two overarching phenomena were identified as the outcome of the axial coding process. The first phenomenon to result from the axial coding process is *IFW Systems* (Figure 4.11), and the second is *Hazard, Impact, Vulnerability, and Exposure (HIVE) Data* (Figure 4.12). These two phenomena were then broken down into five categories based on the open code groupings.

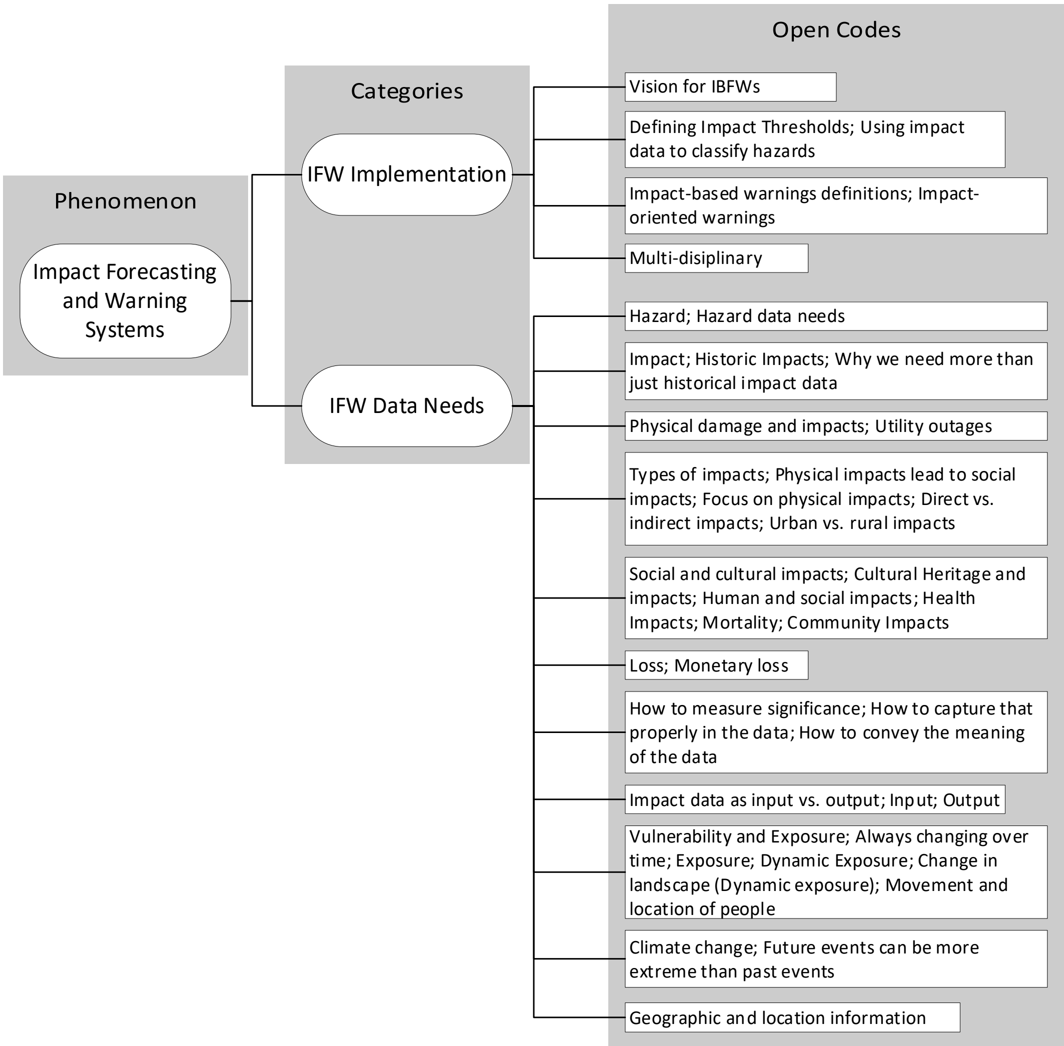


Figure 4.11. The open codes and categories that make up the Impact Forecasting and Warning Systems Phenomenon.

Phenomenon 1: Impact Forecasting and Warning (IFW) Systems

Open codes were grouped based on similar characteristics and themes. For example, the codes 'Defining Impact Thresholds' and 'Using impact data to classify hazards', were grouped together because they both relate to the concept of identifying triggers or thresholds for IFWs. The codes for the IFW Implementation category relate to defining and understanding IFW systems and what is needed to implement them. Initially IFW Data Needs were grouped under IFW implementation, but it was elevated to its own category after all codes were consolidated and it was apparent that enough[8] codes with a common theme exist for it to be a category. The codes in the IFW Data Needs category relate to identifying the different types of data needs for IFWs (e.g., hazard, impact, vulnerability, and exposure data), and justification and uses for these different data types in the IFW systems context.

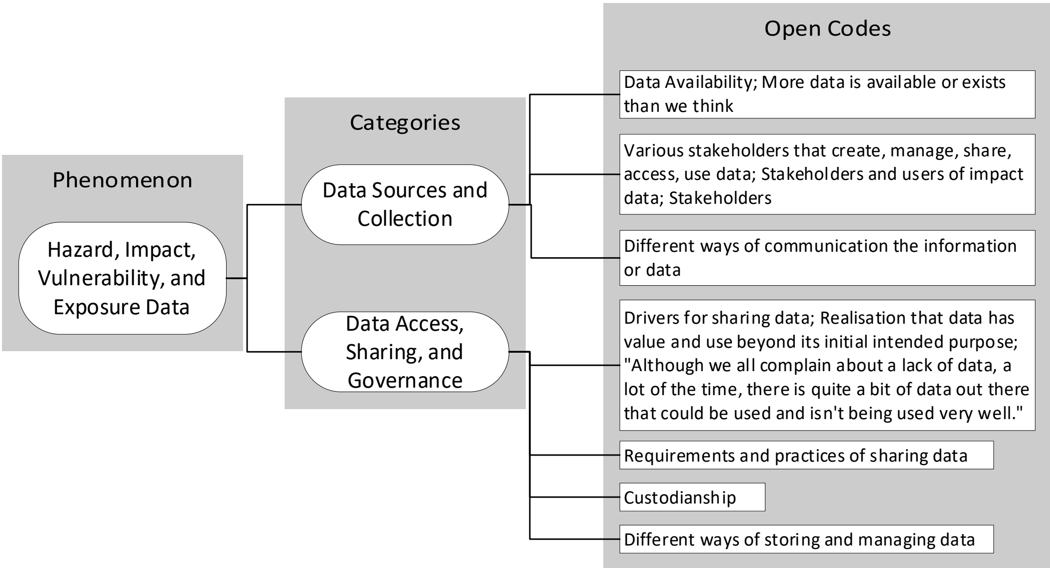


Figure 4.12. The open codes and categories that make up the HIVE Data phenomenon.

Phenomenon 2: Hazard, Impact, Vulnerability, and Exposure (HIVE) Data

The Hazard, Impact, Vulnerability, and Exposure (HIVE) Data phenomenon consists of three categories: Data Sources and Collection, Data Access and Sharing, and Data Management and Governance (Figure 4.12). During the axial coding process, it was found that enough codes with a common theme existed to form these three categories. These three category topics arose organically by the participants and were discussed at length. Thus, they were deemed to be important enough to be their own categories. Furthermore, these three categories are inherently linked to each other. For example, in the Data Sources and Collection category, two codes emerged

[8] Note that there is no pre-defined number of codes needed to constitute a category. A category is formed based on commonalities between open codes and concepts. It is the discretion of the Grounded Theory researcher to develop categories and their names based on the data (Corbin & Strauss, 2013).

regarding the existence of many datasets and sources: ‘More data is available or exists than we think’ and ‘Various stakeholders that create, manage, share, access, use data’. These two codes led to the idea that if all of these datasets and sources exist and are collected by various sources, then there must be a way to share these data. As such, the data was then interrogated with questions around data sharing and access, resulting in codes identifying drivers for sharing data, and one particular in vivo code was produced: “Although we all complain about a lack of data, a lot of the time, there is quite a bit of data out there that could be used and isn’t being used very well” (Risk Modelling NZ. A; see Table 3.6). This in vivo code resulted in questions around why these data are not being used very well, and this led to identifying challenges with accessing these data (i.e., intervening conditions), as well as issues of Data Management and Governance, where the data are not managed or maintained very well, making it difficult to share and effectively use the data. Questions were asked around the potential causes of data management and governance issues that are inhibiting HIVE data collection and sharing practices in NZ.

Contextual Conditions

Contextual conditions are conditions or characteristics surrounding the phenomena and resulting in action/interaction strategies taken to address the two phenomena (e.g., IFW Systems, and HIVE Data) (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019). Cultural Conditions, Governance, and NZ Warnings were the three categories identified as contextual conditions, as shown in Figure 4.13. These were identified as contextual conditions because they provide a background understanding of the systems in place that influence actions and decisions in practice and operations. For example, when attempting to understand current barriers and inhibitors to data collection, access, and sharing, the contextual conditions of top-level government priorities and investment provided clarity; participants indicated that top-level government priorities, which are embedded in governance structures, influence directions of research and practice (e.g., Smith et al., 2003).

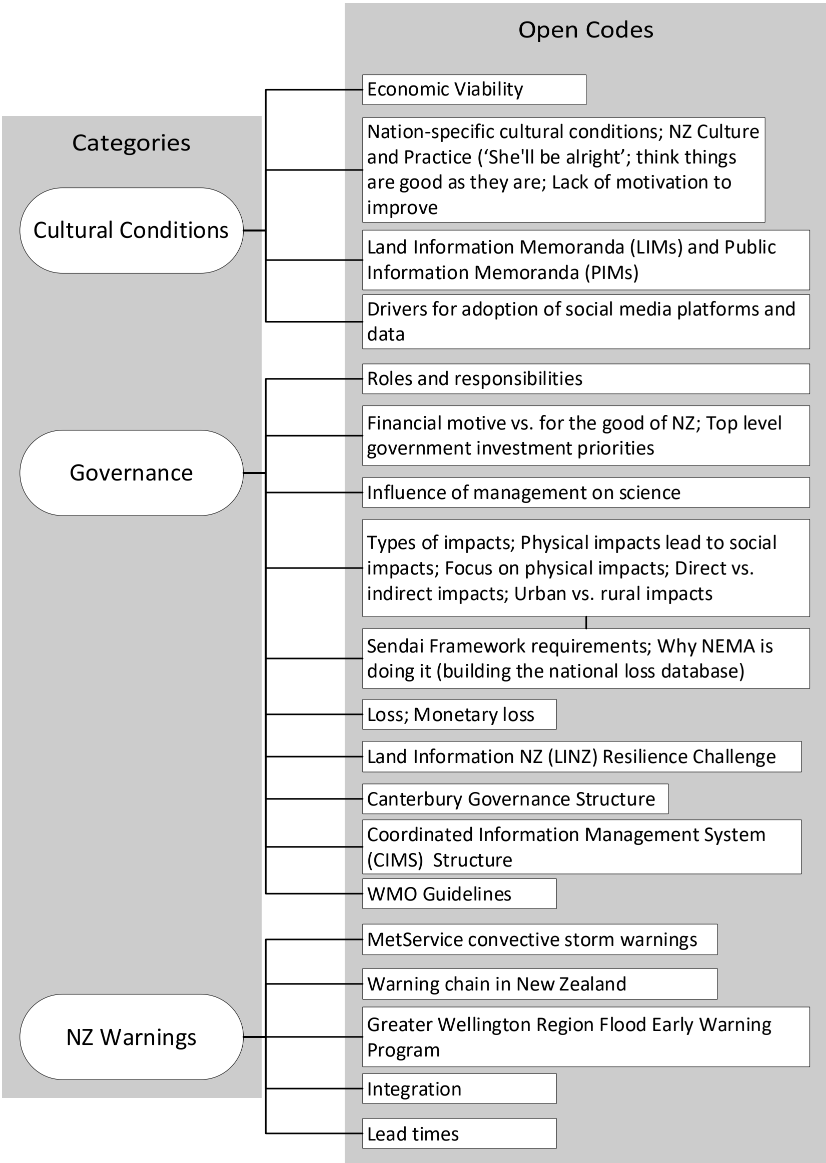


Figure 4.13. Contextual conditions identified from axial coding.

Causal Conditions

Causal conditions are events that influence phenomena or result in the appearance or development of a phenomena. The causal conditions were identified as events that directly drove the need for implementing IFWs (the first phenomenon), and the collection, sharing, and management of HIVE data (the second phenomenon). The four main causal conditions for these phenomena, shown in Figure 4.14, are: (1) Disaster or emergency events, (2) The Need to Improve Warnings, (3) Research, and (4) Technological Advancements. Disaster and emergency events, the need to improve warnings, and research efforts were found to be important drivers for incorporating impact messaging into severe weather warnings, while research, technological advancements, and disaster and emergency events were identified as drivers for collecting, creating, sharing, and managing HIVE data.

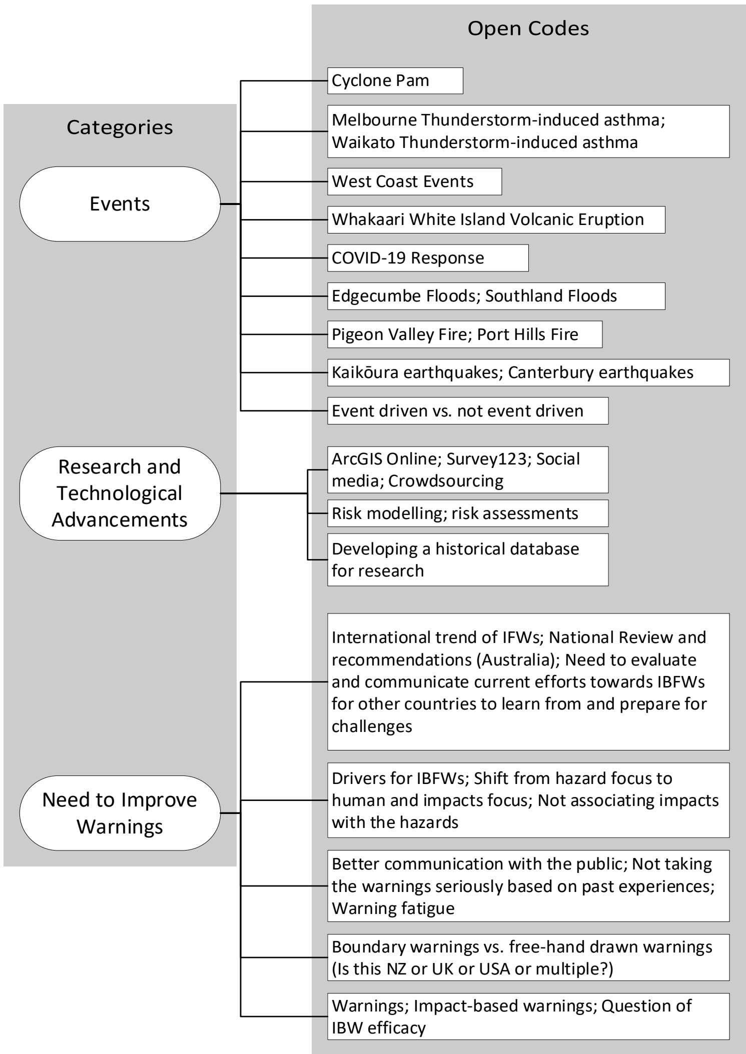


Figure 4.14. The causal conditions identified in the axial coding process.

Intervening Conditions

Intervening conditions are unexpected events or factors leading to action/interaction strategies (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019). Intervening conditions were identified as inhibitors and facilitators that influence the actions that are required to implement IFWs (the first phenomenon; Figure 4.15), and to collect, access, and use HIVE data (the second phenomenon; Figure 4.16).

Three categories of intervening conditions resulted from grouping the open codes for the IFW Systems phenomenon, as shown in Figure 4.15: (1) IFW Data Usability and Needs; (2) Challenges with applying the knowledge, data, and information; and (3) Uncertainty.

IFW Data Usability Needs relates to the needs that participants identified for them to use data or sources of data. For example, participants indicated that they need to be able to trust the data and be confident in resulting analyses. They also need the data to be timely, identifying real-time or near real-time data as particularly useful. Challenges were identified with applying the various types and sources of knowledge, data, and information. For example, differences in spatial scale of warnings and available data make it difficult to use the data. Uncertainty was found to be a notable challenge to implementing IFWs. Uncertainty appeared to be present not only in the operational aspects of formulating, issuing, and communicating IFWs, but also in roles and responsibilities, and in the terminology used for IFWs.

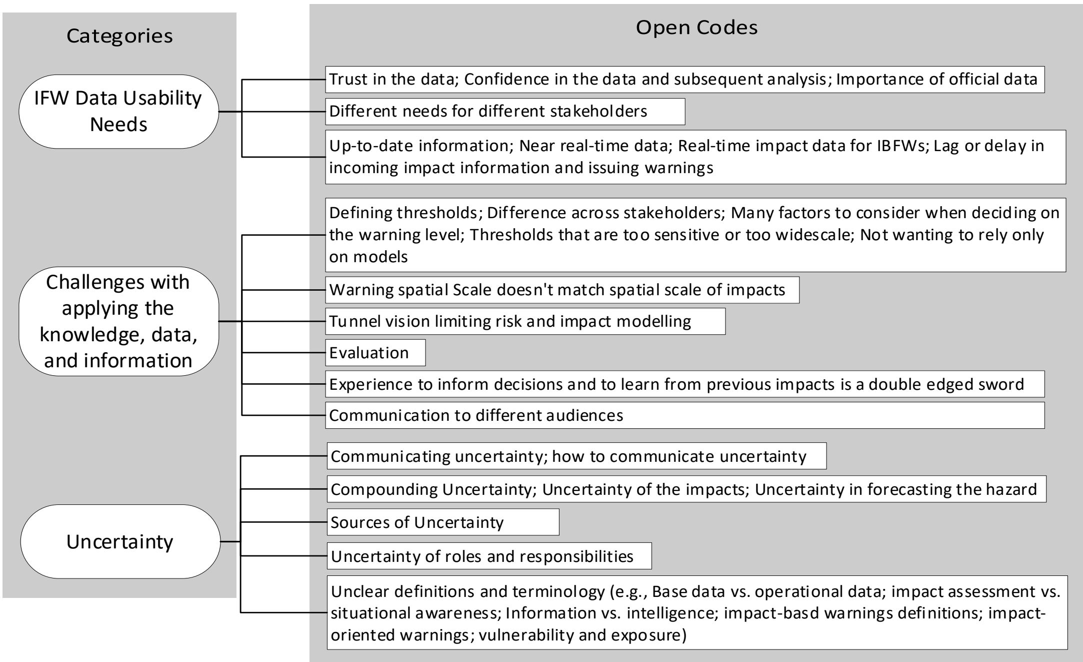


Figure 4.15. Intervening conditions identified relating to the IFW Systems phenomenon.

Six categories emerged to represent intervening conditions affecting the second phenomenon, HIVE Data, as shown in Figure 4.16. These six categories are: (1) Data Collection Challenges and Considerations, (2) Data Management Challenges, (3) Social challenges to sharing data, (4) Ethical Considerations, (5) Technical challenges to sharing data, (6) Alternative or unofficial data challenges. Data Collection Challenges and Considerations consists of codes outlining various challenges or issues with collecting HIVE data, such as lack of motivation or interest in doing so or trying to find a balance between collecting too much and enough data to prevent information overload.

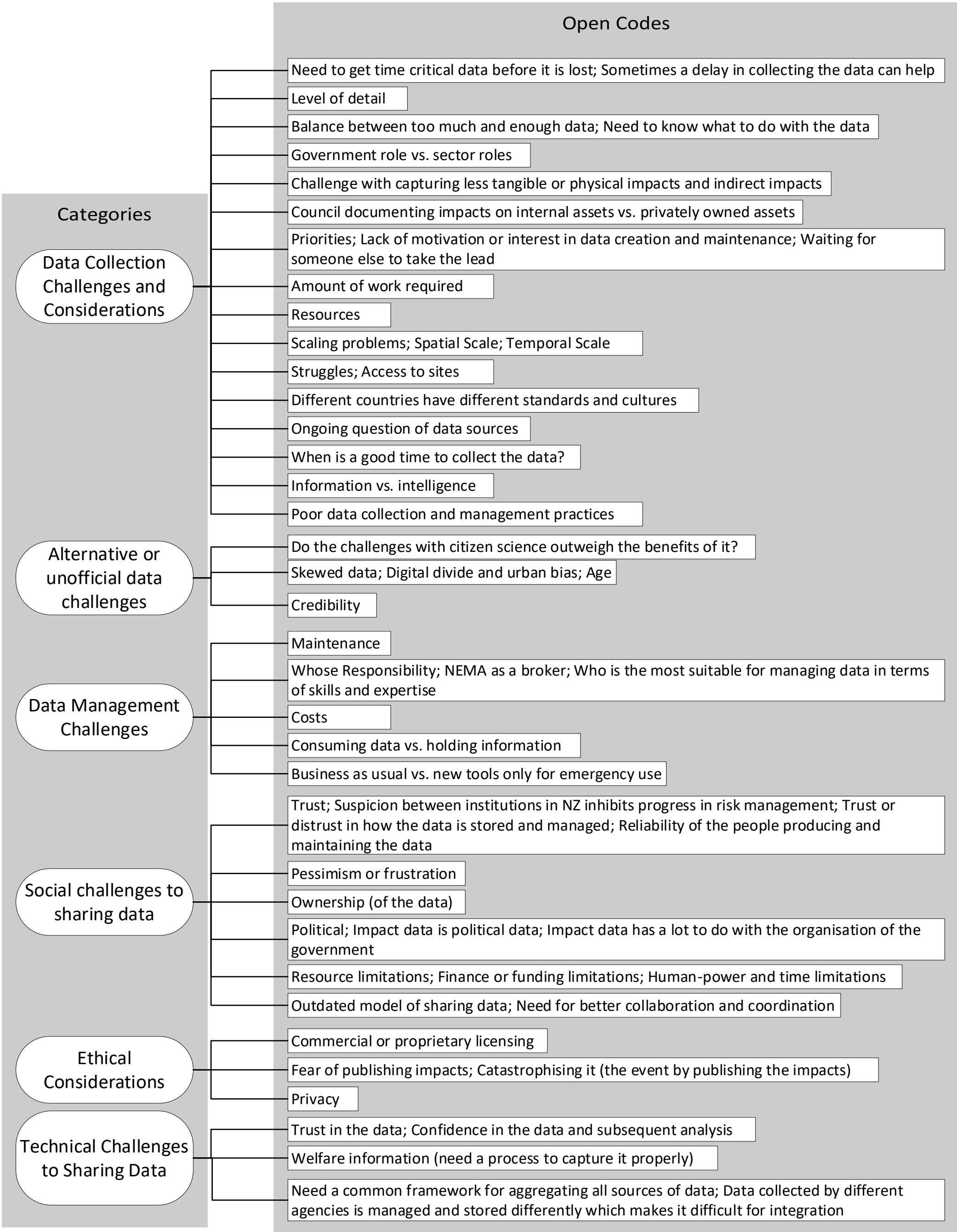


Figure 4.16. Intervening conditions identified relating to the HIVE Data phenomenon.

Data Management Challenges involve issues with managing the resulting data, which includes concerns with maintenance, costs, and responsibilities. Both social and technical challenges were identified for sharing data. Social challenges relate to partnerships and trust, while technical challenges relate to processes for integrating datasets/sources. Ethical Considerations were first identified as part of a social challenge to sharing HIVE data, but it was elevated to its own category because of the number of code groupings relating to it. Alternative or Unofficial Data Challenges were also elevated to their own category because the challenges identified were specific to alternative and unofficial data sources and could not be applied to official data sources or datasets. Furthermore, there is a growing interest in using alternative/unofficial data for IFWs and beyond (e.g., Spruce et al., 2020; Spruce et al., 2021), thus it was decided that this topic should have its own category.

In addition to the above identified intervening categories, some of the open codes relating to the contextual condition of Governance were found to influence both IFW Systems and HIVE Data phenomena, and thus could not be associated with just one of these phenomena. As such, they were elevated to their own category of 'Governance Challenges', shown in Figure 4.17. For example, roles and responsibilities are a point of confusion for both the IFW Systems and the HIVE Data phenomena. The NZ MetService and CDEM Groups both questioned who was responsible for conveying impact information and messaging in severe weather warnings, because the MetService is the mandated authority for issuing severe weather warnings, but they do not have the impact knowledge that CDEM Groups possess. With regards to HIVE Data, questions arose around data custodianship and who should take on that role for HIVE data, particularly impact data. These questions of roles and responsibilities link back to governance, as legislation and policies typically identify the roles and responsibilities of each agency.

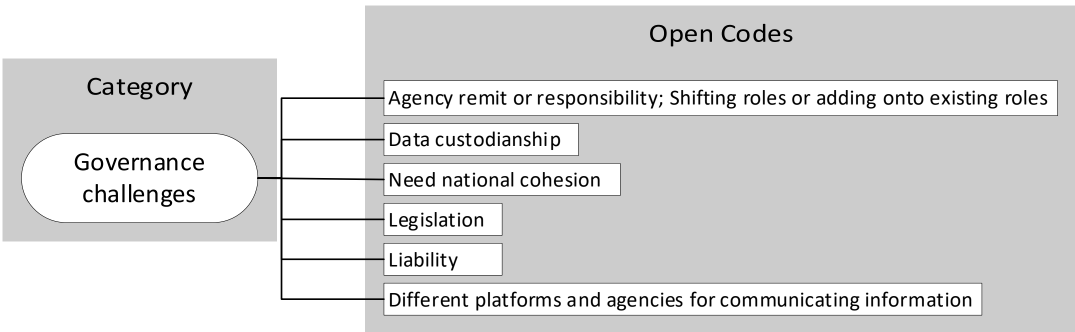


Figure 4.17. Intervening conditions relating to governance.

Action/Interaction Strategies

The original definition of action/interaction strategies in the ES-GT coding paradigm is 'purposeful and deliberate acts that are taken to address the phenomena' (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019). However, during the axial coding phase for this study, it was found that the action/interaction strategies fit more appropriately with acts taken to address the intervening conditions that arose from the phenomena. For example, action/interaction strategies were identified to address some intervening conditions regarding data collection, such as applying quality control measures to ensure credibility and quality of the data. As such, the definition of action/interaction strategies was expanded for this study to apply to those actions/interactions that were either implemented or suggested to address intervening conditions, as well as action/interaction strategies addressing contextual conditions, such as governance.

Three categories were identified for action/interaction strategies relating to IFW Systems and the associated intervening conditions of this phenomenon. As shown in Figure 4.18, these categories are: (1) Defining and setting thresholds, (2) Strategies for improving warnings, and (3) Strategies for addressing uncertainty. Action/interaction strategies for defining and setting thresholds for IFW systems centred around partnerships, sharing data, and joint decision-making, because an intervening condition of IFW system implementation was the variety of stakeholders that IFW systems are designed for which require different warning thresholds (see Figure 4.15).

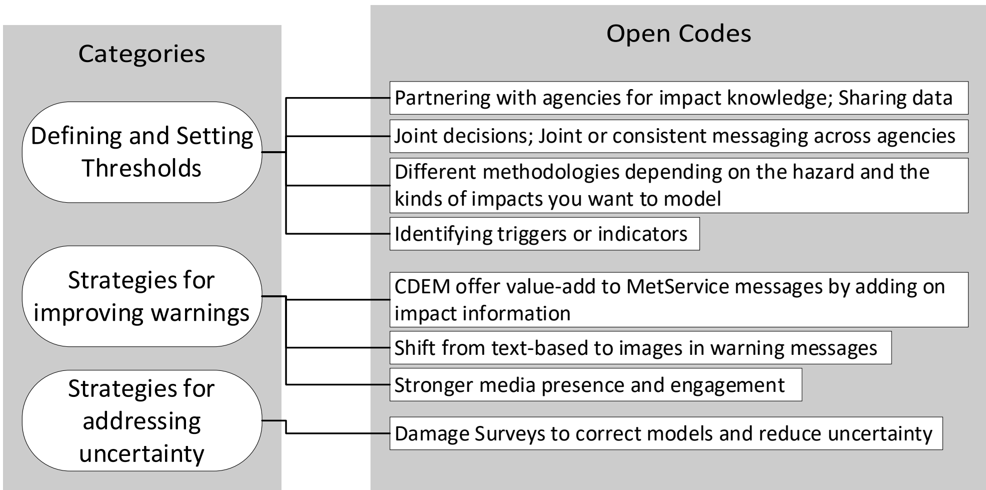


Figure 4.18. Action/interaction strategies identified to address intervening conditions and other characteristics of the IFW Systems phenomenon.

Partnerships, sharing data, and joint decision-making were actions identified for addressing this challenge. Several strategies were identified for improving warnings, not all related to IFWs. For example, the NZ MetService's shift from text-based messages to using images in warning messages was a strategy employed for improving warning communication and understanding. One cause of uncertainty was identified as the lack of data, knowledge, and expertise in forecasting and warning for impacts. As such, collecting more of the appropriate data in a form that makes the data usable for impact forecasting was identified as an action/interaction strategy to address uncertainty.

For the HIVE Data phenomenon, action/interaction strategies relating to the intervening conditions were grouped into two themes: (1) Data collection; and (2) Data sharing, management, and Integration. The 'data collection' action/interaction strategies pertains to the two intervening conditions of 'data collection challenges and considerations' and 'alternative or unofficial data challenges previously' previously presented in Figure 4.16. The 'data sharing, management, and integration' action/interaction strategies pertain to the intervening conditions of 'social challenges to data sharing,' 'technical challenges to data sharing,' and 'ethical considerations.' These intervening conditions were grouped into one action/interaction strategy theme because they were found to relate to each other and influence each other. For example, data integration depends on data management practices (Ludäscher et al., 2006).

Three categories were identified for action/interaction strategies pertaining to the 'data collection challenges and considerations' and 'alternative or unofficial data challenges' relating to the HIVE Data phenomenon. These categories, shown in Figure 4.19, are (1) Data collection strategies, (2) Identifying data sources, and (3) Alternative or unofficial data strategies. Data collection strategies centred around improving data quality and implementing measures to ensure that the right balance is achieved for data quality and quantity. Identifying data sources was an action/interaction strategy to address the question of data sources and where existing data are. Strategies for addressing concerns with alternative or unofficial data sources also centred around ensuring data quality and credibility.

Another three categories were identified for action/interaction strategies relating to 'data sharing, management, and integration' in the HIVE Data phenomenon. As shown in Figure 4.20, these are: (1) Building partnerships for better data sharing practices, (2) Data management and integration strategies, and (3) Data standardisation strategies. 'Building partnerships for better data sharing practices' consisted of codes relating to strategies for building and nurturing partnerships, strengthening collaboration, and improving coordination. Strategies for 'data management and integration' identified technical tools to support these actions, such as building data directories, using Geographic Information Systems (GIS) and spatial data, and utilising machine learning and artificial intelligence.

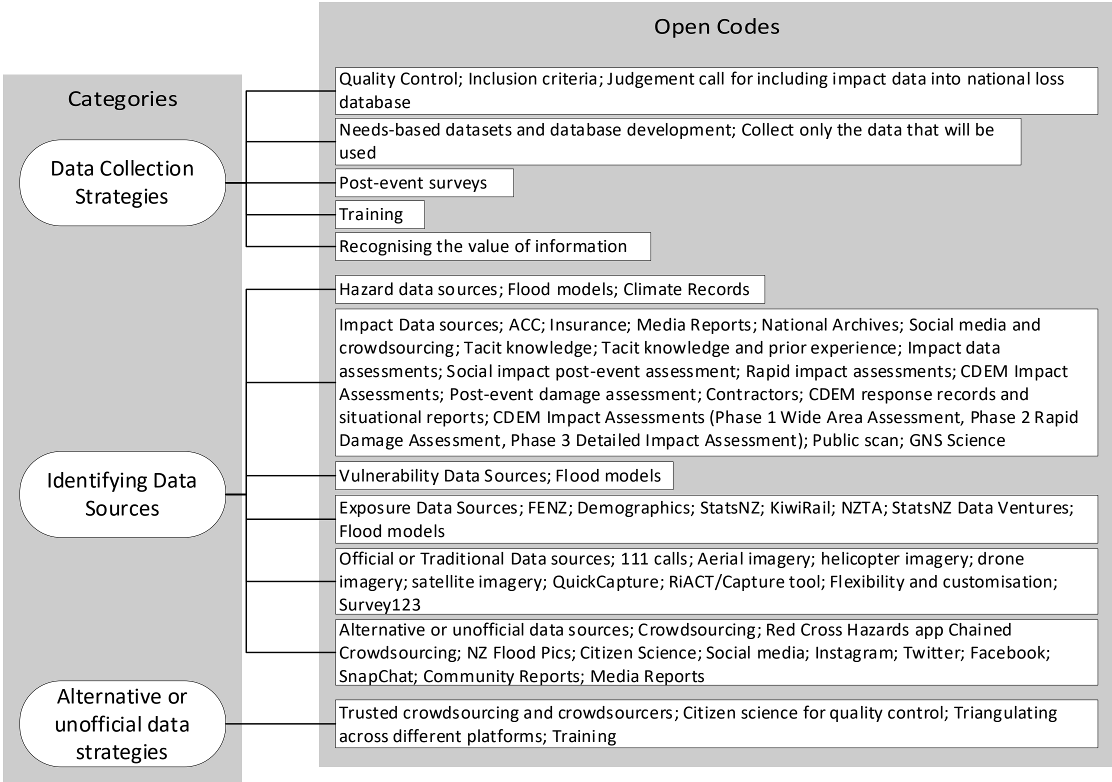


Figure 4.19. Action/interaction strategies identified to address data collection intervening conditions.

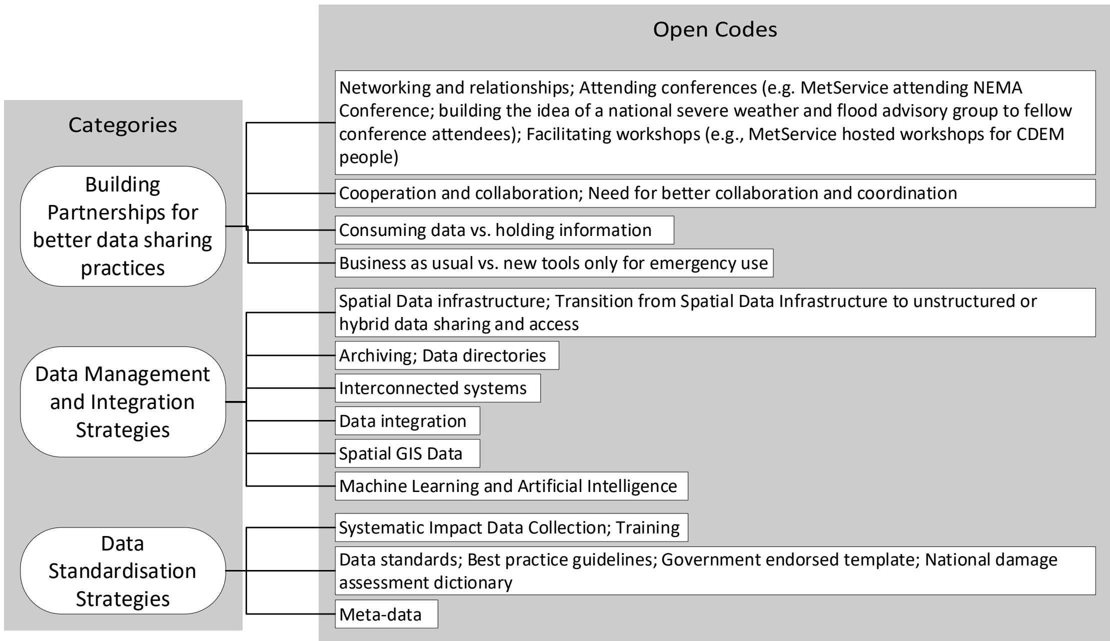


Figure 4.20. Action/interaction strategies identified for addressing data sharing, management, and integration intervening conditions.

Finally, two categories were identified for action/interaction strategies relating to governance contextual conditions (e.g., strategies for driving innovation and change) and technological advancement causal conditions (e.g., 'push and pull' system design strategies), as shown in Figure 4.21. 'Strategies for driving innovation and change' were found to be influenced by leadership, political direction, bottom-up organisation, and organisational culture. 'Push and pull system design strategies' involve conducting needs-based research and development, focusing on the users and uses of the data, and being innovative.

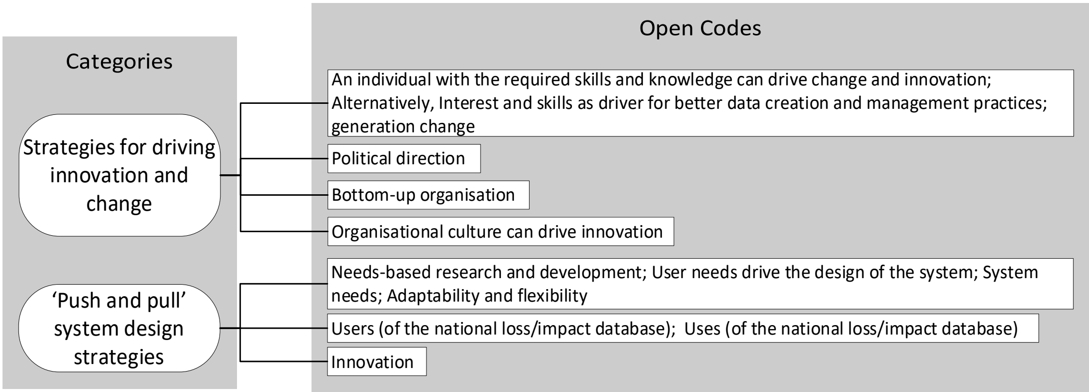


Figure 4.21. Action/interaction strategies for addressing governance contextual conditions and technological advancement causal conditions.

Consequences and Outcomes

Consequences and outcomes are the predictable or unpredictable, intended, or unintended, positive or negative outcomes of the action/interaction strategies (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019). The resulting outcome categories were organised by the phenomena and contextual conditions.

Three categories were identified for the outcomes and consequences of implementing IFW systems (i.e., the IFW Phenomenon). As shown in Figure 4.22, these categories are: (1) IFW outcomes, (2) IFW Products, and (3) Consequences of uncertainty. 'IFW outcomes' relates to the outcomes from the impact forecasts and warnings themselves, such as potential or observed changes in warning audience decision-making and behaviour. 'IFW Products' are meteorological products and services that were identified by participants that had some aspect of impact forecasts and/or warnings. 'Consequences of uncertainty' related to reasons for warning services' and agencies' hesitancy to issue IFWs and the perceived increased potential for audiences and stakeholders to misunderstand impact models, forecasts, and warnings.

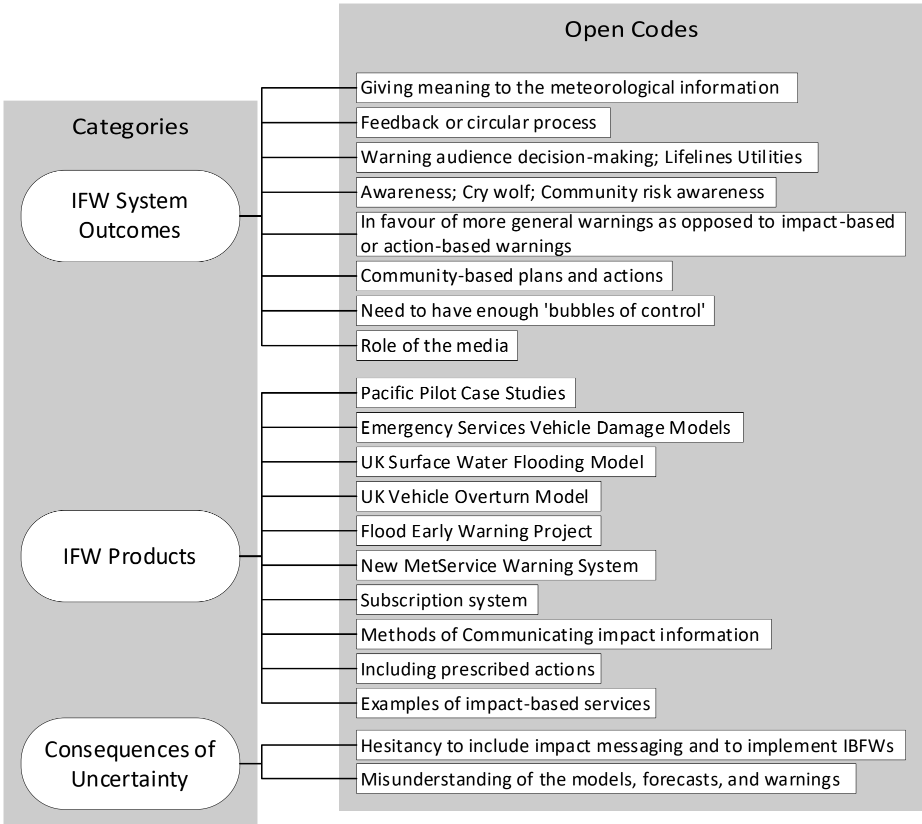


Figure 4.22. Consequences and outcomes of implementing IFW systems.

Mirroring the action/interaction strategies for the HIVE Data phenomenon, outcomes were grouped into two themes: (1) Data collection, and (2) Data sharing, management, and integration. Three categories were identified for outcomes and consequences relating to HIVE data collection, as shown in Figure 4.23. These are (1) Impact databases, (2) Data uses, and (3) Alternative or unofficial data risks and benefits. 'Impact databases' are products of data collection efforts carried out by agencies and stakeholders identified by participants. 'Data uses' are IFW and non-IFW uses that were identified for the HIVE data. The risks and benefits of collecting and using alternative or unofficial data sources were also identified. Risks in this context differ from intervening conditions because they are an observed outcome of using this data or of people creating or contributing to this data. For example, the code 'people interfering in the response and putting themselves and others at risk' is an observed behaviour of people taking photos and videos during a disaster or emergency event to post on social media or contribute to other crowdsourcing platforms (EM. NZ. Nat. I).

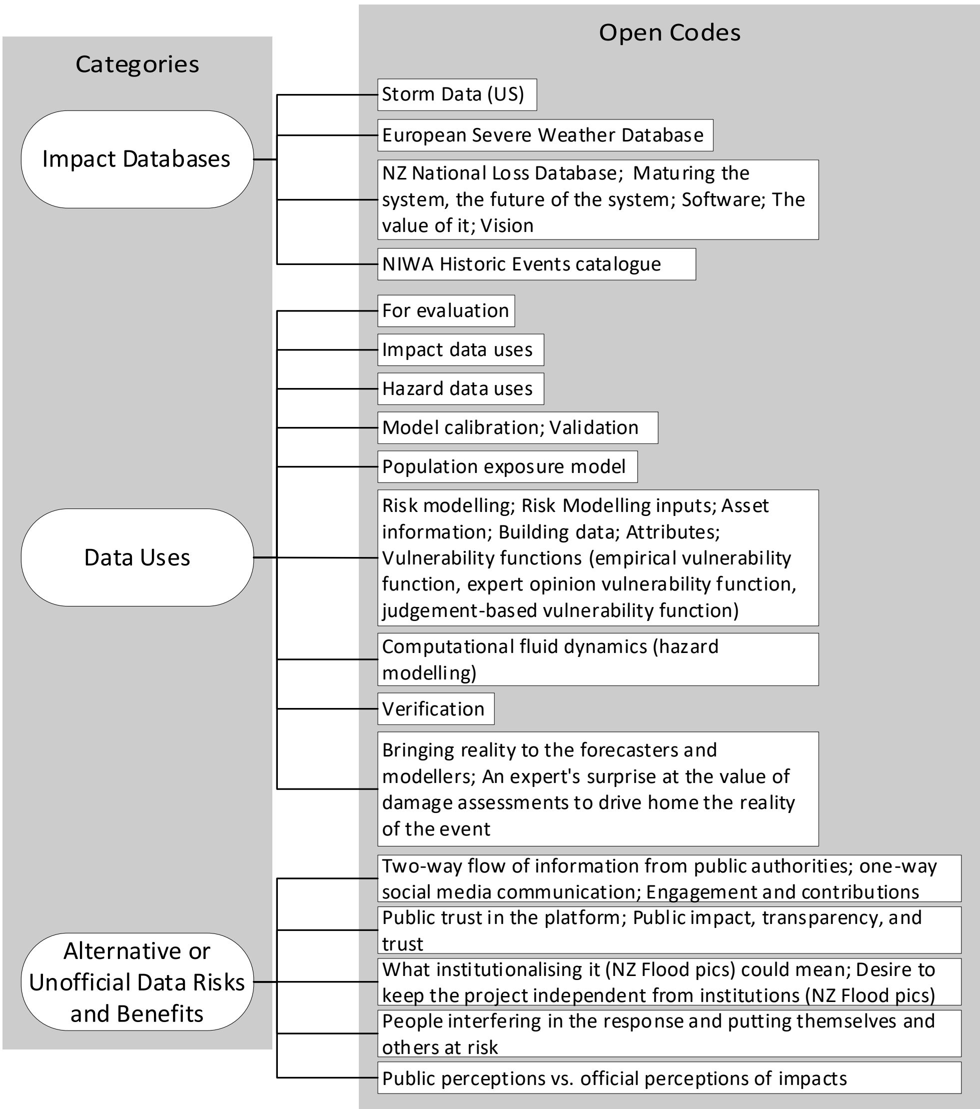


Figure 4.23. Consequences and outcomes of collecting HIVE data.

Two categories were identified for outcomes of 'data sharing, management, and integration,' the second theme of the HIVE Data phenomenon. These are (1) Social data sharing outcomes, and (2) Technical data sharing outcomes, as shown in Figure 4.24. These outcomes resulted from applying a socio-technical (Ghaffarian, 2011) lens to the analysis, where both technical and social aspects of data sharing were identified and explored. Social data sharing outcomes relate to the social outcomes, benefits, and risks of sharing data, such as affecting property values (risk), increasing transparency (benefit), facilitating a community of knowledge (benefit), etc. Technical data sharing outcomes relate to technical products and innovations that resulted from sharing data, such as the Common Alerting Protocol, the Common Operating Picture, online web maps, etc.

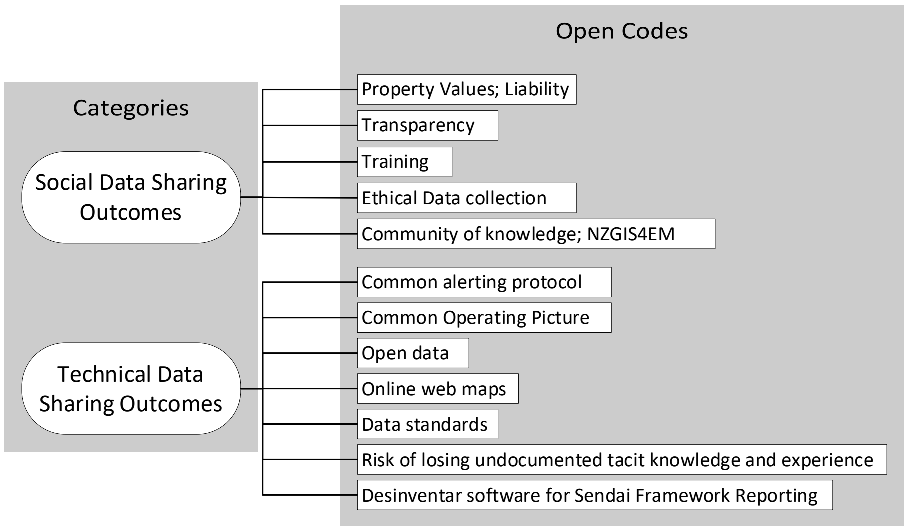


Figure 4.24. Consequences and outcomes of data sharing, management, and integration.

Finally, one category of outcomes and consequences relating to governance contextual conditions, specifically 'policy, decision-making, and practice' was identified. The open codes for this are shown in Figure 4.25. These outcomes are not specific to IFW System implementation but apply to overall Disaster Risk Reduction (DRR) policy, practice, and governance. This is because IFW implementation involves many stakeholders beyond the meteorological service (e.g., Hemingway & Gunawan, 2018), and the collection, use, sharing, and governance of HIVE data expands beyond IFW system implementation, and is needed for other aspects of DRR (e.g., UNDRR, 2015b). For example, one overarching theme was found to be that of reactive vs. proactive EM practice, whereby EM practice tends to be more reactive by traditionally focusing on emergency response and recovery (Kox, Lüder, et al., 2018). This reactive practice has resulted in poor data collection and management practices to meet immediate needs, which can then reduce the availability and accessibility of HIVE data for IFW system implementation. Alternatively, proactive EM practice where processes have been pre-established for data collection, access, and sharing in advance of a disaster event can enable more effective and efficient data collection, access, and sharing.

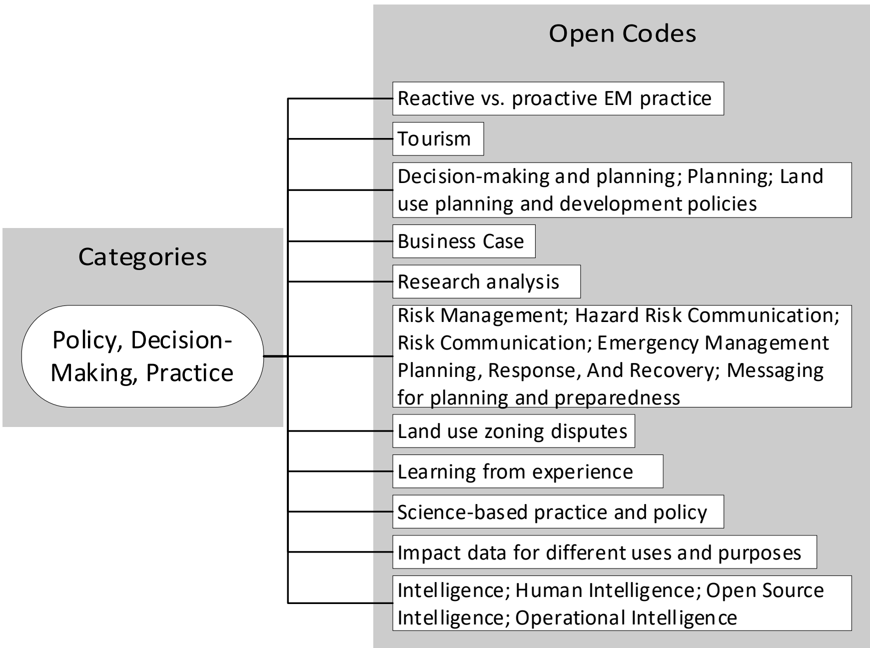


Figure 4.25. Consequences and outcomes related to governance.

4.3.2.3 Selective Coding

During the selective coding phase, decisions were made regarding the inclusion and exclusion of codes and categories based on their explanatory power and based on the objectives of this research (Corbin & Strauss, 2008). For example, cultural conditions were initially identified as a contextual condition to provide contextual understanding of the other categories. While cultural conditions offer an interesting and complex layer to this research, it was determined that further exploration of this category did not align with the research objectives, and as such no further data was collected for this category. Thus, explanatory power and relevance of this category was diminished.

Through selective coding, the core categories were also identified. A core category is that which "incorporates or supersedes other categories in explanatory importance and hence is 'elevated' to the status of an important concept" (Timonen et al., 2018, p. 7). Two core categories were initially identified in this research because of their influence and relation to each category identified in the analysis. The two core categories are: (1) Governance, and (2) Partnerships and Collaboration.

While governance was initially classified as a contextual condition to provide contextual understanding of the other categories, it was found that governance plays a critical role in the implementation of IFWs and in the collection, use, accessibility, and sharing of HIVE data. The underlying influence of each phenomenon and the categories resulting from the axial coding process pointed to some form of governance. For example, in trying to understand the intervening conditions of IFW implementation, governance was identified as a major influencer of role designation for EWSs. The introduction of new or shifting roles and responsibilities for IFW systems is a point of confusion that is interfering with the implementation of IFWs in New Zealand (Potter et al., 2021). With regards to HIVE Data, governance influences the priorities of data collection, and the roles of data custodianship and management. These in turn influence how and what data is collected, used, and shared. However, as with the cultural contextual condition, Governance is a topic area deserving of its own doctoral thesis. Thus, it was determined that there was not enough capacity to explore this as a core category in this PhD study, and it is identified as an area for future research.

Partnerships and Collaboration was identified as the second core category, as it too threads throughout the themes and categories resulting from the analysis. Partnerships and Collaboration appear to be essential for both IFW Systems and HIVE Data. This is shown by the open codes in Table 4.2 and visualised in Figure 4.26. For the IFW System Phenomenon, defining impact thresholds is required for IFWs. Discussions with participants showed that the process of defining impact thresholds requires partnering with agencies that possess the kind of knowledge needed to define these impact thresholds. Such agencies include transportation agencies, flood management agencies, health agencies, insurance agencies, etc.

Table 4.2. Open codes about Partnerships and Collaboration relating back to the two phenomena that are the focal points of this study: IFW Systems, and HIVE Data.

Phenomenon	Relevant Partnerships and Collaboration Open Codes
IFW Systems	Nodes\\IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge
HIVE Data	Nodes\\Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Need for better collaboration and coordination Nodes\\Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Cooperation and collaboration Nodes\\Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Need for better collaboration and coordination to establish data collection needs and standards
Other	Nodes\\Partnerships, Collaboration, and Relationships \Agencies running profession development workshops to build relationships \Cohabitation \Community of knowledge \Informal Partnership \MetService-NIWA \Regional flood group \Science advice groups

For the HIVE Data phenomenon, the concept of Partnerships and Collaboration emerged in two categories: (1) Data and Information Sharing, and (2) Data Collection and Creation. In the first category, 'Data and Information Sharing', the need for cooperation and collaboration was identified as a strategy for facilitating data sharing between the various agencies that possess the data. In the second category, 'Data Collection and Creation', the need for collaboration and coordination was identified for establishing data collection needs and standards across the different agencies that collect the data or need the data. The need for this arises from the idea of agencies collaborating with each other after an event to co-design data collection forms, etc. such that the data is collected to suit various users' needs (Met. Research NZ. J; Risk Modelling NZ. C).

Other codes around partnerships and collaboration were created outside of the direct relation to these two phenomena and are listed in Table 4.2 as 'Other' phenomena which was elevated to the core category of Partnerships and Collaboration. After establishing this category, existing codes were identified relating to this category and relationships were established, as portrayed by the dashed arrows in Figure 4.26.

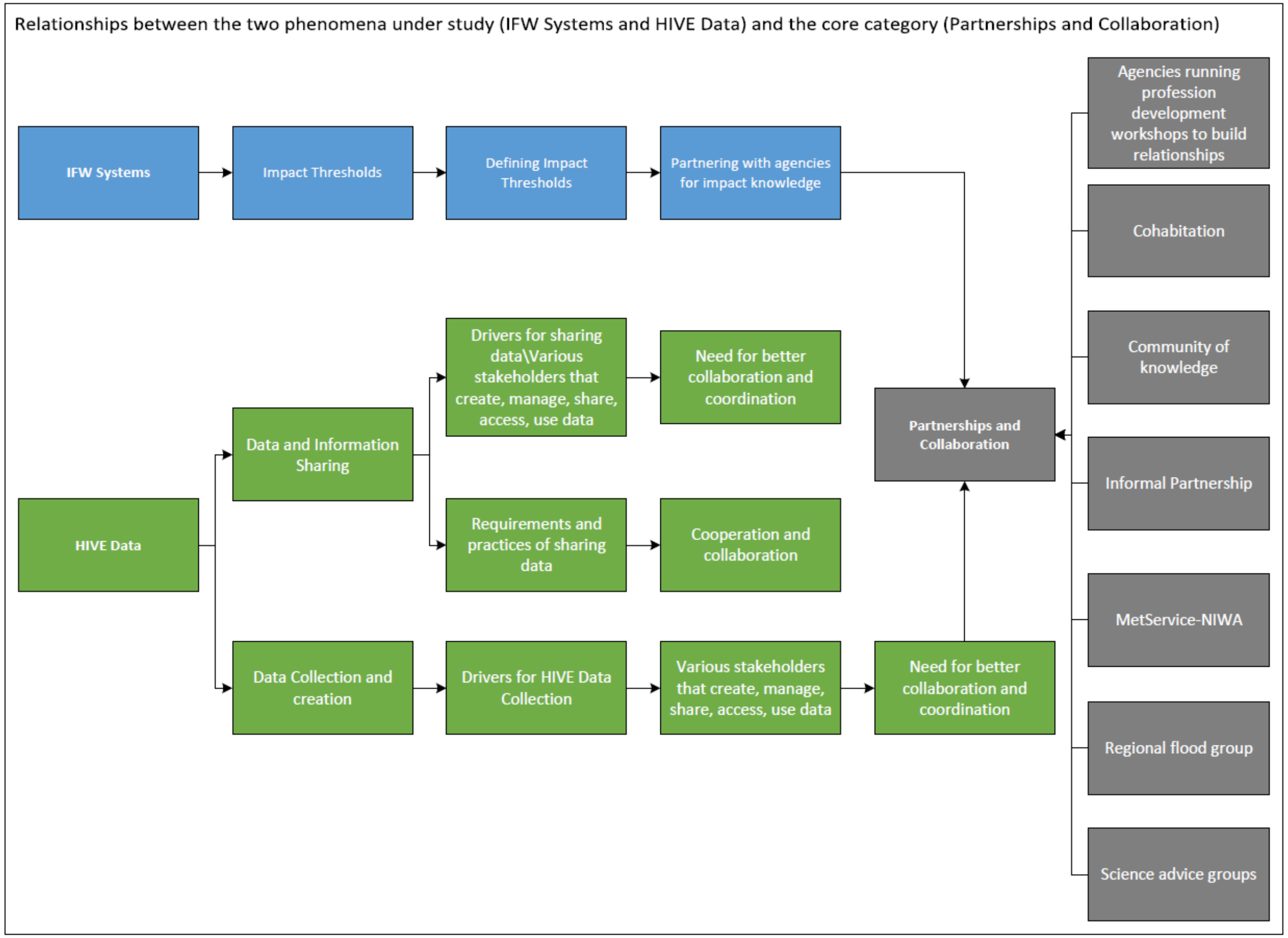


Figure 4.26. Relationships between the two phenomena under study and the core category.The boxes represent codes developed throughout the analysis. The blue boxes represent the IFW System phenomenon and associated categories and codes. The green boxes represent the HIVE Data phenomenon and associated categories and codes. The grey boxes represent the core category of Partnerships and Collaboration. The solid arrows portray the coding hierarchy. The dashed arrows represent the relationships between the two phenomena and the core category.

The value of forming partnerships and collaboration is further exemplified in the following memo about the New Zealand Geographic Information System for Emergency Management (NZGIS4EM) group, a grassroots community of GIS specialists and EM practitioners in NZ that began working together in the mid-2010s to identify how they could build and use geospatial tools for better emergency response. The following memo identified the ability to work together to drive innovation for GIS in EM as a true strength of the NZGIS4EM group.

Memo: NZGIS4EM, Harrison, S., 13 January 2021:

The NZGIS4EM group is a big driver for technological advancement, for pushing the needle forwards on sharing, accessing, and creating geospatial data and tools for emergency response. This is a great example of how people and groups can work together to get the data to where it needs to go in the format that it needs to be in.

Memo: NZGIS4EM, Harrison, S., 21 January 2021:

Great words that describe NZGIS4EM (from Interviewee 19): relationships and community. These are the core values of NZGIS4EM (from my perspective); or rather, it's the true strength of this group of volunteers for fostering this community and building relationships across organisations, which then drives innovation, knowledge sharing, and data sharing.

4.4 Chapter Summary

This chapter provided an overview of the data collection results and findings from the analytical techniques employed according to the ES-GT research strategy guiding this PhD research. Thirty-nine individuals involved in hydrometeorological warning systems and DRR both within and outside of New Zealand were interviewed for this study, with an additional twenty individuals participating in a series of virtual workshops.

Following the ES-GT research strategy, three stages of coding (open, axial, and selective coding) formed the analytical process, accompanied by memo writing and diagramming. The coding paradigm provided by Strauss and Corbin (1990) aided the axial coding stage of this research. As a result of employing the coding paradigm, two phenomena were identified that made up the main subjects under study for this PhD research. These two phenomena are IFW Systems and HIVE Data. As such, following an exploration of the literature on the potential use of Volunteered Geographic Information (VG) for IFWs presented in Chapter Five, the results of this thesis are organised by phenomenon, as represented in Figure 4.27. Chapter Six presents the results specific to the IFW implementation phenomenon, and Chapter Seven and Chapter Eight present results specific to the HIVE Data phenomenon. Finally, the core category of Partnerships and Collaboration resulting from the selective coding process is defined in Chapter Nine and integrated with the results presented in Chapter Six to Chapter Eight.

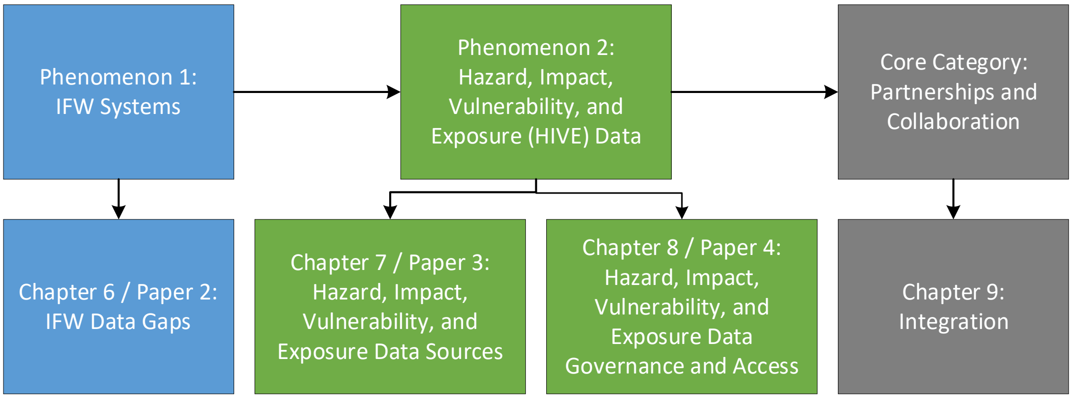


Figure 4.27. Links between the two phenomena and the resulting core category for this PhD studyand the corresponding results chapters.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Five: **Volunteered Geographic Information for people-centred severe weather early warning: A literature review**

This chapter presents the first manuscript for publication: a literature review of the role of Volunteered Geographic Information (VGI) for EWSs. The initial topic of this doctoral project was to explore alternative sources of impact data for IFWs, including crowdsourcing, citizen science, and social media. VGI was chosen as the alternative data type to explore due to its geospatial nature, which was found to be a necessary component of impact data. VGI encompasses crowdsourced data, citizen science data, and social media data that contain geospatial components of the data (i.e., location information). This literature review was performed to explore the role of VGI in EWSs, and to achieve Objective 1.1. of this thesis: To establish VGI as a potential source of impact data for IFWs.

The article presented in this chapter was published in 2020 in the *Australasian Journal of Disaster and Trauma Studies*, as:

Harrison, S. E., Potter, S. H., Prasanna, R., Doyle, E. E. H., & Johnston, D. (2020). Volunteered Geographic Information for people-centred severe weather early warning: A literature review. *Australasian Journal of Disaster and Trauma Studies*, *24*(1). http://trauma.massey.ac.nz/issues/2020-1/AJDTS_24_1_Harrison.pdf

The published form is provided in Appendix J.

5.1 Abstract

Early warning systems (EWSs) can prevent loss of life and reduce the impacts of hazards. Yet, recent severe weather events indicate that many EWSs continue to fail at adequately communicating the risk of the hazard, resulting in significant life and property loss. Given these shortcomings, there has been a shift towards people-centred EWSs to engage with audiences of warnings to understand their needs and capabilities. One example of engaging with warning audiences is through the collection and co-creation of volunteered geographic information (VGI). Much of the research in the past has primarily focused on using VGI in disaster response, with less exploration of the role of VGI for EWSs.

This review uses a scoping methodology to identify and analyse 29 research papers on EWSs for severe weather hazards. Results show that VGI is useful in all components of an EWS, but some platforms are more useful for specific components than are others. Furthermore, the different types of VGI have implications for supporting people-centred EWSs. Future research should explore the characteristics of the VGI produced for these EWS components and determine how VGI can support a new EWS model for which the World Meteorological Organization is advocating: that of impact-based forecasting and warning systems.

5.2 Introduction

Early warning systems (EWSs) can prevent loss of life and reduce the impacts of hazards by providing members of the stakeholders and the public with information about likely, imminent risks on which they can act to prepare themselves and their property. As such, they have been a focus of disaster risk reduction since the Hyogo Framework for Action 2005-2015 through to the current Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR, 2015b; UNISDR, 2005). EWSs are described as having four key operational components: Disaster Risk Knowledge; Detection, Monitoring, and Warning Services; Communication and Dissemination Mechanisms; and Preparedness and Response Capacity (see Figure 5.1; Basher, 2006; Golnaraghi, 2012).

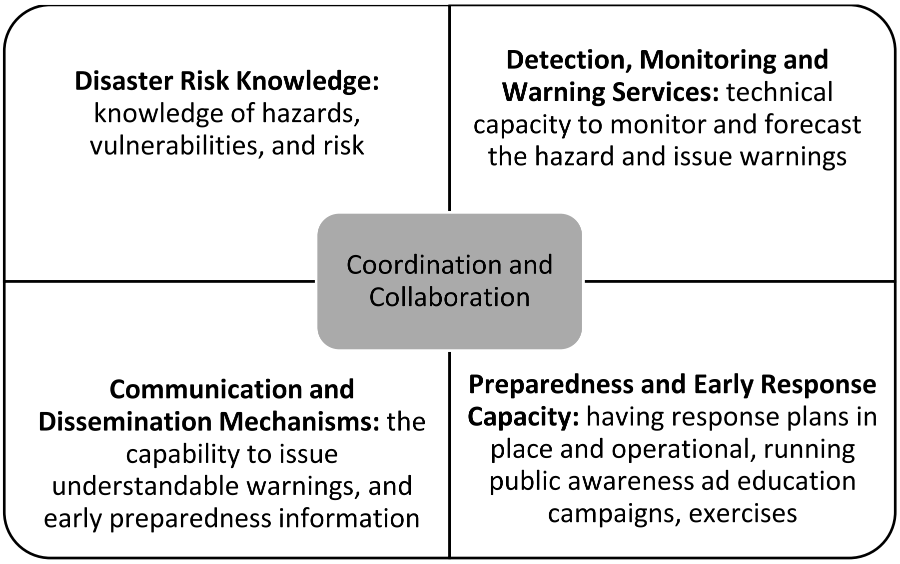


Figure 5.1. Four operational components of an Early Warning System. Adapted from Basher (2006); Golnaraghi (2012); WMO (2018).

The first component, Disaster Risk Knowledge, involves systematically collecting and analysing data related to risk, such as the exposure and vulnerability of people and infrastructure to nearby hazards (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). This involves assessing risk and vulnerability, building evacuation plans, and tailoring warning systems. Detection, Monitoring, and Warning Services make up the second component and are central to EWSs. This component requires reliable technology and involves continuous, automated detection and hazard monitoring (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Furthermore, data, forecasts, and warnings should be archived for post-event analysis and for continual system improvements (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Impact data collected during and after a severe weather event would support both of these first two components (Harrison et al., 2015).

The third component of an EWS is Communication and Dissemination, which is needed to reach those at risk. This involves using clear, concise, and understandable messages to enable proper preparedness (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Multiple communications channels are necessary to reach as many people as possible (Ahmed et al., 2012; Basher, 2006). The fourth component of an EWS is Preparedness and Early Response Capacity. This involves running education and preparedness programmes to help people "understand their risks, respect the national warning services, and know how to react to warning messages" (WMO, 2018, p. 6). All four components of an EWS play a key role in crisis and risk communication.

EWSs share common characteristics with crisis and emergency risk communication theory. Like EWSs, the goal of crisis and risk communication theory is to provide sufficient and appropriate information to stakeholders that would allow them to "make the best possible decisions about their well-being" in a short period of time under uncertainty (Reynolds & Quinn, 2008, p. 14S). This involves understanding stakeholder (including the public) perceptions of risk and of the effectiveness of response, understanding the needs, capabilities, experiences, and predispositions of the stakeholders, and formulating messages based on these understandings for different audiences throughout the stages of crisis (Morgan et al., 1992; Reynolds & Seeger, 2005; Veil et al., 2008). Crisis and emergency risk communication theory is applied in risk messaging, crisis messaging, and warnings for health and emergency situations including, but not limited to, disease outbreaks, bioterrorism, hurricanes, and tornadoes (Reynolds & Seeger, 2005). The EWS framework presented in Figure 5.1 is thus supported by objectives of crisis and emergency risk communication theory, although the EWS framework does not include an apparent consideration for two- way communication: a key component in crisis and emergency risk communication theory for evaluating the effectiveness of communication (Garcia & Fearnley, 2012; Veil et al., 2008).

Recent severe weather events indicate that many EWSs continue to fail at adequately communicating the risk (and associated impacts) of the hazard, resulting in significant life and property loss due to limited understanding of, and response to, warnings (Ching et al., 2015; Wagenmaker et al., 2011; WMO, 2015). As such, there has been a push for "people-centred" EWSs to bring the "human factor" into consideration when designing and implementing EWSs and issuing warnings.

5.3 People-Centred Early Warning Systems

The broader EWS literature has recognised a communication gap between warning services and warning recipients, resulting in target audiences taking inadequate protective action despite receiving warnings (Anderson-Berry et al., 2018; Basher, 2006; Weyrich et al., 2018). In 2006, Basher introduced the concept of people-centred EWSs to address the "human factor" in EWSs, as he stated "failures in Early Warning Systems typically occur in the communication and preparedness elements" (Basher, 2006, p. 2168). Since then, there has been a shift towards people-centred EWSs which are developed for, and with, the target audiences to identify their needs and capacities and to transfer responsibility back to the audience to take protective actions (Basher, 2006; Scolobig et al., 2015). The United Nations Office for Disaster Risk Reduction (UNDRR; formerly known as the UNISDR) listed "investing in, developing, maintaining and strengthening people-centred multi-hazard, multi-sectoral forecasting, and Early Warning Systems" as an objective towards meeting the fourth priority of the Sendai Framework (UNDRR, 2015b, p. 21). This "people-centred" aspect involves incorporating local and indigenous knowledge about hazards, promoting and applying low-cost EWSs that are appropriate to the audience based on their needs and capabilities, and broadening information channels (UNDRR, 2015b; WMO, 2018). According to the Sendai Framework, people-centred EWSs can be developed through engagement with the audiences of warnings (e.g., individuals, communities, sectors: UNDRR, 2015b; WMO, 2018). One such example of engaging with warning audiences and understanding their needs and capabilities is through volunteered geographic information (VGI; WMO, 2017). VGI is information produced by or gathered from the public with associated locational attributes. The location-based information from VGI allows officials to identify high-risk areas, populations, and infrastructure (Goodchild & Glennon, 2010; Granell & Ostermann, 2016; Haworth, 2018; Roche et al., 2011).

5.4 Volunteered Geographic Information

VGI is valuable to disaster management because disasters are inherently location- and time-dependent and the location information from VGI allows officials to understand where the high-risk areas and populations are (Goodchild, 2007; Goodchild & Glennon, 2010; Granell & Ostermann, 2016; Haworth, 2018; Roche et al., 2011). The broader literature body around VGI, crowdsourcing, citizen science, and social media discusses and debates the relationship of these terms to each other and their associated characteristics and differences. It is argued that VGI overlaps both with citizen science and crowdsourcing (Cooper et al., 2018; Haklay, 2013, 2017). In Haklay's (2013) typology, crowdsourcing is classified as the lowest level of participation in citizen science. Citizen science (including crowdsourcing) is considered VGI when the information produced through the differing levels of participation includes geographic information (Haklay, 2017).

VGI can be collected in various ways, producing different types and formats of data. From reviewing the VGI and disaster risk reduction literature, we identified four types of VGI that are generally produced and/or collected for disaster risk reduction; these are summarised in Table 5.1. Geo-located social media refers to VGI that is posted online by social media users that has associated geographical location information. The term social media recognises online blogs, micro-blogs, online social networking, and forums, which enable sharing of text, audio, photographs, and videos (Alexander, 2014). Facebook, Twitter, Sina Weibo, WeChat, Instagram, and SnapChat are some examples of popular social media platforms. During a severe weather event, authorities can use social media to disseminate alerts and warnings and collect information from members of the public about the event and its impacts (Alexander, 2014; Goodchild, 2007; Harrison & Johnson, 2016; Porto de Albuquerque et al., 2017; Roche et al., 2011; Simon et al., 2015; Slavkovikj et al., 2014).

Table 5.1. Summary of VGI types.

VGI Process	Spatial Data Format	Data type	Data Sources	Disaster Risk Reduction Phase	Analysis/Outcomes
Geo-located social media harvesting	Point data	Impact data, exposure data, vulnerability data, hazard data Photos, videos, text	Facebook, Instagram, Twitter, Snapchat, Flickr, Sina Weibo, etc.	All	Cluster analysis, early detection, situational awareness, post-event damage/impact assessment, response coordination
Crowd-sourcing	Point data	Impact data, exposure data, vulnerability data, hazard data Photos, videos, text	Online reporting forms, mobile application	Readiness, Risk Reduction, During, Response	Cluster analysis, early detection, situational awareness, damage/impact assessment, response coordination
Participatory mapping / Participatory GIS	Point, line, polygon	Impact data, exposure data, vulnerability data, hazard data, expert local knowledge Shapefiles	Community members, community leaders, stakeholders	Readiness, Risk Reduction, Recovery	Hazard and risk assessments/modelling, impact forecasting, customise/personalise warnings systems for the community, identify impact thresholds, inform/improve readiness and reduction efforts based on local knowledge
Local Knowledge	Point, line, polygon, written, audio	Impact data, exposure data, vulnerability data, hazard data, expert local knowledge Shapefiles	Community members, community leaders, stakeholders, experts	Readiness, Risk Reduction, Recovery	Hazard and risk assessments/modelling, impact forecasting, customise/personalise warnings systems for the community, identify impact thresholds, inform/improve readiness and reduction efforts based on local knowledge

For this review, crowdsourcing refers to gathering information from active public participation, namely reports submitted via online forms or mobile applications (Harrison & Johnson, 2016). Crowdsourcing has historically been used in the response to a disaster for building situational awareness, coordinating resources, and aiding response efforts (Harrison & Johnson, 2016; Haworth & Bruce, 2015; Poblet et al., 2014). Within the severe weather context, crowdsourcing was used in the aftermath of Hurricane Katrina to locate missing people and allocate response efforts (Roche et al., 2011). In other examples, crowdsourcing is used for people on the ground to submit reports on flood levels and weather phenomena observations (Harrison & Johnson, 2016; Horita et al., 2018).

Participatory mapping and participatory Geographic Information Systems (participatory GIS) use local spatial knowledge to create spatial data or to verify and update existing data (Peters-Guarin et al., 2012). Participatory mapping generally evolves into participatory GIS when hand-drawn maps or features are digitised and integrated into a GIS for further analysis (Brown & Kyttä, 2014; Forrester & Cinderby, 2011). Participatory mapping is often used to map exposure and vulnerability to hazards in communities to support disaster risk planning (Gaillard & Pangilinan, 2010; Haklay et al., 2014). For weather-related hazards, Haworth et al. (2016) found that participatory mapping enabled local knowledge exchange for community preparedness to bushfire risks.

Local knowledge refers to knowledge possessed by locals about their communities, neighbourhoods, traditions, history, environment, and hazards, among others. Local knowledge has not been clearly defined in the literature. For the purposes of this paper, we consider local knowledge as information gathered in similar participatory mapping and participatory GIS processes but not translated into a map or GIS. Recently, the access to and integration of local knowledge has been recognised for its importance to disaster risk reduction (Anderson-Berry et al., 2018; Gall & Cutter, 2016; Sebastian et al., 2017; UNDRR, 2015b).

Past research has focused heavily on the role of VGI in disaster response, with less exploration in understanding how VGI can inform warnings before or during a severe weather event (Harrison & Johnson, 2016; Haworth & Bruce, 2015; Horita et al., 2013; Klonner et al., 2016). In Klonner et al. (2016) systematic literature review, the authors focused on documenting research on VGI for preparedness and mitigation but did not provide clear findings in the context of warnings for severe weather. Assumpção et al. (2018) identified the role of citizen observations in providing data for flood modelling and forecasting to solve issues of data scarcity, but again with no mention of warnings.

The original conception of VGI began with identifying its value for early detection and warning of hazards, using 'citizens as sensors' (Goodchild, 2007). Since then, some work has emerged exploring VGI for early warnings of various hazards, such as earthquakes, landslides, and tsunami (Carley et al., 2016; Elwood et al., 2012; Goodchild, 2007; Granell & Ostermann, 2016; Harrison & Johnson, 2016). Horita et al. (2016) argued that VGI may help address challenges of assigning proper warning thresholds by incorporating local knowledge of response capabilities. Meissen and Fuchs-Kittowski (2014a) developed a conceptual framework which demonstrated how crowdsourced data can be fully integrated into an existing EWS as another dataset to augment or enhance the warnings by providing context. However, no further evidence to date indicates the adoption into practice of this framework for any type of EWS. Finally, Marchezini et al. (2018) conducted a literature review of research on citizen science and EWSs and found that more research is needed to identify how citizen science can be "mainstreamed" into EWSs.

Some agencies have started collecting VGI to detect, monitor, and track events and their impacts. In the United Kingdom (UK), the British Geological Survey collects landslide impact data from Twitter including text descriptions, photos, and video footage of the resulting impacts (Pennington et al., 2015). These data are integrated into the National Landslide Database, which is used to create a Hazard Impact Model (Pennington et al., 2015). In Canada, the National Meteorological Service uses hazard information posted by the public on Twitter to detect weather events such as tornadoes and to verify and update current weather watches and warnings (Harrison & Johnson, 2016). However, there is a gap in the literature for fully characterising the role of VGI for severe weather warnings. It is important to fill this gap because information and knowledge possessed by citizens have the potential to uncover "areas of importance or concern" that have yet to be identified in an official capacity (Haworth et al., 2012). VGI offers a way to capture local knowledge about previous severe weather events and their extent, severity, and resulting impacts, as well as information on the local exposure and vulnerability that warning services may not necessarily possess (GFDRR, 2016; Krennert, Pistotnik, et al., 2018; Sai et al., 2018; WMO, 2015, 2017). This paper uses a scoping review method to identify previous research into the use of VGI for severe weather EWSs, to attempt to answer the research question: What are the current and potential uses of VGI for severe weather warnings? The objective of this review is to determine how VGI has been, or could be, used within EWSs for severe weather hazards.

5.5 Method

This literature review uses a scoping method to explore areas of existing research and identify research gaps in VGI for severe weather early warning systems (Arksey & O'Malley, 2005; Paré et al., 2015). Scoping reviews provide a "rigorous and transparent method for mapping areas of research" in a short time (Arksey & O'Malley, 2005, p. 30). The aim is to describe the nature of the current literature on VGI for severe weather EWSs by describing the quality and quantity of the research (Grant & Booth, 2009; Paré et al., 2015). Scoping reviews are recognised for their strength in providing a broad picture of the state of research in a given topic area and are well-cited in the information systems field (Grant & Booth, 2009; Paré et al., 2015; Tan et al., 2017). This scoping review follows the five- step process defined by Arksey and O'Malley (2005): (1) identify the research question, (2) identify relevant studies, (3) select studies, (4) chart the data, and (5) report the results.

The initial literature search involved developing a search string to capture the broad topic area of VGI and social media for warning of severe weather hazards. The search string comprised three joined statements, shown in Table 5.2, to cover warnings and Disaster Risk Knowledge (as per the first component of the EWS framework: Basher, 2006; Golnaraghi, 2012), VGI, and severe weather, which were entered into two academic- focused databases, Scopus and EBSCO Discovery Service, in August 2018. Literature review papers have been published on similar topics in this space that have searched no more than two databases (e.g., Klonner et al., 2016; Tan et al., 2017). Furthermore, Scopus is recognised for indexing a larger number of journals than other databases and is the largest searchable citation and abstract source for various scientific fields (Falagas et al., 2008; Guz & Rushchitsky, 2009). Moreover, when searching the two databases many duplicate results were found between the two databases, ensuring confidence in the coverage.

Table 5.2. Search string employed in EBSCO Discovery and Scopus databases.

Topics covered	Search string statement
Warnings and Disaster Risk Knowledge	("risk communication" OR "warning*" OR "impact model*" OR "risk model*" OR "impact warning*" OR "impact*based warning*" OR "impact forecast*" OR "impact*based forecast*" OR "risk*based warning*" OR "risk*based communication")
	AND
A broad definition of VGI to include social media, participatory mapping, local knowledge based on location	("participatory" OR "participatory mapping" OR "VGI" OR "volunteered geographic information" OR "participatory GIS" OR "PPGIS" OR "geographic crowdsourc*" OR "citizen science" OR "crowdsourc*" OR "social media")
	AND
Severe weather hazards as defined under the WWRP HIWeather Implementation Plan (Jones & Golding, 2014)	("weather" OR "storm*" OR "snow*" OR "wind*" OR "tornado*" OR "hurricane*" OR "cyclone*" OR "typhoon*" OR "monsoon*" OR "flood*" OR "mudslide" OR "flash flood*" OR "rain*" OR "wildfire")

"Participatory GIS" and "participatory mapping" are different types of VGI, and thus were identified as separate search terms. During the process of developing the search string, it was found that additional VGI research was left out of the search due to the specificity of "participatory mapping" and "participatory GIS", thus the search was widened with the term "participatory" to capture more VGI studies. Similarly, "flash flood" and "flood" are likely redundant, however, they were both included to ensure full coverage. The asterisk in the search string acts as a wildcard to search for variations of the root term. The search covered all years from the earliest available until mid-2018 and included only peer-reviewed journals and conference proceedings in English. The search resulted in 1,015 hits from Scopus and 122 from EBSCO. After removing duplicates, 1,027 unique publications were captured.

The following inclusion-exclusion criteria were used to select publications most relevant to this study:

1) Publications that specifically focused on severe weather hazards as defined under the World Weather Research Programme's (WWRP) High Impact Weather Implementation Plan (Jones & Golding, 2014, p.; n = 254);
2) Studies that explicitly discussed warnings, preparedness, mitigation, impact modelling and
3) Studies that focused on VGI, crowdsourcing, citizen science, participatory mapping, local knowledge gathering, or social media data (reducing to n = 42).
4) Finally, publications had to be original, complete research papers (n = 29).

After applying the inclusion-exclusion criteria, information from the resulting papers was extracted according to different categories (see Table 5.3). Initially, the severe weather hazard(s) considered in the study were identified, after which the EWS framework was used to classify the papers and determine how VGI is or could be used within the EWS framework (these results are presented later in Figure 3). This classification involved identifying for which EWS component the VGI was used (see Figure 1), followed by the element within the EWS component (i.e., the specific task, tool, or process that the VGI was used for within the EWS component, such as risk mapping, detection, monitoring, forecasting, or warning dissemination). The VGI platform was identified (e.g., participatory mapping, participatory GIS, social media, crowdsourcing, citizen science, local knowledge), as well as the type of data that was collected (Haklay, 2017; Harrison & Johnson, 2016). These categories were chosen to determine the representation of VGI in severe weather EWSs.

5.6 Results

The search of the two databases led to 1,027 unique publications. After applying the inclusion-exclusion criteria, the final number of papers selected for this study was 29. The categories listed in Table 5.3 were used as a structure for analysis and discussion and were chosen based upon the dominance of those themes in the papers.

Table 5.3. Categories for literature review.

Category	Description
Hazard	The type of severe weather hazard(s) considered in the study.
Early Warning System Component	The component from the EWS framework that each study applies to.
VGI Platform	The source of the VGI data, such as from social media, or from crowdsourcing (i.e., citizen observation), citizen science (i.e., a high level of engagement than crowdsourcing (Haklay, 2013)), participatory mapping, participatory GIS, or local knowledge.
Data Type	The type of data that was collected through the VGI process, such as local knowledge captured through interviews and/or participatory mapping, hazard data from social media or crowdsourcing, etc.

5.6.1 Hazard Type

The selected articles covered a range of severe weather hazards as defined in the World Weather Research Programme (WWRP) High Impact Weather (HIWeather) implementation plan (Jones & Golding, 2014). Some hazards are represented more than others; of the 29 articles, 16 focused on flood hazards, followed by seven studies that covered general severe weather hazards, two studies that examined rain-induced landslides, two for cyclones, and one each for air quality and urban heat wave.

The 16 flood studies covered a range of elements within the EWS components. These elements were identified by reviewing the selected studies and aligning them with the EWS components. Table 5.4 provides a summary of the selected studies which examined floods. Most studies covered flood detection, monitoring, and forecasting using VGI collected from social media and crowdsourcing. The next most common elements that were covered in the flood studies were vulnerability assessments and risk mapping and modelling, using VGI from participatory GIS, participatory mapping, local knowledge, and social media. Just one study looked at using social media for detection, warning messaging, and for informing preparedness decisions (Allaire, 2016).

The remaining 13 studies covered other hazards, such as general severe weather, cyclones, landslides, air quality, and urban heatwaves. Table 5.5 provides a summary of the selected studies covering these various hazards. The general category refers to studies that did not identify a specific severe weather hazard, but referred only to "severe weather", usually in the context of severe weather warnings (Fdez-Arroyabe et al., 2018; Grasso & Crisci, 2016; Grasso et al., 2017; He et al., 2018; Krennert, Pistotnik, et al., 2018; Longmore et al., 2015; Lu et al., 2018).

In the general category, most of the selected studies looked at detection and forecasting using social media and crowdsourcing, followed by tracking warning dissemination across social media, and one study that used crowdsourcing for both risk and vulnerability assessment and providing warnings. The two cyclone studies each used social media and local knowledge to detect and forecast cyclone damage and to understand local responses to warnings, respectively. The two landslide studies both used VGI for landslide hazard and impact modelling, using crowdsourcing and social media. Finally, both the air quality and urban heatwave studies explored VGI from social media to forecast air quality and detect heatwaves based on individual exposure.

These studies indicate that VGI is used in the mapping, modelling, detection, monitoring, and warning of a number of severe weather hazards but that floods are the most heavily studied, with the widest range of VGI application across all of the elements. How these studies fit within the EWS framework is analysed in the following section.

Table 5.4. Summary of selected studies covering flood hazards.

EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
Disaster Risk Knowledge	Modelling	To integrate local knowledge into GIS outputs for flood risk management using PGIS in order to understand how people cope and adapt	Participatory GIS	Interviews with households in Barangay, Philippines	(Peters-Guarin et al., 2012)
	Modelling	Validating flood models using quantitative and qualitative VGI	Participatory Mapping	Local knowledge from workshop participants and interviewees	(Rollason et al., 2018)
	Risk mapping	To provide an example of how to engage and collaborate with local stakeholders for flood management	Participatory Mapping	Land feature layers, input from locals	(Lavers & Charlesworth, 2018)
	Vulnerability assessment	To present a risk management framework that is based on local knowledge of the vulnerability to water hazards	Local knowledge	Meetings, workshops, interviews with people, media, and public sectors related to risk management	(Arias et al., 2016)
	Vulnerability assessment	To present a new methodology for incorporating stakeholder's participation, local knowledge, and locally spatial characteristics for vulnerability assessments of flood risk	Participatory GIS	Demographic data, infrastructure, hazard data (e.g., average annual rainfall), questionnaire interviews with experts and community members	(Hung & Chen, 2013)
	Vulnerability assessment	To present a new database for collection and assessment of flood damage using a bottom-up approach to gather and identify damage data	Social media	Personal blogs, on-site observations, public administration, social media, online media, local authorities, corporate websites	(Saint-Martin et al., 2018)

EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
Detection, Monitoring, Warning Services	Detection	To develop a service-oriented architecture for flood management to capture information real-time about floods	Crowdsourcing	Rainfall, river, news, OpenStreetMap	(Sharma et al., 2016)
	Detection	To develop a methodology for interpreting image tags on social media to allow for early detection of a flood and recording the impacts	Social media	Flickr posts - timestamps and location metadata	(Tkachenko et al., 2017)
	Detection, Forecasting	SWOT analysis of web-based access to data and model simulations, and insight on pEWMS, and conceptual framework for a Nordic pEWMS	Crowdsourcing, Social Media	Denmark: groundwater level observations Iceland: flood photos Finland: mobile phone observations	(Henriksen et al., 2018)
	Detection, Monitoring	To assess social media feasibility for flood detection, monitoring, and forecasting and develop a novel methodology for doing so	Social media	Twitter data	(Rossi et al., 2018)
	Forecasting	To develop a methodology using social media for estimating rainfall runoff estimations and flood forecasting	Social media	Twitter data	(Restrepo-Estrada et al., 2018)
	Forecasting	To present a real-time modelling framework to identify likely flooded areas using social media	Social Media	Twitter data, LiDAR	(Smith et al., 2017)
	Monitoring	To estimate flood severity in an urban coastal setting using crowdsourced data	Crowdsourcing	Crowdsourced street flooding reports	(Sadler et al., 2018)
	Monitoring	To present a conceptual framework for collecting and integrating heterogeneous data from sensor networks and VGI	Crowdsourcing	Flood data from in-situ sensors and volunteers	(Horita et al., 2015)
	Monitoring	To present a new methodology for monitoring flood hazards using remote sensing and VGI	Crowdsourcing, Social Media	Volunteered data (photos, videos, news), Landsat, DEM, meteorological data, river data	(Schnebele & Cervone, 2013)

EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
Detection, Monitoring, Warning Services; Communication and Dissemination Mechanism; Preparedness and Early Response Capacity	Warning messaging, preparedness	To test if evidence exists for social media reducing flood losses by informing mitigation decisions before the flood	Social media	Surveys, in-depth interviews with households who experienced flooding in Bangkok, 2011	(Allaire, 2016)

Table 5.5. Summary of selected studies covering other severe weather hazards.

Hazard	EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
General	Disaster Risk Knowledge; Detection, Monitoring, Warning Services	Risk mapping	To present a data infrastructure that can be used to delineate individual vulnerability to meteorological changes	Crowdsourcing	User profiles on a mobile app	(Fdez-Arroyabe et al., 2018)
	Detection, Monitoring, Warning Services	Detection	To present an Android-based application for geohazard reduction using crowdsourcing	Crowdsourcing	Crowdsourced information (field data, photos, videos)	(He et al., 2018)
		Detection, Monitoring	To present a conceptual framework for collecting weather photos	Crowdsourcing	User reports, photos, videos	(Longmore et al., 2015)
		Detection, Monitoring	To evaluate the occurrence of crowdsourcing for severe weather within European NMHSs	Crowdsourcing, Social Media	Surveys with European National Meteorological and Hydrological Services	(Krennert, Pistotnik, et al., 2018)
		Forecasting	To use social media as a new way of forecasting and generating traffic alerts due to weather hazards	Social media	Temporal, spatial, traffic, and meteorological data from Weibo	(Lu et al., 2018)
	Communication and Dissemination Mechanism	Warning dissemination	To study the use of codified hashtags relating to weather warnings in Italy	Social media	Twitter data	(Grasso & Crisci, 2016)
		Warning dissemination	To evaluate the use of a list of predefined codified hashtags for weather warnings in Italy	Social media	Twitter data	(Grasso et al., 2017)
Cyclone	Detection, Monitoring, Warning Services	Forecasting	To determine if social media and geo-location information can contribute to a more efficient early warning system and help with disaster assessment	Social media	Twitter data, Hurricane damage loss data	(Wu & Cui, 2018)
	Preparedness and Early Response Capacity	Response to warnings	To integrate local and scientific meteorological knowledge and actions within coconut farming communities in the Philippines	Local knowledge	Interviews with key stakeholders	(Ton et al., 2017)

Hazard	EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
Landslide	Disaster Risk Knowledge	Modelling	To present a crowdsourcing smartphone app for landslide reports which populates a landslide database	Crowdsourcing	Crowdsourced landslide reports from app users	(Choi et al., 2018)
		Modelling	To present a national landslide database in the U.K. which is partially populated with social media data to capture the impacts of landslides and for early detection of landslides	Social media	Twitter data	(Pennington et al., 2015)
Air quality	Detection, Monitoring, Warning Services	Forecasting	To explore the use of social media as a real-time data source for forecasting smog-related health hazards	Social media	Social media data and physical sensors data	(Chen et al., 2017)
Urban heat wave	Detection, Monitoring, Warning Services	Detection	To investigate the relationship between heat exposure and tweet volume over time	Social media	Twitter data	(Jung & Uejio, 2017)

5.6.2 Early Warning System Components

The papers were categorised by EWS component, as per Basher's (2006) framework (see Figure 5.1): (1) Disaster Risk Knowledge (n = 8); (2) Detection, Monitoring, and Warning Services (n = 16); (3) Communication and Dissemination Mechanisms (n = 2); and (4) Preparedness and Early Response Capacity (n =1). Two studies were found to fall into more than one EWS component. The studies were then classified by the specific elements within each component (e.g., hazard mapping, risk mapping, vulnerability assessment, modelling, hazard monitoring, detection, monitoring, warning, messaging, dissemination).

5.6.2.1 Disaster Risk Knowledge

Eight studies fall into the Disaster Risk Knowledge component of the EWS framework. Four of these studies looked at the use of VGI for hazard, risk, or impact modelling for landslides and floods (Choi et al., 2018; Pennington et al., 2015; Peters-Guarin et al., 2012; Rollason et al., 2018). Choi et al. (2018) presented a crowdsourcing-based smartphone application to aggregate landslide reports, which populates a landslide database for further hazard analysis. Similarly, Pennington et al. (2015) presented a landslide database for the UK that is partially populated by reports from Twitter to capture their impacts for further modelling. In the floods space, Peters-Guarin et al. (2012) utilised participatory GIS to integrate local knowledge of coping and adaptation practices into GIS-based flood risk analysis. Alternatively, Rollason et al. (2018) used participatory mapping to validate existing flood models.

The other four studies in the Disaster Risk Knowledge component involved risk mapping and vulnerability assessments, also for floods (Arias et al., 2016; Hung & Chen, 2013; Lavers & Charlesworth, 2018; Saint-Martin et al., 2018). Lavers and Charlesworth (2018) engaged with landowners to capture their knowledge of flood risk to inform flood management. Arias et al. (2016) presented a risk management framework for floods based on local knowledge of the vulnerability to water hazards. Hung and Chen (2013) incorporated stakeholders' participation and local knowledge through participatory GIS for vulnerability assessments of flood risk. Saint-Martin et al. (2018) developed a flood damage database (DamaGIS) to collect and assess flood damage, sourced from corporate websites, personal blogs, local authorities, on-site observations, social media, and online media. Furthermore, Saint-Martin and colleagues argued that social media can extend coverage to areas lacking regular media coverage and reveal damage that might have otherwise gone undetected.

5.6.2.2 Detection, Monitoring, and Warning

Within the Detection, Monitoring, and Warning component, 16 studies were identified. Four studies used VGI for hazard detection. Tkachenko et al. (2017) and Sharma et al. (2016) looked at VGI for detecting floods and capturing impacts from social media and crowdsourced data respectively. Jung and Uejio (2017) tested the effectiveness of measuring heat exposure on social media and consequently detecting urban heatwaves. Similarly, He et al. (2018) developed a crowdsourcing application to detect various weather hazards and to capture impacts to improve the decision-making of local governments. Henriksen et al. (2018) indicated the role of social media and crowdsourcing for both detection and forecasting of floods, while Rossi et al. (2018) assessed the feasibility of social media for flood detection and monitoring. Longmore et al. (2015) presented a conceptual crowdsourcing framework for collecting photos of severe weather hazards in the United States to improve weather monitoring by the National Weather Service. In Europe, Krennert, Pistotnik, et al. (2018) assessed the occurrence of crowdsourcing (either through specialised applications or social media) by national hydrological and meteorological services to capture severe weather observations and impacts for real-time warning verification and improvement.

VGI for forecasting alone was used for floods, cyclone damage, general severe weather traffic impacts, and air quality. Restrepo-Estrada et al. (2018) developed a methodology using social media for estimating rainfall runoff estimations and flood forecasting, while Smith et al. (2017) presented a real-time modelling framework to identify likely flooded areas using social media. Alternatively, Wu and Cui (2018) found that geo-located social media can help with disaster assessment, and for future forecasting. Lu et al. (2018) explored how social media might be used to forecast and generate traffic alerts due to severe weather. Likewise, Chen et al. (2017) explored social media for real-time forecasting of smog-related hazards.

Finally, three studies used VGI to monitor floods. Schnebele and Cervone (2013) crowdsourced from social media and other online media to monitor flood hazards and to create hazard maps, finding that the VGI is useful when satellite data is unavailable. Horita et al. (2015) developed a framework to integrate crowdsourced flood observations with official sensor data. The authors found that the VGI made it possible to capture data from areas lacking flood sensors (Horita et al., 2015). Sadler et al. (2018) crowdsourced street flooding reports to estimate flood severity for flood prediction, but the poor temporal and spatial coverage of the crowdsourced reports hindered the performance of the prediction model (Sadler et al., 2018).

5.6.2.3 Communication and Dissemination Mechanisms

Two studies were identified for the third EWS component, Communication and Dissemination Mechanisms. Both studies used VGI to assess warning dissemination via social media (namely Twitter) for general severe weather (Grasso & Crisci, 2016; Grasso et al., 2017). Grasso and Crisci (2016) analysed codified hashtags of regions in Italy impacted by rainfall and found that codified hashtags for different regions effectively enable the sharing of useful information during severe weather events. Additionally, many tweets included geo-location information along with hazard information to update and complement official data. As such, the authors argued that institutions might adopt codified hashtags to improve the performance of systems for disseminating and retrieving information. Grasso et al. (2017) built on this work by adding more regions to their tweet analyses and emphasised the importance of institutions and warning services to promote codified hashtags for warnings to streamline message delivery and reach.

5.6.2.4 Preparedness and Early Response Capacity

For the last component, Preparedness and Early Response Capacity, only one study applied. Ton et al. (2017) collected VGI in the form of local knowledge using interviews and questionnaires with farmers to understand their response to cyclone warnings. In this process, the farmers identified economic, physical, social, and natural impacts of cyclone hazards. The authors found that while farmers forecast weather conditions and impacts based on their local knowledge, their confidence in the lead-time of their forecasts has declined due to changing climate conditions. As such, the authors argued for the integration of local knowledge with scientific forecasts to verify local knowledge-based forecasts and increase confidence.

5.6.2.5 Multiple Components

Two studies were found to fall into more than one EWS component. Allaire (2016) used VGI for Detecting, Monitoring, and Warning, assessing Communication and Dissemination Mechanisms, and for measuring Preparedness and Early Response capacities for flood hazards. Allaire (2016) found that social media was an effective tool for flood monitoring (falling in the Detection, Monitoring, and Warning component), for receiving and spreading flood information (as a Communication and Dissemination Mechanism), and for receiving and spreading preparedness information, leading to reduced impacts (informing Preparedness and Early Response Capacity). Alternatively, Fdez-Arroyabe et al. (2018) developed a mobile application to obtain individual vulnerabilities to meteorological changes (thus informing Disaster Risk Knowledge) and to provide personalised alerts based on the individual vulnerabilities to meteorological conditions (informing Detection, Monitoring, and Warning services).

5.6.3 VGI Platforms and Data Types

In this review, we broadly define VGI to include participatory mapping, participatory GIS, geo-located social media, and location-based local knowledge (Porto de Albuquerque et al., 2016). Figure 5.2 shows the distribution of platforms discussed in each of the selected studies and to which component of the EWS framework they apply. The following section provides definitions of the platforms displayed in Figure 5.2 along with a description of how the VGI is used for severe weather warnings.

	Disaster Risk Knowledge	Detection, Monitoring, Warning Services	Communication and Dissemination Mechanism	Preparedness and Early Response Capacity	Total
Geo-located Social Media	2	9	3	1	15
Crowdsourcing	2	6			8
Crowdsourcing and Geo-located Social Media		3			3
Local Knowledge	1			1	2
Participatory Mapping/PGIS	4				4
Total	9	18	3	2	32

Figure 5.2. Distribution of VGI platforms used for each Early Warning System (EWS) framework component. Note: Two studies fell into multiple components and have been counted for each EWS component that they apply to, which results in a total of 32, rather than 29.

5.6.3.1 Geo-located social media

Geo-located social media refers to VGI that is posted online by users of Facebook, Twitter, Sina Weibo, Flickr, YouTube, Instagram, and SnapChat that has geographical location information associated to it. The heavy representation of social media (15 studies) demonstrates the growing popularity of these platforms as a data source for severe weather events (Tkachenko et al., 2017). The results indicate that social media is a valid tool for measuring the effectiveness of warning dissemination by following Twitter hashtags (Allaire, 2016; Grasso & Crisci, 2016; Grasso et al., 2017; Taylor et al., 2018). The online platforms are also useful for early hazard detection and for estimating event magnitude for early warnings (Chen et al., 2017; Jung & Uejio, 2017; Restrepo-Estrada et al., 2018; Tkachenko et al., 2017). Reasons for collecting social media data were to increase coverage of the dataset(s), the ease of access and quantity of data available, real- time or near-real-time monitoring and collection, and the multi-directional communication during disaster enabled by social media (Allaire, 2016; Chen et al., 2017; Grasso & Crisci, 2016; Grasso et al., 2017; Jung & Uejio, 2017; Pennington et al., 2015; Rossi et al., 2018; Saint-Martin et al., 2018; Smith et al., 2017; Wu & Cui, 2018).

5.6.3.2 Crowdsourcing applications and forms

Eight of the selected studies used crowdsourcing via mobile applications, reporting forms, or other active contributions (e.g., storm spotters). The crowdsourcing applications in the selected studies were used for hazard detection and monitoring and for developing personalised risk knowledge. These applications allow citizens to report the occurrence of hazards such as landslides (Choi et al., 2018; He et al., 2018) and to monitor hazards such as rainfall-induced floods (Horita et al., 2015) and storms (Krennert, Pistotnik, et al., 2018; Longmore et al., 2015). The ability to efficiently collect reports and monitor hazards in real-time, in a standardised format to ensure quality, and to increase the scale and resolution of hazard-related data were arguments made for using crowdsourcing as opposed to other VGI collection types (Choi et al., 2018; He et al., 2018; Henriksen et al., 2018; Horita et al., 2015; Longmore et al., 2015; Sadler et al., 2018; Sharma et al., 2016).

5.6.3.3 Participatory mapping and participatory GIS

In the selected studies, participatory mapping and participatory GIS were employed for severe weather risk assessments and hazard modelling. Lavers and Charlesworth (2018) engaged UK farmers in participatory mapping to identify flood impacts on their properties and subsequent opportunities for mitigation. Peters-Guarin et al. (2012) had locals in the Philippines map their historical knowledge of recurring floods and impacts for a risk assessment. In Taiwan, Hung and Chen (2013) consulted with locals and stakeholders to verify flood vulnerability maps. Participatory mapping and interviews were utilised by Rollason et al. (2018) to validate flood models using local knowledge and experiences. In all of these studies, the mapped information was entered into a GIS for further mapping and analysis, thus qualifying it as participatory GIS. Reasons for using participatory GIS and participatory mapping over other types of VGI were formally recognising and integrating local knowledge in a systematic way, and supporting local engagement (Hung & Chen, 2013; Lavers & Charlesworth, 2018; Peters-Guarin et al., 2012; Rollason et al., 2018).

5.6.3.4 Local Knowledge

For the purposes of this paper, we consider local knowledge as information gathered in participatory processes containing knowledge of the participants' local area and geography, that may or may not be translated onto a map. Just one selected study included local knowledge. After evaluating local knowledge of cyclone hazards and response capabilities to scientific knowledge, Ton et al. (2017) argued that local knowledge should be integrated with scientific meteorological knowledge for verification and to increase confidence in forecasts. The choice of using local knowledge for this study was to begin a dialogue between the locals and the meteorologists towards building trust (Ton et al., 2017).

5.7 Discussion

The results show that VGI is useful in all components of the early warning system (EWS) framework, but some platforms are more useful for specific components than are others. Furthermore, the different types of VGI have implications for supporting people-centred EWSs, which is a guiding principle for EWSs under the Sendai Framework.

5.7.1 Volunteered Geographic Information in Severe Weather Early Warning Systems

The purpose of this study is to determine the current and potential uses of VGI for severe weather warnings. We used the EWS framework to guide the analysis of the results.

The results from this literature review show that VGI has value in all four components of an EWS for severe weather hazards (Basher, 2006), but some forms of VGI are more useful for specific EWS components than are others (see Figure 5.3). Figure 5.3 is an update of Figure 5.1 based on the findings from this literature review to better represent how the different types of VGI inform or support the EWS components. For example, the majority of included studies used social media and crowdsourcing for hazard detection, monitoring, and early warning, while all of the included participatory mapping and participatory GIS studies used VGI for building disaster risk knowledge.

The selected studies show that social media and crowdsourcing for severe weather are effective for early detection, monitoring, and verifying warnings (e.g., Harrison & Johnson, 2016; Henriksen et al., 2018; Krennert, Pistotnik, et al., 2018). The value of social media and crowdsourcing for EWSs lies in the real-time, or near- real-time, hazard and impact detection, forecasting, and warning verification (Henriksen et al., 2018; Kox, Kempf, et al., 2018; Krennert, Pistotnik, et al., 2018). However, the papers included in this scoping review lack forward-thinking for integrating these tools into official EWSs which is a challenge for warning services and emergency management services (Haworth, 2016; Henriksen et al., 2018; Kox, Lüder, et al., 2018). Despite this challenge, some national hydrological and meteorological services and emergency management agencies in Europe and North America collect information from social media for detection, monitoring, and warning verification (Harrison & Johnson, 2016; Henriksen et al., 2018; Krennert, Pistotnik, et al., 2018; Pennington et al., 2015).

Social media supports multi-directional communication, which allows for both crowdsourcing and broadcasting severe weather information. While most of the selected social media studies demonstrated the value of social media for detection and early warning, two studies also indicated its utility for disseminating warnings and assessing the spread of, and response to, warning messages (Grasso & Crisci, 2016; Grasso et al., 2017). This allows warning services to gauge the reach of their message, understand the responses to their message, and update subsequent messages based on what they see on social media (Harrison & Johnson, 2016).

Before warnings are issued, knowledge of disaster risk is needed to be able to create tailored warnings. Participatory mapping and participatory GIS might be considered a long-term process for building knowledge and datasets for improving disaster risk knowledge as well as validating hazard and risk maps or models. While social media is valuable for real-time detection and communication, the participatory nature of participatory mapping enables more in-depth engagement with locals and communities in other areas of the EWS process to produce new knowledge (Haworth et al., 2018; Lavers & Charlesworth, 2018; Maskrey et al., 2016; Peters-Guarin et al., 2012; Zolkafli et al., 2017). Integrating local, spatial knowledge about disaster risk into an EWS through participatory mapping and participatory GIS fosters efforts towards people-centred EWSs as it translates local knowledge into usable and useful spatial data for risk analysis and for improved warnings (Basher, 2006; UNDRR, 2015b).

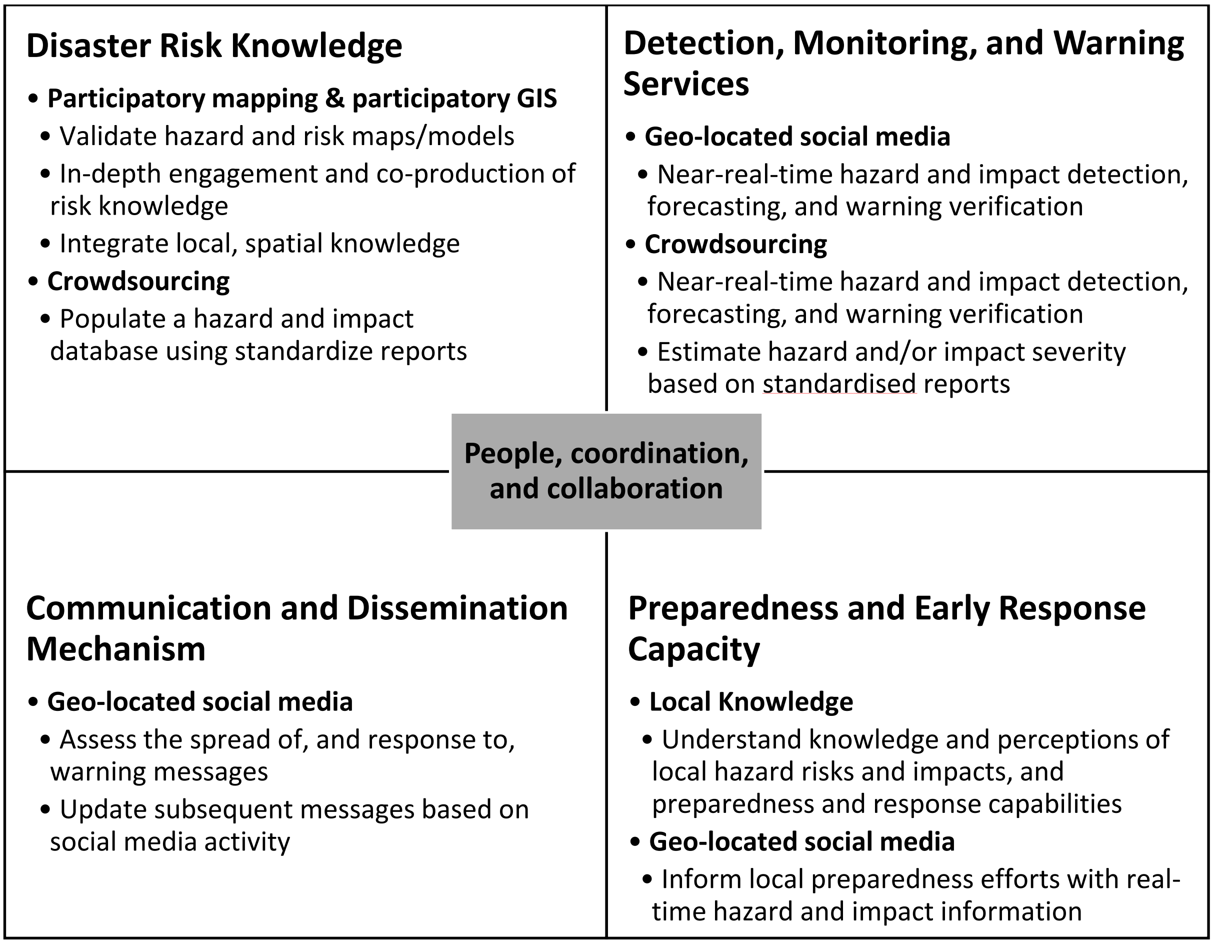


Figure 5.3. Volunteered Geographic Information for people-centred severe weather early warning systems.

These results support the findings from Marchezini et al. (2018), who presented a framework for bridging citizen science into EWSs. Like Marchezini et al. (2018), we found that VGI processes can bridge the gap between EWSs and audiences of warnings by incorporating local knowledge and personal experiences from stakeholders into the EWS components (see also Ton et al., 2017). This creates new data and unearths vulnerabilities at various scales (e.g., from the individual level to the community level; Haworth et al., 2018; Henriksen et al., 2018; Kox, Kempf, et al., 2018; Ton et al., 2017).

5.7.2 Implications for the different types of VGI

The results show that social media is a dominant platform for collecting VGI across severe weather hazards. Given the ease of access to, and the versatility of, social media (Harrison & Johnson, 2016), it is not surprising that social media is the most common platform used across hazards for collecting VGI (Granell & Ostermann, 2016). Social media is also now considered a "go-to" for collecting data because it is where the members of the public already are, thus groups or agencies looking to crowdsource do not have to do the heavy-lifting of creating a new app and attracting new users (Harrison & Johnson, 2016).

The perceived benefits of social media also come with some caveats. The data tend to be biased due to the uneven distribution of the social media user base (Granell & Ostermann, 2016; Harrison & Johnson, 2016). By relying on social media as a data source, those members of the public who are not present on social media are not represented in the data nor in the EWS process (i.e., the digital divide; Allaire, 2016; Harrison & Johnson, 2019). Additionally, tweet or post ambiguity and keyword selection for data-capture hinder data collection and analysis (Chen et al., 2017; Longmore et al., 2015; Tkachenko et al., 2017). Assimilating data of different formats into a database remains a challenge (Horita et al., 2015; Lu et al., 2018).

Capturing enough geo-located social media data is a constant challenge. It is widely known that only a small percentage of tweets contain geo-located information (Steed et al., 2019). Furthermore, the accessibility and availability of geo-located social media data are continuously limited. For example, Facebook does not offer an Application Programming Interface (API) to allow for researchers or media agencies to systematically collect Facebook posts, much less geo-located posts; it only offers an API for marketing and advertising agencies (Dubois et al., 2018; Thakur et al., 2018). In addition, in June 2019 Twitter announced plans to disable the geo-location feature for tweets due to its limited adoption by users and growing privacy concerns; however, the feature will still be available on photos taken within the Twitter mobile application (Benton, 2019; Khalid, 2019). While geo-located information on Instagram appears to be available for the moment (Arapostathis, 2019; Boulton et al., 2016), given the recent trends in the other major social media platforms, the continued availability and accessibility of this data in the future is uncertain.

A specialised crowdsourcing application can help to address some limitations found in social media. Crowdsourcing applications offer quality assurance, noise avoidance, application customisation, and citizen engagement (Choi et al., 2018; Longmore et al., 2015). On the other hand, crowdsourcing applications remain limited in the volume of participation due to public motivation to participate, the digital divide, and privacy concerns (Choi et al., 2018; Fdez-Arroyabe et al., 2018). Bias in reporting is also a concern, as contributors may over-exaggerate their personal experiences (Fdez-Arroyabe et al., 2018). Developing an application has the potential to streamline the integration of crowdsourced data into official processes, yet maintenance costs impede the willingness of officials to do so (Choi et al., 2018).

Capturing and representing local knowledge through participatory mapping and participatory GIS may help in bridging the digital divide, ensuring data quality, and enabling data integration. Participatory mapping and participatory GIS also enable community engagement (Haworth, 2016; Lavers & Charlesworth, 2018; Peters-Guarin et al., 2012). Participatory mapping and participatory GIS can be done using paper-mapping, as was done by Rollason et al. (2018), Lavers and Charlesworth (2018), and Peters-Guarin et al. (2012), or through digital-mapping (Haworth, 2016). In addition to the value of the resulting information and data itself, the process of engaging with and between locals provides another level of value in the social context by strengthening social networks, growing social capital, and increasing civic participation (Haworth, 2016).

Participatory GIS and participatory mapping do not come without their own limitations. For example, participatory GIS appears to be more effective with small-scale local projects. This is because most of the data collected is at a local or small scale, resulting in poor spatial distribution if scaled-up to a larger area. This could lead to underrepresentation and potential biases in the participatory GIS data (Rollason et al., 2018). Nevertheless, the rich quality and the ease of integrating this VGI into official processes may outweigh this limitation if the study is well-designed and the data is used appropriately (Brabham, 2013; Lauriault & Mooney, 2014). Within the EWS context, these perceived benefits further the movement towards people-centred EWSs by incorporating knowledge and information produced by the people into warnings that are ultimately for them (UNDRR, 2015b).

5.8 Conclusion

This paper conducted a scoping literature review and explored 29 journal papers published in academic journals and conference proceedings retrieved from EBSCO Discovery and Scopus. The literature review found that VGI plays various roles for severe weather early warning systems (EWSs). The examples from the selected studies show that VGI furthers the development of people-centered EWSs; it brings people, their knowledge, and their experiences into EWSs. Still, the current research captured in this scoping review lacks forward-thinking for integrating these tools into official EWSs which is a challenge for warning services and emergency management services (Haworth, 2016; Henriksen et al., 2018; Kox, Kempf, et al., 2018).

In the always shifting EWSs landscape, a new type of severe weather EWS is emerging that is causing national meteorological and hydrological services and warning services to re-think their traditional warning practices. The World Meteorological Organization is advocating for the aforementioned services to adopt impact-based forecasts and warning systems (Fleming et al., 2015). Impact-based forecasts and warnings are meant to shift the focus from the physical hazard phenomena to the risk of impacts produced by the hazard, including communicating impacts in warning messages and building new warning thresholds based on risk of impact (Morss et al., 2018; Poolman, 2014; Potter et al., 2018; Rogers et al., 2017; Sai et al., 2018; WMO, 2015). However, warning services have indicated a limited understanding of, and access to, the data required for developing impact-based forecasting and warning systems (Harrison et al., 2014; Kox, Kempf, et al., 2018; Obermeier & Anderson, 2014).

Future research would benefit from a systematic review of this topic area in the future. Additional research should investigate the data needs for impact-based forecasts and warnings and explore how VGI can help in meeting these data needs while also maintaining a people-centred focus. This would align with the goals of the World Meteorological Organization's High Impact Weather research programme (http://hiweather.net) which aims to improve the effectiveness of weather-related warnings in support of advances in weather prediction and forecasting (Zhang et al., 2019). While this literature review characterised the role of VGI within severe weather EWSs and demonstrated how it supports people-centred EWSs, future research can delve into the nature of the resulting data and how it might support impact-based forecast and warning systems. It should be noted that in spite of the popularity of collecting and using social media data, given the uncertainty of reliable access to social media data in the future (e.g., disestablishing the geolocation function on Twitter), it would be wise to minimise reliance on these platforms and consider additional VGI sources and collection processes to capture the desired information.

Position of the reader

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Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
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Chapter Six: **Identifying the impact-related data uses and gaps for hydrometeorological impact forecasts and warnings**

This chapter presents the second manuscript prepared for publication that identifies the data uses and gaps for severe weather IFWs. Chapter 5 explored the potential uses of VGI within EWSs and identified that further research is needed to explore additional data sources to support the implementation of IFWs. This was confirmed through conducting a series of preliminary interviews with officials from meteorological agencies both within and outside of NZ, and EM agencies within NZ, where it was also determined that exploring VGI as an alternative source of impact data was not a critical need of the NZ-based participants. Further analysis of the preliminary interview data also identified that more clarity was needed around the implementation processes involved with IFW, namely who needs the data to issue IFWs, how the underpinning data is used, and where the gaps are.

Thus, Chapter Six focuses on research Objectives 2.1: Identify the actors involved in an IFW system and their associated roles; 2.2 Determine how HIVE data are used in an IFW system; and 2.3 Identify further data gaps/needs for implementing IFWs. It presents the results of the research conducted for this thesis as described in Chapters Three and Four relating to these objectives.

The article presented in this chapter was published in 2022 in the *Weather, Climate, and Society Journal*:

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6.1 Abstract

Impact forecasts and warnings (IFW) are key to resilience for hydrometeorological hazards. Communicating the potential social, economic, and environmental hazard impacts allows individuals and communities to adjust their plans and better prepare for the consequences of the hazard. IFW systems require additional knowledge about impacts and underlying vulnerability and exposure. Lack of data or knowledge about impacts, vulnerability, and exposure has been identified as a challenge for IFW implementation.

In this study, we begin to address this challenge by developing an understanding of the data needs and uses for IFWs. Using the grounded theory method, we conducted a series of interviews with users and creators of hazard, impact, vulnerability, and exposure data (e.g., warning services, forecasters, meteorologists, hydrologists, emergency managers, data specialists, risk modelers) to understand where these data are needed and used in the warning value chain, a concept used to represent and understand the flow of information among actors in the warning chain. In support of existing research, we found a growing need for creating, gathering, and using impact, vulnerability, and exposure data for IFWs.

Furthermore, we identified different approaches for impact forecasting and defining impact thresholds using objective models and subjective impact-oriented discussions depending on the data available. We also provided new insight into a growing need to identify, model, and warn for social and health impacts, which have typically taken a back seat to modeling and forecasting physical and infrastructure impacts. Our findings on the data needs and uses within IFW systems will help guide their development and provide a pathway for identifying specific relevant data sources.

6.2 Introduction

Warning systems are key to resilience for hydrometeorological hazards as they alert people to the risk of potential hazards and encourage protective action to be taken (Basher, 2006). To improve early warning systems, the World Meteorological Organization (WMO) is encouraging nations to adopt Impact Forecasts and Warnings, as they argue that communicating the potential social, economic, and environmental hazard impacts allows individuals and communities to adjust their plans and better manage the potential consequences of the hazard (Harrowsmith et al., 2020; WMO, 2015).

Traditionally, warnings have relied solely on weather-based factors (e.g., wind speeds, snowfall depth) and hazard timing and location, but 'impact-based' warnings also consider exposed and/or vulnerable populations and infrastructure (Harrowsmith et al., 2020; WMO, 2015). Impact Forecasting and Warning (IFW) systems differ from traditional warnings by communicating what the hazard(s) will do, rather than only what they will be. They are built on impact-based rather than hazard-based thresholds (Harrowsmith et al., 2020; WMO, 2015) that may misrepresent the impacts of the hazard(s) (Sai et al., 2018). Furthermore, hazard-based warnings may lack messaging about risk, leading to potential inaction (Sai et al., 2018).

The risk of hydrometeorological hazard impacts depends on the vulnerability of the people, infrastructure, and environment, and the exposure of these 'assets' multiplied by the likelihood of the hazard (Harrowsmith et al., 2020; Poolman, 2014; Tarchiani et al., 2020; WMO, 2015). Accurately communicating the risk of hydrometeorological hazard impacts in IFWs thus requires combining likelihood and hazard severity with exposure and vulnerability (Poolman, 2014; Tarchiani et al., 2020; WMO, 2015).

Notable historic severe weather events revealed communication gaps between warning services and recipients. These have been attributed to various underlying social behaviours such as warning fatigue (Mackie, 2013; Wagenmaker et al., 2011), and understanding warning terminology (Ching et al., 2015). IFW systems may help reduce the effects of these factors and increase warning compliance (Morss et al., 2018; Potter et al., 2018; Weyrich et al., 2018). However, their effectiveness depends on several caveats in design and implementation (see Morss et al., 2018; Potter et al., 2018; Ripberger, Silva, Jenkins-Smith, & James, 2015; Scolobig et al., 2015; Weyrich et al., 2018).

Implementing IFW systems can be costly, requiring careful cost-benefit analysis (Merz et al., 2020). Potter et al. (2021) found that key benefits include a perceived increase in understanding impacts, added awareness of antecedent conditions, possible reductions of 'false alarms', and increased interagency communication. Others found benefits to be enhanced situational awareness (Kox, Kempf, et al., 2018), and improved planning and response efforts (Terti et al., 2015). Alternatively, Potter et al. (2021) identified key challenges to be lack of data, the potential for conflicting messages, and an increased burden on agencies providing information to forecasters.

Verification and conflicting roles and responsibilities are other significant challenges identified by Hemingway and Robbins (2019) and Kaltenberger et al. (2020), respectively. Data challenges can be another roadblock, including their availability, processing capabilities, and management (Hemingway & Robbins, 2019; Potter et al., 2021; Wei et al., 2018).

There is a growing need to address challenges with data availability and access and identify appropriate data sources. To begin addressing these challenges, we must begin to understand the data needs and requirements for implementing IFWs, such that we can identify appropriate datasets and data sources. To achieve this, we first present a review of IFW system elements and data needs, followed by findings from a series of qualitative interviews, the majority of which were producers of severe weather warnings and users of hazard, impact, vulnerability, and exposure data in New Zealand.

6.2.1 Elements of Impact-Based Forecasting and Warning Systems

Traditional (hazard-based) severe weather warning systems rely on hazard forecasting and observations, with warning thresholds based on measurable characteristics of the hazard (e.g., minimum/maximum windspeeds, snow depth) (Harrison et al., 2014; Obermeier & Anderson, 2014). IFW systems introduce the human element to early warning systems.

The terminology of IFWs varies across the literature. In this paper, we will use the definitions in Table 6.1, largely from the WMO guidelines on IFW systems (see WMO, 2015)[9]. Kaltenberger et al. (2020) proposed an additional term of 'impact-oriented warnings' to refer to warnings that are independent of the production process (i.e., the warning thresholds or criteria) used to issue warnings. These may be hazard-based or impact-based and include both a tangible and understandable description of expected impacts and clear advice on what to do. Impact-based warnings and impact warnings differ based on the production process used to issue them. The goal of the WMO Guidelines is to evolve severe weather warning services into the final 'impact forecasting and warning' form, where vulnerability and exposure are integrated into the thresholds. Herein, we refer to all as Impact Forecasts and Warning (IFW) systems to align with the goal of the WMO. However, when the type of warning is specified, we will refer to its proper term according to the WMO definitions.

[9] Note that an update on the WMO Guidelines on Multi-Hazard Impact-Based Forecast and Warning Services is anticipated to be released soon. A more recent resource providing further guidance on IFW implementation was published by the International Federation of Red Cross and Red Crescent Societies and is cited as (Harrowsmith et al., 2020) throughout this paper for further support.

Table 6.1. Definition and examples of the warning terms used in this paper.

Warning Type	Definition	Example	Data Considered
Hazard-based warning	These are traditional warnings, with thresholds based on the physical characteristics of the hazard (WMO, 2015).	"Bora winds are expected tonight with wind speeds of 20 metres per second" (WMO, 2015, p. 6).	Hazard only
Impact-oriented warning	These warnings are independent from the criteria of a warning, which may be hazard-based or impact-based and contain information on impacts and clear protective action advice (Kaltenberger et al., 2020).	"Power and phone distribution networks may be disrupted for relatively long periods. Roofs and chimneys can be damaged…" (Météo-France via Kaltenberger et al., 2020, p. 30).	Hazard and impact
Impact-based warning	These warnings include hazard and vulnerability, and are "designed to express the expected impacts as a result of the weather" (WMO, 2015, p. 6).	"Bora winds are expected tonight which may result in delays or cancellation to ferry services" (WMO, 2015, p. 6).	Hazard and vulnerability
Impact warning	These warnings include hazard, vulnerability, and exposure, and are designed to provide detailed messages down to the individual, activity, or community level (WMO, 2015).	"Ferry services for the island of Brač will most likely be cancelled tonight due to Bora winds" (WMO, 2015, p. 6).	Hazard, vulnerability, and exposure

IFW Systems require knowledge of hazards and their likelihood, as well as the underlying vulnerability and exposure of the assets (e.g., people, infrastructure) at risk (Poolman, 2014; Tarchiani et al., 2020; WMO, 2015). Thus, the four data types needed for an IFW system are hazard (incorporating likelihood), impact, vulnerability, and exposure; defined in Table 6.2.

These types of data form the conceptual basis of IFWs. The lack of data and knowledge around impacts and risks relating to hydrometeorological hazards amongst meteorologists has been identified as a key barrier to implementing IFWs (Harrison et al., 2014; Obermeier & Anderson, 2014; Potter et al., 2021). In particular, exposure and vulnerability data appear to be largely left out of weather warning systems (Potter et al., 2021). Thus, the WMO highlights the need for better collection and access to vulnerability and exposure information and understanding of how vulnerability and exposure data can be integrated into an IFW system (WMO, 2015). The Warning Value Chain provides a framework for understanding how hazard, impact, vulnerability, and exposure data fit into an IFW system.

Table 6.2. The four types of data needed for IFWs.

Hazard	A hazard is "a hydrometeorological-based, geophysical or human-induced element that poses a level of threat to life, property or the environment", such as rainfall, snowfall, high winds, tornado, hail, flood (WMO, 2015, p. 4). In weather forecasting, likelihood is usually combined with hazard (WMO, 2015).
Impact	Impacts are the negative outcomes of an event (Casteel, 2016), and are defined as "a loss of life and injuries, damage to the environment, infrastructure, and private property, often followed by secondary effects like psychological trauma, or disruption of workflow and traffic" (Kox, Lüder, et al., 2018, p. 116). Direct and indirect impacts may be a function of vulnerability and exposure to the hazard (WMO, 2015). Impact data refers to observed post-event impacts and outputs and results from risk/impact models.
Vulnerability	Vulnerability is "the susceptibility of exposed elements, such as human beings and their livelihoods and property, to suffer adverse effects when affected by a hazard" (WMO, 2015, p. 6). Predispositions, sensitivities, fragilities, weaknesses, deficiencies, or lack of capacities that favour adverse effects on exposed elements can increase vulnerability (WMO, 2015). Vulnerability may also be time- and space-dependent.
Exposure	Exposure refers to people, infrastructure, housing, and other tangible human assets that may be affected in an area where hazards may occur (WMO, 2015). Exposure is time- and space-dependent, and it is possible to be exposed to a hazard but not vulnerable.

6.2.2 The Impact Forecasting and Warning Value Chain

Golding et al. (2019) outlined the Warning Value Chain approach for representing the flow of information amongst actors in the warning chain for designing and operating hydrometeorological warnings. The Value Chain consists of six components for an operational IFW system: (1) Observation, Monitoring, and Detection; (2) Weather Forecasting; (3) Hazard Forecasting; (4) Impact Forecasting; (5) Warning; and (6) Decision/Action, as shown in Figure 6.1.

The first component of the Warning Value Chain is Observation, Monitoring, and Detection. Meteorological monitoring and observation are routine practices (WMO, 2018). Observation, Monitoring, and Detection traditionally use ground-based observations (e.g., from weather stations) and remote sensing tools such as satellite and radar imagery for meteorological phenomena (e.g., Brotzge et al., 2013). Social media and crowdsourcing have also become useful tools for detecting and monitoring hydrometeorological phenomena such as tornados, hail, etc. (Harrison & Johnson, 2016).

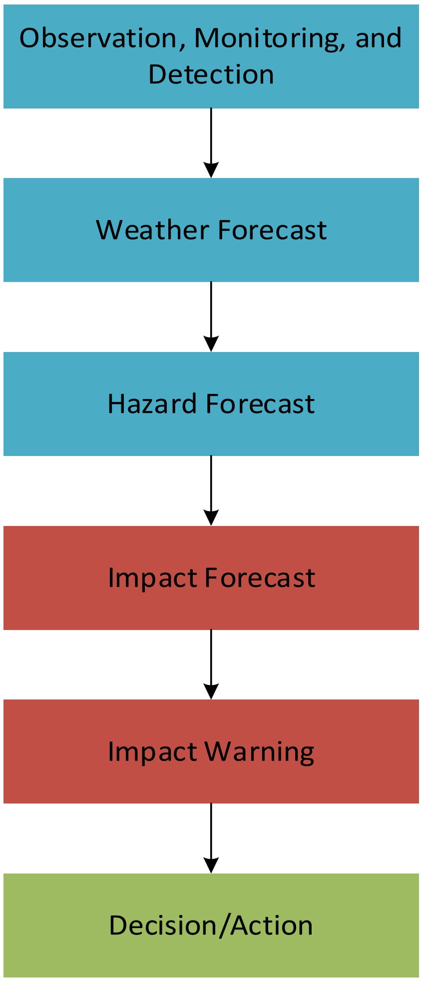

Figure 6.1. A visual representation of the severe weather Warning Value Chainbased on Golding et al. (2019), where blue boxes relate to hazards, red boxes relate to impacts, and green relates to the outcomes.

Weather forecasting makes heavy use of computer modelling, which has seen technological advances in the last half-century to increase accuracy (Bauer et al., 2015). A shift occurred from deterministic forecasting to probabilistic forecasting, with the advent of approaches such as ensemble prediction systems (GFDRR, 2016; WMO, 2015). In South Africa and the UK, the implementation of an Impact-Based Forecasting and Warning system is solely based on probabilistic forecasting (e.g., Neal et al., 2014; Poolman, 2014). With probabilistic forecasting, warnings can be issued earlier using low probabilities that can increase or decrease as confidence in the likelihood increases (Neal et al., 2014). Adding probabilistic uncertainty estimates in forecasts was found to improve both compliance and decision quality amongst technical forecast users (LeClerc & Joslyn, 2015).

Upon producing weather forecasts, Hazard Forecasting may occur. Weather-induced hazards include flood and flash flood, storm surge, drought, wildfire, snowfall, ice, extreme temperatures, and damaging winds, etc. Weather forecasts are typically used in conjunction with other data/information about a hazard to produce a hazard forecast. For example, storm surge forecasts in the UK are produced using wind forecasts, sea-level models, and wave/tidal models (Flowerdew et al., 2013).

Hazard forecasting is challenging due to errors in predicting atmospheric conditions (Golding et al., 2019; National Research Council, 2006). For example, forecasting for heavy rainfall in a nearby catchment, rather than the catchment that experienced the downstream flooding (Majumdar et al., 2021).

Impact Forecasting is the next step in the Warning Value Chain to identify and understand the potential impacts of a given hazard. Impact Forecasting involves combining meteorological and hazard information with information about exposed and/or vulnerable assets (e.g., people, property) (Merz et al., 2020). Risk modelling can support impact forecasts by providing quantitative assessments of impacts and loss based on the hazard and asset information using a vulnerability/fragility function (Schmidt et al., 2011). However, the use of risk models by practitioners has been met with key challenges around data availability and investment priorities (Crawford et al., 2018). The data needs for this part of the Warning Value Chain are thus the main topic of this paper.

The Warning may be considered the end-product or service of the warning system. Warnings are intended to communicate information about an oncoming hazard and the associated risk(s) to exposed and vulnerable audiences (WMO, 2018). Design and delivery are two key factors in the success of a warning (Golding et al., 2019). Design involves having organisational and decision-making processes, and operational communication systems and equipment (WMO, 2018). Delivery involves disseminating and communicating the relevant information to the target audiences in terms that are understandable and actionable by the audiences (WMO, 2018).

Upon receiving a warning alert or message, recipients face many decisions. The Decision-making end of the Warning Value Chain has received a plethora of social science research. IFWs emerged from that research as a recommendation for inciting the desired responses to warnings (e.g., Ching et al., 2015; Wagenmaker et al., 2011). Much research has since been done to evaluate IFWs on their effectiveness for recipient decision-making indicating that behaviour to impact-oriented warnings varies across studies and hazards (see Casteel, 2018; Morss et al., 2018; Potter et al., 2018; Ripberger, Silva, Jenkins-Smith, & James, 2015; Taylor et al., 2019; Weyrich et al., 2018; Weyrich et al., 2020a; Weyrich et al., 2020b).

Evidence has shown that including impact information with warnings can improve understanding of and response to warnings (Potter et al., 2018; Ripberger, Silva, Jenkins-Smith, Carlson, et al., 2015; Taylor et al., 2019; Weyrich et al., 2018; Weyrich et al., 2020a, 2020b) by aligning with how people already tend to interpret warnings based on the impacts of the severe weather (Williams et al., 2017) and to contextualise the information (Schroeter et al., 2020). However, caution is advised when formulating the messages as research has found that the terminology used in impact-oriented warnings may induce fear and can cause undesired responses to warnings (Ripberger, Silva, Jenkins-Smith, & James, 2015). For example, impact-oriented warnings can incite people to evacuate from hurricanes (the desired behaviour for those at risk) (Morss et al., 2018; Morss, Demuth, et al., 2016; Ripberger, Silva, Jenkins-Smith, & James, 2015). However, impact-oriented warnings and fear-based messages also have the potential to increase 'shadow evacuations'[10] during hurricanes (Morss, Demuth, et al., 2016), causing gridlock on motorways, increasing exposure, and thus risk, of even more people (Baker, 1991; Lamb et al., 2012; Yin et al., 2016).

For tornadic hazards, Casteel (2016, 2018) found that impact-oriented warnings led to greater behavioural intentions of sheltering in place. Conversely, Ripberger, Silva, Jenkins-Smith and James (2015) found that impact-oriented messages have the potential to 'backfire' as their results showed a decreased probability of taking shelter and an increased probability of evacuating for events with tags of higher impacts such as 'devastating' or 'incredible'. This behaviour could result in people putting themselves at even more risk in situations where sheltering in place is advised (Ross et al., 2015).

The implications for these effects must be seriously considered when designing an IFW system. Limiting the use of fear-inducing messages can enhance the perceived credibility of the messages and reduce the effects of shadow evacuations (Morss et al., 2018). Including clear prescribed actions can also increase perceptions and appropriate intended responses to impact-oriented warnings (Weyrich et al., 2018).

Partnerships and sharing information amongst the various agencies involved are an important aspect of the Warning Value Chain framework (Golding et al., 2019). It has been argued that poor linkages between warning system components have been major causes for warning systems to fail, resulting in disasters (Garcia & Fearnley, 2012). Thus, linking the components into an integrated early warning system is critical to their effective performance (Garcia & Fearnley, 2012). This requires coordination and collaboration across the various agencies and levels that have the relevant information about hazards, impacts, vulnerability, and exposure (Garcia & Fearnley, 2012; Golnaraghi, 2012).

As outlined in relevant guidelines and resources (e.g., Harrowsmith et al., 2020; WMO, 2015), there is a need for not just hazard data, but also impact, vulnerability, and exposure data. However, it is unclear where each of these data types is used in the Warning Value Chain. Thus, the objective of this research is to identify the uses and gaps for hazard, impact, vulnerability, and exposure data within an IFW system for each component of the Warning Value Chain framework. We adopt a Grounded Theory methodology, described next, to collect and analyse interviews to address the question '*what are the data uses and gaps for impact forecasts and warnings?* This will be explored in a New Zealand context to support the country's efforts towards fulfilling the WMO's objectives for member nations to implement IFWs.

[10] Shadow evacuation occurs when people who are not at risk or are not in the official evacuation zone evacuate unnecessarily (Zeigler, Brunn, & Johnson, 1981).

6.3 Research Method

To address the objective of this research, we adopted a qualitative research approach to explore the issues in depth with participants both within and outside of Aotearoa New Zealand. This is opposed to a quantitative approach, which is more relevant for understanding the breadth of results across a population (Mack et al., 2005). We adopted a Grounded Theory Methodology (GTM) to collect and analyse the data. As an exploratory strategy, GTM is particularly useful for research on areas with little to no prior research and where theory building is needed or desired (Fernandez, 2005; Lehmann, 2010; Seidel & Urquhart, 2016). This study employed the Evolved-Straussian Grounded Theory Methodology (ES-GTM) due to its wide use in relevant fields (Matavire & Brown, 2013; Urquhart et al., 2010), its ease of use (Charmaz, 2006; Kelle, 2005), and its allowance for a priori literature review (Hughes & Jones, 2003; Matavire & Brown, 2013).

A purposive sampling method (Chun Tie et al., 2019) was used to target and recruit participants based on their roles in severe weather risk communication and response, and use of impact, vulnerability, and exposure data. After the initial interviews, theoretical sampling guided the rest of the data collection process for this research, which is "the process of data collection for generating theory whereby the analyst jointly collects, codes, and analyses [their] data and decides what data to collect next, and where to find them, to develop [their] theory as it emerges" (Glaser & Strauss, 1967, p. 45)

Thirty-nine (n=39) experts in weather forecasting, warning, response, risk modelling, and data collection and management were interviewed between November 2018 to May 2021 (described in Table 6.3). These 30-60 minute in-person or virtual semi-structured interviews aimed to address the gaps in the literature regarding IFW data needs and sources. Questions asked for participants' thoughts on (1) IFWs (e.g., what they know about IFWs, perceived challenges and benefits, requirements for implementation); (2) what kind of impact, vulnerability, and/or exposure data they use or need, why, and how; (3) the life path of the data (e.g., how it is obtained, used, stored, what happens to it after its intended use); (4) experienced and/or perceived challenges obtaining data required for IFWs and other uses; and (5) thoughts on collecting and using alternative data sources (e.g., social media and crowdsourcing). Interviews were audio-recorded and transcribed verbatim. In support of achieving the objective of this paper, findings regarding the data uses and gaps for IFWs are reported here, while findings regarding data sources and access will be reported in separate papers currently under preparation (See Harrison et al., 2021).

Table 6.3. Summary classification of interview participants.

Category	n	General Roles	Representation
Hydro-meteorological Experts	6	Senior, consultant, and communication meteorologists, social scientists, operational manager, senior policy advisors, and public safety managers	International: Argentina, Australia, Austria, United Kingdom, USA
	6	Meteorologists, operational manager, communication meteorologist, senior policy advisor, Weather analyst	New Zealand: MetService, NIWA, Private Weather Service
	1	Regional flood specialist	New Zealand: Greater Wellington Regional Council
Emergency Management and Response Sector	3	First responder, Senior Hazard Risk Management Advisor	New Zealand National Level: National Emergency Management Agency (NEMA), Fire and Emergency New Zealand (FENZ)
	9	Chief operators, communications specialists	New Zealand Regional Level: Auckland, Bay of Plenty, Canterbury, West Coast, Northland, Wellington
Data Creation, Management, Standards, Custodianship	2	Geographic Information Systems (GIS) specialists	Private Industry: Eagle Technology, Independent
	3	GIS specialists, Statistical Analysis specialist	Public Sector: Land Information New Zealand, Stats NZ/DataVentures, West Coast
	1	GIS specialist	Research: Massey University
Risk and Loss Modelling	4	Risk modellers	Research and policy: GNS Science, NIWA
	1	Loss modeller	Research and policy: Victoria University of Wellington
Other	1	Respiratory Doctor	Practice: Regional hospital
	1	Civil Engineer	Practice: Wellington Region Lifelines Group
	1	Agriculture policy coordinator	Practice: Federated Farmers
Total	39		

A 'low risk' ethics notification was lodged with the Massey University Human Ethics Committee before data collection in 2018. All participants remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by the area of expertise and/or practice, industry, location, or governance level (Table 6.4). Interviews were audio-recorded and transcribed verbatim. Qualitative analysis (including coding and memo-writing) was conducted using NVivo 12 (Bergin, 2011) following the ES-GTM.

Table 6.4. Participant Codes. All participants remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by the area of expertise and/or practice, industry, location, or governance level.

Interview Code	Position	Classification	Location	Government Level
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ	National
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ	National
Data Management Private NZ. B	Geospatial Specialist	Data Management	NZ	
Data Management Research NZ. C	GIS Specialist	Data Management	NZ	
Data Management Private NZ. D	GIS Specialist	Data Management	NZ	
Data Management Gov. NZ. Nat. E	Head of Data	Data Management; Governance	NZ	National
EM. NZ. Reg. A	Director	Emergency Management	NZ	Regional
EM. NZ. Reg. B	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. C	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ	Regional
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ	Regional
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ	National
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Nat. I	First Responder	Emergency Management	NZ	National
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ	National
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ	Regional
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ	Regional
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ	Regional

Code	Position	Classification	Location	Government Level
Hyd. Gov. NZ. Reg. A	Flood EWS Programme manager	Hydrology; Governance	NZ	Regional
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ	Regional
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ	
Met. Int. A	Science Manager	Meteorology	International	National
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	International	National
Met. Int. C	Senior Policy Officer	Meteorology	International	National
Met. Int. D	Senior Social Scientist	Meteorology	International	National
Met. Int. E	Consultant Meteorologist	Meteorology	International	National
Met. NZ. F	Senior Meteorologist	Meteorology	NZ	National
Met. NZ. G	Communications	Meteorology	NZ	National
Met. NZ. H	Public Relations	Meteorology	NZ	National
Met. Int. I	Division Chief/Meteorologist	Meteorology	International	National
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ	National
Met. NZ. K	Senior Meteorologist	Meteorology	NZ	National
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ	
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ	National

6.4 Findings and Discussion

We identified two key themes from the interview data: (1) Data uses for IFWs, and (2) the need for more understanding on different types of impacts, discussed next.

6.4.1 Data Uses in the Impact Forecasting and Warning Value Chain

The actors and data uses for IFWs are discussed in the following sections using the Warning Value Chain as a framework for guiding the discussion. The focus of this paper is on the data uses and gaps of the impact forecasting and warning portion of the Warning Value Chain. As such, a brief overview of results on the data uses and actors in the first three components of the Warning Value Chain (Observation, monitoring, and detection; Weather Forecasting; and Hazard Forecasting) will be provided. Following this, results and discussions will be presented for each of the Impact Forecasting and Impact Warning Components.

6.4.1.1 Weather and Hazard Observation and Forecasting

Extensive research has been conducted for weather and hazard observation and forecasting that documents more comprehensive explanations of the data gaps and uses for weather and hazard observation and forecasting (e.g., Gneiting & Raftery, 2005; Saima et al., 2011).

In NZ, meteorological services (e.g., the NZ MetService), hydrological services (e.g., regional and local council hydrologists in NZ), and hydrometeorological services (e.g., New Zealand's National Institute of Water and Atmospheric Research or NIWA) are the primary actors in this value chain component. The NZ MetService monitors the weather, council hydrologists monitor river networks while simultaneously monitoring the weather themselves, and NIWA collaborates with councils to set up monitoring and modelling scenarios for flood early warning systems. Forecasters also use media and social media to monitor areas where radar coverage is lacking (Met. Int. C; Met. NZ. K; see Table 6.4).

Weather forecasting is primarily done by the meteorological services (public and private), as outlined by an NZ meteorologist: "our responsibility is for the forecast of rain until it hits the ground. After that it's the responsibility of other agencies to deal with what that rain does" (Met. NZ. F). By using Numerical Weather Prediction (NWP) models, weather forecasts can provide meteorologists, hydrologists, and lifelines sectors such as transportation with advance notice, such as 48 hours, 3 days, or 5 days, of a potentially hazardous event, which allows for extra preparation time (Met. Int. I; Met. NZ. K). 'Nowcasts' use observational data (e.g., lightning strikes, and spatiotemporal extrapolation of observed precipitation) or very short-range NWP for near-real-time forecasting out to a few hours (Farnell et al., 2017; Kotsuki et al., 2019; Srivastava & Bhardwaj, 2013). It is important to note the differentiation between the data needs for IFWs in terms of timescale; the needs, type, and availability of data for real-time operations and for developing warning systems can differ. For example, social media and crowdsourcing have value in their real-time contribution to a warning system for hazard and impact detection, forecasting, and warning verification

(Harrison et al., 2020), but may be less useful due to the qualitative nature for defining impact warning thresholds. This should be explored in future research.

In NZ, hazard forecasting can be triggered by an initial discussion between the meteorological service and the council hydrologists[11]. For example, when a NZ MetService forecaster issues a watch or warning, they typically make a direct phone call to the regional council hydrologist to alert them of a potentially impactful rainfall that could lead to flooding. From there a follow-up conversation can occur where the MetService asks:

> 'are there particular concerns for your region? Is there anything that we should be on the lookout for?' And it's really those interactions that also feed into the decision for 'should this be red?' because if we talk to them after we issue a Watch, but before initiating the Warning, and we say 'look, we're considering a warning for 300mm', they might go 'oh, that's going to flood our entire region' and that might spark that two-way discussion to say 'well, okay, that's really interesting, how concerned are you, what level of flooding do you anticipate?' Which might lead us down the path of 'this should be red (Met. NZ. K).

From this discussion, a watch or warning decision is made, as well as the warning level. The hydrologist possesses more knowledge of the current conditions (e.g., river levels, soil moisture content) and is thus able to contribute to a more informed warning decision (Met. NZ. A, K).

The NZ MetService primarily uses hazard-based thresholds for their watches and warnings, such as "widespread (over an area of 1000 square-kilometres or more) rainfall greater than 50mm within 6 hours or 100mm within 24 hours" (MetService, 2021b). In some cases, the MetService uses more dynamic thresholds depending on the region, antecedent conditions, and feedback from EM groups and councils. For example, in Auckland, the minimum speed of strong winds was lowered for Northeasterly winds as these winds tend to be more damaging in Auckland than Southwesterlies (Met. NZ. K). Furthermore, senior meteorologists also use their tacit knowledge developed over the years to make a judgement call on issuing hazard forecasts and warnings (Met. NZ. K). The meteorologists also use media reports and social media to detect hazards and impacts and inform their warnings (Met. NZ. K).

Floods were the main hydrometeorological hazard that participants discussed. In NZ, participants described how regional councils typically conduct flood hazard forecasting using meteorological forecast data combined with their hydrological data (e.g., river level and flow gauges) (Met. NZ. A), and sometimes their local and historical knowledge of past impacts (EM NZ. Reg. A, B, C). These hazard forecasts usually do not provide impact information, as one NZ regional council flood warnings specialist

[11] Not all hydrological services are provided by councils, this depends on the governance structure of the location under study. In the case of New Zealand, hydrological services are provided by councils as per the Resource Management Act 1991.

stated, "we don't then do any quantitative work to … determine how much impact that flood financially … damaged, that type of thing. We've not done that in the past to my knowledge" (Hyd. Gov. NZ. Reg. A).

6.4.1.2 Impact Forecasting

The WMO Guidelines briefly suggest that impact forecasting "could be done in a subjective way working alongside [partners], or in an objective way through developing an impact model using vulnerability and exposure datasets as well as meteorological information" (WMO, 2015, p. 3). Interview findings corroborate this suggestion. Figure 6.2 provides a conceptual visualisation, based on our interviews, of the four data types used as inputs for impact forecasts, which then support either the more objective risk/impact modelling approach, or the more subjective impact-oriented discussion approach. These two approaches will be discussed next.

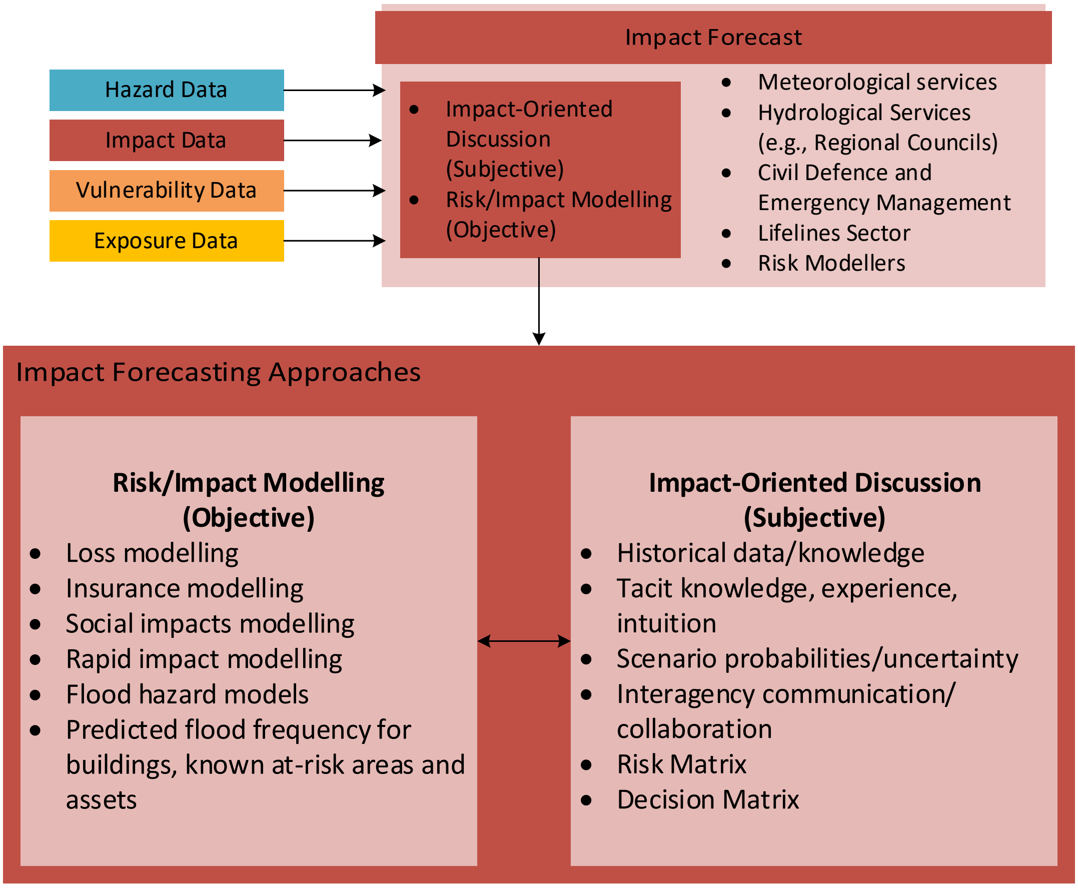

Figure 6.2. Data inputs and uses for Impact Forecasts and the two main approaches. The data inputs are represented in the top-left with arrows pointing to the impact forecast component. Blue is associated with hazard, red with impacts, orange with vulnerability, and yellow with exposure. The two approaches of impact forecasting are listed on the left side of the impact forecast box, and the actors involved are listed on the right. More details on the activities used for each impact forecasting approach are provided in the bottom box. The multi-directional arrow between the two impact forecasting approaches signifies that these two approaches are best used complementarily with each other.

Model-Based Impact Forecasting Approaches

Model-based impact forecasting approaches use computer models, algorithms, and quantitative data to identify potential impacts of varying severity. Specifically, risk models require detailed data about the fragility/vulnerability of assets (including buildings, infrastructure, people, vehicles, etc.), dynamic exposure data, and hazard data[12] (Schmidt et al., 2011). In the UK, under the Natural Hazards Partnership (NHP), several models have been developed, or are under development, for real-time forecasting of various hazards and impacts. Two of these models were discussed in interviews.

The *Vehicle OverTurning (VOT) Model* is an impact forecasting model for UK highway networks during high wind events (Hemingway & Robbins, 2019). The model uses a "classic risk assessment approach" (Met. Int. A), by defining a hazard footprint (i.e., the wind affecting vehicles), and using vulnerability and exposure indices to calculate the risk of vehicles overturning (Met. Int. A). Vulnerability factors are road altitude, number of lanes, road direction relative to the wind, and road attributes (e.g., tunnel, bridge) (Met. Int. A). The exposure index "is split out by vehicle type because we recognise that different vehicles are more susceptible to being overturned than others" (Met. Int. A; see Hemingway & Robbins, 2019 for more). The UK MetOffice does not traditionally possess knowledge or data on traffic flows (Met. Int. A), thus they partnered with agencies that do, namely transportation agencies in England and Scotland (Met. Int. A).

The second impact forecasting model that is under development with the NHP in the UK is the *Surface Water Flooding Model* (SWFM) and is "very much focused on heavy rainfall leading to surface water and that can lead to property flooding, infrastructure flooding, effects on critical infrastructure" (Met. Int. A). Like the VOT, the UK MetOffice lacked the key data or knowledge for this model, including property types (vulnerability) and people movement (exposure). Thus, partnership again played a key role in acquiring this data:

> We needed a lot of information on different property types and we needed information on how people move around the city and things like that to account for the fact that people commute in and out ... And … within our broader partnership under that Natural Hazards Partnership we have an organisation called the Health and Safety Executive and they do a lot of work in the risk assessment space and have a lot of available data. And that allowed us to really produce that whole second part ... Had we not had that; I think we would've really struggled (Met. Int. A).

[12] For the purposes of this study, hazard data will refer to meteorological and hydrological data. For example, wind speed and rainfall data may be considered meteorological hazard data, while river level and river flow data are considered hydrological hazard data.

The approach of the SWFM is slightly different from the VOT as vulnerability is included but not via a vulnerability index layer; rather via classification of the property itself (e.g., commercial properties vs. residential properties) (Met. Int. A). Output is impact grades ranging from lesser to greater impacts to life and safety (Met. Int. A; see Aldridge et al., 2016; Cole, Moore, Aldridge, et al., 2016; Cole, Moore, Wells, et al., 2016 for more).

Similarly, a *Flood Early Warning System* (FEWS) is under development in collaboration with the Samoan Ministry of Natural Resources and Environment for the Vaisagano River in Apia, Samoa, which incorporates outputs from RiskScape[13]. An impact-forecasting component has been integrated into this FEWS to assess life and vehicle road closure safety needs (Risk Modelling NZ. C, D). After a post-event analysis of flooding in Wellington, NZ, it was suggested that risk modelling would have been useful to identify the risk of flood damage to emergency vehicles that drove through floodwaters and were subsequently damaged (Risk Modelling NZ. C). The data/tools used in this system are near real-time rain intensity forecasts based on available NWP models (e.g., PACIOOS 3km grid), rainfall-runoff predictive relationships, exposure of assets (e.g., roads, buildings), LiDAR topography, flood inundation models for different annual exceedance probability events, and vulnerability functions (Risk Modelling NZ. D). More exploration into characterizing these data sources will be covered in future research.

These impact forecasting systems are still under development and testing and thus are not yet fully operational (Met. Int. A; Risk Modelling NZ. C, D). Consequently, impact forecasting models are not currently the sole tool used for designing and issuing IFWs (Met. Int. A). "Impact-oriented discussions" (Met. Int. A) between different agencies and groups are still the main approach for designing and issuing IFWs, which aligns with the suggestion for a subjective approach in the WMO Guidelines (WMO, 2015), discussed next.

Impact-Oriented Discussions

Impact-oriented discussions typically involve many stakeholders that possess the different types of knowledge and information needed to understand and forecast impacts. In New Zealand, the impact forecasting approach tends to be an impact-oriented discussion. For example, the Red Warnings from the MetService's new warning system (see MetService, 2019a) are issued based on impact-oriented discussions with hydrologists and EM groups (Met. NZ. K). A Red Warning does not have "fixed thresholds" (Met. NZ. K); it is only issued if the event is expected to produce significant impacts. The information used to inform a Red Warning decision is gathered from directly communicating with the local EM groups and regional/local councils where the impacts are expected to occur (Met. NZ. K). Impacts reported in the media and on social media platforms then help to verify and update warnings (Met. NZ. K).

[13] RiskScape is an open-source risk modelling software that was co-developed in New Zealand by GNS Science and NIWA (see Schmidt et al., 2011).

Similar impact-oriented discussions occurred when ex-Tropical Cyclone (TC) Debbie and ex-TC Cook made landfall in New Zealand in 2017 and caused significant flooding in Edgecumbe. After ex-TC Debbie impacted the Bay of Plenty Region in NZ from 3-6 April 2017, causing widespread flooding (Cullen et al., 2017), "[the Bay of Plenty] were suddenly faced with ex-TC Cook coming in after that [on 13 April 2017]" (EM NZ. Reg. A). In preparation of ex-TC Cook, the Bay of Plenty EM group had a team conduct a probability assessment to "look at what … the potential impact [might] be of this event coming in, given the current situation that we already had been impacted" (EM NZ. Reg. A).

This risk assessment helped identify which neighbourhoods needed to be evacuated in response to the forecast for ex-TC Cook (EM NZ. Reg. A). It relied on discussions and collaboration where decision-makers and stakeholders shared knowledge of recent impacts caused first by ex-TC Debbie that made some areas and assets more vulnerable to damage/flooding from ex-TC Cook (EM NZ. Reg. A). Additional hazard information such as river and stream levels were also shared (EM NZ. Reg. A).

Impact-oriented discussions also make use of decision support systems and integration of spatial data to identify exposed and vulnerable areas and assets. For example, an impact-based decision support system was set up between the National Weather Service and emergency managers in New York to support forecast updates, response decisions, and public and partner messaging (Hosterman et al., 2019). Integration of spatial layers has also been used to analyse social vulnerability to extreme precipitation in Colorado (Wilhelmi & Morss, 2013) and to support flood risk management decision-making in Brazil (Horita et al., 2015). More work is needed to explore these similar efforts for integrating hazard, impact, vulnerability, and exposure (HIVE) data to support IFWs in New Zealand.

These examples demonstrate various approaches and methodologies for conducting impact forecasts. Further examples are provided in a review of Impact Forecasting capabilities worldwide (see Schroeter et al., 2020).The most appropriate approach depends on the goals of the system, the available data, and the type(s) of hazard(s) to be forecasts:

> … if you're doing the collaborative approach with very broad scenario-type impacts, then perhaps the update frequency can be less. If you're doing a more robust, sort of bespoke risk algorithm, then I would hope the update frequency would be higher because you are trying to actually capture risk given the current circumstances. And if you're not updating frequently, then you're using a historical dataset to inform the current risk and I don't think that's very accurate (Met. Int. A).

In these examples, all four data types (hazard, vulnerability, exposure, and impacts) come into play for impact forecasting (Figure 6.2). Model-based impact forecasting uses quantitative datasets, typically in spatial format (e.g., GIS shapefiles). Alternatively, impact-oriented discussions utilise the forecasts along with more holistic qualitative information in the forms of tacit knowledge and experience, observations from social media and/or media reports, meteorological observations, hydrological observations, etc. Discussions between stakeholders bearing different knowledge are critical for the subjective approach. While objective model-based approaches may be considered the more "sophisticated" approach (e.g., Schroeter et al., 2021), our participants indicated that both approaches have value, and the most effective approach is to use them together rather than preference one over the other (EM. NZ. Reg. D). This exemplifies the importance of incorporating different scientific epistemologies into transdisciplinary science and research to inform policy and decision-making (see International Science Council, 2021).

6.4.1.3 Impact warning

Findings from the interviews show that impact warnings introduced new needs for setting warning thresholds, discussed below.

Defining Impact Thresholds

Hydrometeorological warnings are based on thresholds traditionally set around physical hazard characteristics, such as 'x' amount of rainfall in 'y' amount of time. Participants indicated that previous event impact data can help determine warning thresholds (Met. Int. A, B, D; EM. NZ. Reg. B, C). For example, investigating the drivers of the resulting impacts from a recent event can help redefine thresholds such that they are specifically impact-related (Met. Int. A). This can involve identifying the rainfall and windspeed leading up to the event that resulted in the impacts to determine which thresholds result in such impacts (Met. Int. A), such as 'x' windspeed will result in 'y' type of damage to 'z' structures. A NZ EM official highlighted the value of cataloguing impact data to prevent "history from repeating itself", by allowing officials to identify trigger points (or thresholds) based on past events (EM. NZ. Reg. B). Like the impact forecasting approaches, countries and regions appear to use different approaches to defining impact-based thresholds, varying in how systematic they are (Figure 6.3).

Tacit knowledge and experience are less systematic ways to identify future event thresholds. NZ EM officials use tacit knowledge to identify different river level impacts (EM. NZ. Reg. B, C). The Northland EM agency works with council hydrologists to informally forecast these flood impacts and inform responders and communities (EM. NZ. Reg. B). Similarly, West Coast EM officials have identified and logged river level thresholds for specific points in the river network and are looking to do this more systematically with GIS.

The UK MetOffice has a slightly more systematic approach to documenting tacit knowledge. They use a series of "impact tables" (Met. Int. A) that were developed in consultation with local EM to "discuss what impacts are observed at different levels" to identify response capacity levels (Met. Int. A). These tables helped the MetOffice understand "how different impacts have occurred related to different hazards" (Met. Int. A). The MetOffice then uses a risk matrix (see WMO, 2015, p. 14), with impacts on one dimension and likelihood on the other to relate the level of impact from the tables to the level of impact in the matrix (Met. Int. A). The MetOffice still relies on contacting EM authorities to verify the most appropriate warning level from the impact matrix (Met. Int. A). This remains a "continual collaborative process" where the warning can be updated based on feedback from the authorities on the ground (Met. Int. A).

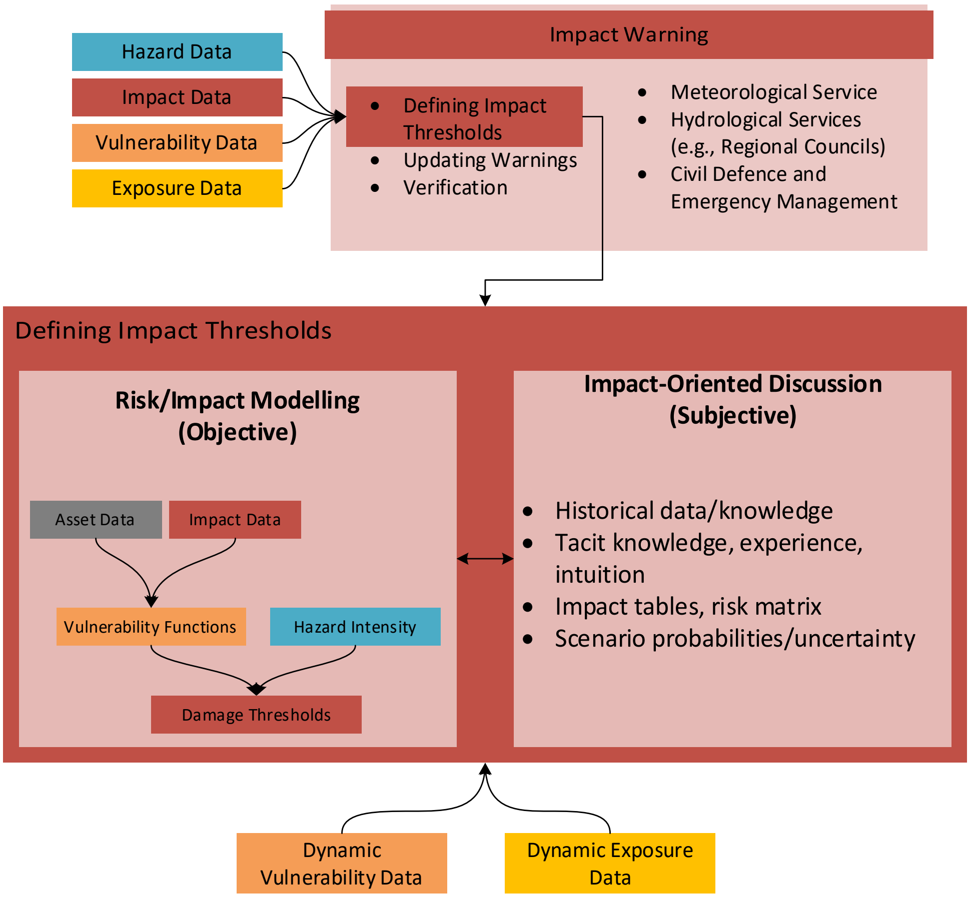

Figure 6.3. Data inputs and uses for defining Impact Thresholdsfor the Impact Warning Component. This component uses similar approaches to Forecasting Impacts: the objective Risk/Impact Modelling approach, or the subjective Impact-Oriented Discussion approach, as shown at the bottom of the figure. All four data types feed into both approaches. Asset data is represented in grey as it overlaps with both vulnerability and exposure data. The actors are listed on the side of the Impact Warning box. Dynamic vulnerability (orange) and dynamic exposure (yellow), such as antecedent physical conditions (e.g., drought or over-saturated soil), human response capabilities, or human locations, are needed to update thresholds so that the risk estimates are accurate.

Still, this is less systematic than model-based techniques, and participants envisioned using impact data in risk/impact models to classify what is hazardous. Engineers often use impact data to inform the vulnerability function in risk or impact models by associating levels of damage to hazard intensities for a given asset (Pita & de Schwarzkopf, 2016; Tarbotton et al., 2015). Post-event damage surveys can be used to develop and calibrate vulnerability functions and identify impact thresholds (Met. Int. A, B). For example, an event database with empirical impact data from damage surveys can provide evidence about how hazard intensity will cause damage (Met. Int. B). Eventually, these models can help identify the causes of certain impacts. This includes determining which wind speed or rainfall amount led to high impact events (Met. Int. A). By understanding the mechanisms that led to the impact, forecasters can improve their models and identify the specific impact and warning thresholds (Met. Int. A).

Currently, risk modellers do not appear to be involved in the warning operations of some of the participating meteorological, hydrological, and emergency management agencies, such as in NZ. The VOT developed by the UK MetOffice is undergoing evaluation with operational meteorologists (Hemingway & Robbins, 2019). Furthermore, the FEWS that is currently under development for the Vaisagano River in Apia, Samoa has been developed in collaboration with risk modellers and developers of the RiskScape software and with the Samoan Ministry of Natural Resources and Environment, indicating that risk modelling will play a role in the operational FEWS. There is further interest and future work planned for developing the capabilities of risk model frameworks like RiskScape to conduct rapid impact modelling assessments for warning systems and response and recovery (Risk Modelling NZ. A).

Thresholds based on impact data alone (e.g., observed impacts, post-event damage assessments) are less useful if there is a change in the underlying vulnerability and exposure of assets due to human activity, seasonality, etc., or if the event is more extreme than anticipated due to climate change:

> I think there can be provided a bit of a false sense of what's going to happen? Like people think that that's going to be the impact, but there's always a chance that a) the forecast, there might be an area that might get more rain than that, also we're in a climate change, so things are just a little bit more intense now. And there might be another factor that has never been considered, and it could just be something that's just a change in the landscape, that sort of meant that the storm might just have a bit more sting in its tail and might, you know the local experience might, it can tell you about what's happened but it won't tell you about the really extreme event (Met. Research NZ. J).

There is a need for dynamic vulnerability and exposure data to account for other factors that may change impact thresholds, such as antecedent physical conditions (e.g., drought or over-saturated soil), human response capabilities, or human location (Agriculture/Rural NZ. A; Met. NZ. K). These factors can interact with each other to exacerbate impacts. For example, a drought in the South Island of New Zealand caused farmers to be more vulnerable to medium and low impact snow events than normal, due to drought-impacted feed supply:

> This year the drought's been so widespread that we're really low on specific types of feed that are really common in a farmland system normally, really easy to source ... So … that's … actually put the rural community at a really big risk of not being able to cope for events that otherwise would be quite easy to recover from (Agriculture/Rural NZ. A).

Thus, a low impact snow event can become high impact due to underlying vulnerability conditions caused by a separate event (e.g., drought); discussed further in Section 6.4.2.4. This example also demonstrates the need to consider cascading hazards, as stated by Pascal et al. (2006); Potter et al. (2021); and WMO (2018).

Updating Warnings

Real-time or near real-time hazard and impact data streaming onto meteorologists' screens are highly valuable to participating NMSs, as real-time information allows meteorologists to adjust warnings on the fly (Figure 6.4):

> ... the most important thing here is that [the European Weather Observer is] real-time data, and we will have this data available on our screens as forecasters wants (sic) it ... So ... in our view it's really important for the forecaster to have real-time data available in order to adjust warnings, for example, if things are more severe out there, ... to upgrade the warning or vice versa (Met. Int. E).

This impact data can show forecasters and responders "what's happening now versus what you predicted is going to happen" (EM. NZ. Reg. C). For example, in New Zealand, one MetService participant described how they can upgrade an Orange Warning to a Red Warning if they observe impacts that they were not expecting, "coupled with a forecast with a lot more to come, and that might then prompt you once you've seen those impacts to then escalate to Red" (Met. NZ. K). Social media, crowdsourcing, and media reports are valuable for gathering real-time impact data, which is useful for updating warnings on the fly (Met. Int. E; Met. NZ. K; Krennert, Pistotnik, et al., 2018), despite the limitations in quality and trustworthiness of social media and crowdsourced data (Harrison & Johnson, 2019).

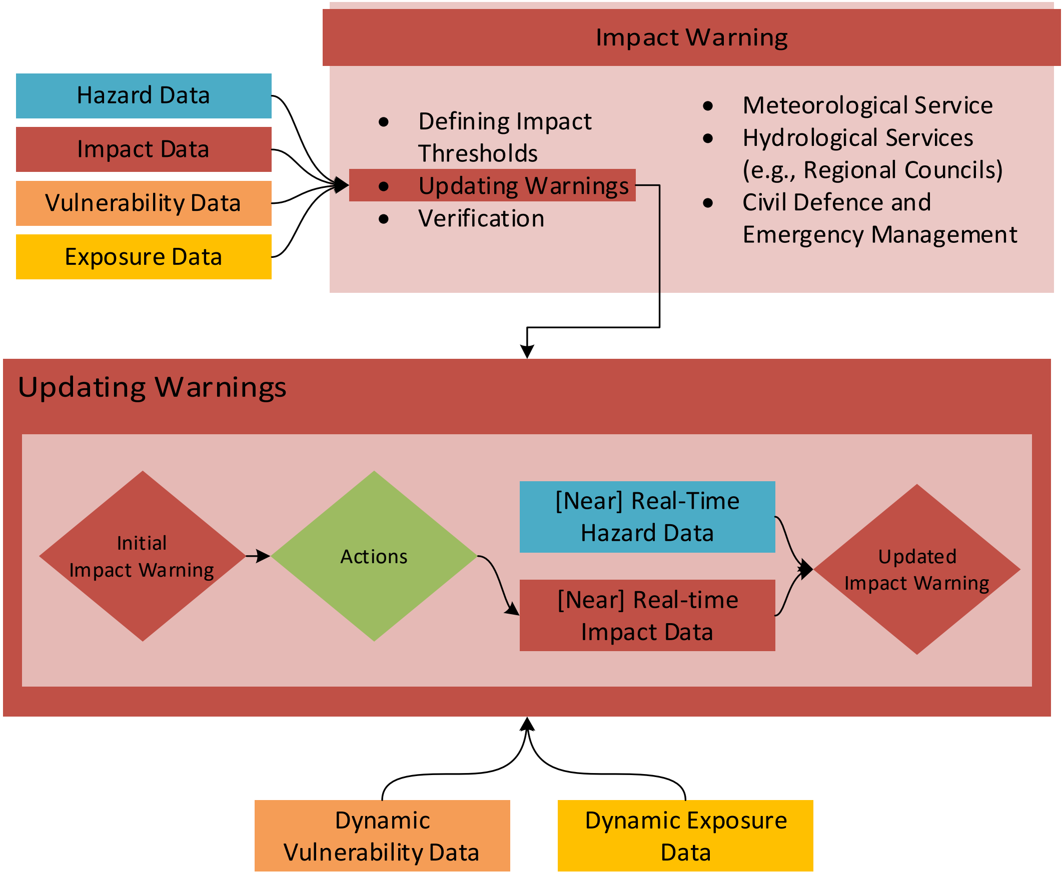

Figure 6.4. Data inputs and uses for updating warnings.Real-time or near real-time data/information on the hazards, impacts, vulnerability, and exposure are key for updating warnings. Updating warnings starts from the initial impact warning, which leads to actions taken by the warning audience. These actions can determine what human impacts occur (e.g., injuries, fatalities, traffic impacts). The hazard can change in space and time, also causing different impacts. Warnings can be updated with this up-to-date information. Dynamic vulnerability and dynamic exposure can also change as impacts unfold and as people take protective actions.

Verification

To continuously improve their services, warning organisations routinely verify and validate models, forecasts, and warnings. Participating NMS officials described how warnings have traditionally been verified based on the occurrence of the forecasted hazard, with little investigation into what happened 'on the ground' (Met. Int. A, B, D, I; Met. NZ. F). This verification involves meteorological observations to confirm the occurrence and timing of the hazard compared to the forecasts and warnings (Sharpe, 2016; Wilson & Giles, 2013). Participating NMS and EM officials indicated that verifying impacts is the next step towards improving forecasts and warnings, as shown in Figure 6.5. This can help determine if they are under- or over-warned and strive for the "right buoyancy of [the] warnings" (Met. Int. E).

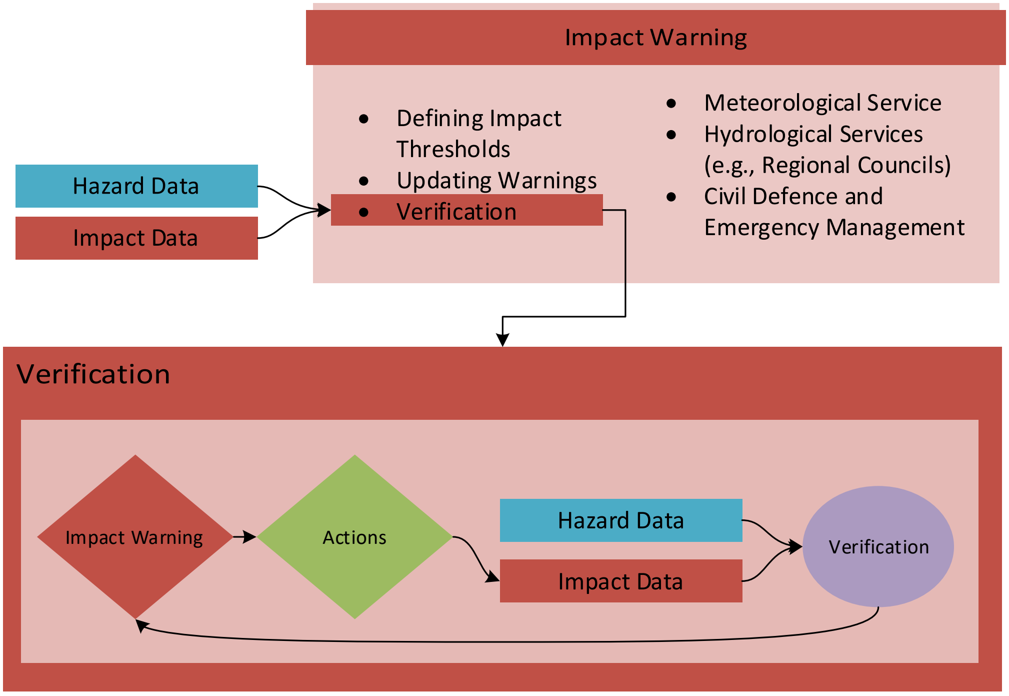

Figure 6.5. Verification of impact warningsrelies on observed hazard and impact data. The impact warnings that were issued lead to certain actions, which then result in impacts (or no impacts). These impacts are then used to verify the warnings that were issued. The feedback loop from learning from verification to adjust procedures and impact thresholds is represented by the arrow pointing back from verification to impact warning.

Along with observational hazard data, impact data from post-event assessments, media reports, social media, and other crowdsourcing or citizen science efforts are used for warning verification (Met. Int. D, E; Met. NZ. F). Post-event assessments offer credible, systematic ways of collecting impact data, useful for post-event analyses (Harrison et al., 2015; Pita & de Schwarzkopf, 2016). For example, NMSs use assessments to determine whether they 'cried wolf' (Met. Int. B). Most participating NMSs use these assessments for post-event analysis and evaluation (Met. Int. B, C, E, I). The NMSs in the USA and Austria use these data, along with crowdsourced storm reports, to build event databases that allow for event comparison, past event learnings, and future preparedness (Met. Int. E, I; Krennert, Kaltenberger, et al., 2018; Krennert, Pistotnik, et al., 2018).

IFW verification challenges exist. Hemingway and Robbins (2019) questioned how verification can be done if the impacts are reduced due to the warnings themselves. These concerns were echoed by Potter et al. (2021), who suggested several approaches for verifying IFWs if and when impact data is not available. These include using predetermined, dynamic hazard-based criteria, or identifying the mitigation decisions that were made in response to the warning (Potter et al., 2021). A NZ meteorologist in our study indicated that verification is not binary (Met. NZ. K). NZ MetService meteorologists use a combination of observational hazard data, impact data from media reports, and experience in a 'pragmatic' approach to assigning a verification score to the warnings. Thus, in line with Potter et al. (2021), a multi-factored and multi-data approach grounded in Pragmatism and experience presents an alternative to verifying IFWs.

6.4.1.4 Decision/Action

After a forecast or warning is issued, the recipients must decide on appropriate protective actions. Investigating the effectiveness of IFWs for warning recipient decision-making was out of the scope of this research, yet some notable comments were made by participants on this topic that should be acknowledged.

Potter et al. (2021) found that NMSs in both New Zealand and internationally perceived the benefits of IFWs to include a reduction of warning fatigue and cry-wolf syndrome. However, our findings have some differences from Potter et al. (2021). While some NMS officials in our study indicated that IFWs may potentially reduce the effects of warning fatigue and cry-wolf, two NZ participants (EM, meteorologist) had concerns about crying wolf when warning for impacts that did not eventuate (EM. NZ. Reg. E; Met. Research NZ. J). They attribute this to the added uncertainty of forecasting and warning for impacts across space and time for different audiences (Met. Research NZ. J), stating "it's not just one person, it's a population you're forecasting for over an area, and people are going to experience different effects" (Met. Research NZ. J). There are also uncertainties around human behaviour, making it difficult to model and forecast impacts based on human behaviour (Risk Modelling NZ. C). This impact uncertainty compounds the pre-existing uncertainty from weather and hazards forecasting (Met. Int. F; Golding et al., 2019), as outlined by a US-based meteorologist who highlighted the uncertainties of forecasting winter weather hazards:

> From just the base physical science aspect, I don't know that … we're at a level at least with consistent, calibrated probabilistic forecasts that we can predict those kind of events, or … consistently in a calibrated way predict what the intensity of a tornado is going to be or the size of hail (Met. Int. F).

More information on hazards and impacts such as hail size, tornado intensity, and resulting damage is needed to calibrate models for hazard forecasting (Met. Int. I). For example, reports of hail size from crowdsourcing and citizen science platforms can help calibrate radar algorithms used for forecasting precipitation types (Met. Int. I), which can then inform hazard and impact forecasts (e.g., damaging hail to crops) by overlaying the hazard forecast with asset data (e.g., crop fields, infrastructure). However, more work is still needed in this area (Met. Int. I).

IFWs may help individuals conceptually link hazards to impacts, thus increasing their risk awareness. For example, with regards to severe thunderstorm-induced asthma attacks, one NZ-based respiratory doctor indicated that people who experience severe thunderstorm-induced asthma attacks and have never experienced an asthma attack before may not realise what is happening to them, resulting in a delay of them seeking appropriate care (Health NZ. Reg. A). IFWs containing information on thunderstorm-induced asthma may benefit warning recipients by clearly drawing the links from the hazard(s) (i.e., the thunderstorm and pollen) to the impacts (i.e., asthma attacks), helping individuals to more quickly identify what may be happening to them and seek proper care.

Studies have found that IFWs may be more effective if they include prescribed actions (Weyrich et al., 2018). Many of our participants from the EM sector reiterated the need to include prescribed actions in the warnings (EM. NZ. Reg. A, E, H). However, one NZ participant from the flood warning space was skeptical of such prescribed actions (Hyd. Gov. NZ. Reg. A), preferring to issue general warnings over specific action-based warnings. This is due to the large size of the communities in their jurisdiction, the high number of stakeholders for which the warning would need to be designed, and concerns with liability and control when introducing prescribed actions (Hyd. Gov. NZ. Reg. A). They questioned whether it would be more effective to issue a general flood warning with the location and duration (Hyd. Gov. NZ. Reg. A). This would shift the responsibility back to property owners and residents where

> people then can react to that in the way that they deem appropriate, and that then moves the responsibility back on the property owner, the residents to be able to react. Obviously we're there to help and guide and advise, but we just haven't got the reach and the people so … you need enough bubbles of control out there that they're able to self-manage and deal with it themselves … so really it's get the message out as quickly as possible and let them react as they see fit. That's sort of where our, for me anyway, our responsibilities should end, we can't help everyone (Hyd. Gov. NZ. Reg. A).

This participant suggested having multiple 'bubbles of control' across the community through self-management, rather than following prescribed actions that may not be situationally appropriate. They acknowledged this would require heavy early community engagement efforts, so communities and individuals understand their local flood risk and develop their emergency response plans for floods. This raises questions around the needs of the warning recipients and the communities, and the need to identify what they deem the most appropriate approach for warnings, as suggested by Thomalla et al. (2006), and done by Tarchiani et al. (2020) in their design of a flood IFW system in Niger. This would align with the concept of people-centred early warning systems (Basher, 2006). Still, the evidence from the literature suggesting the efficacy and value of including guidance messaging cannot be denied (e.g., Weyrich et al., 2018).

In terms of data and information for the Decision component of the Warning Value Chain, the information produced from the previously described components (Observation, Weather Forecasting, Hazard Forecasting, Impact Forecasting, and Impact Warning) and other social data such as past experience and behaviours of peers influence the recipients' decision-making. Furthermore, outcomes of these decisions produce new impact information resulting from the event (Hemingway & Robbins, 2019). Thus, rather than being an input, impact data can also be an output from the Decision Component.

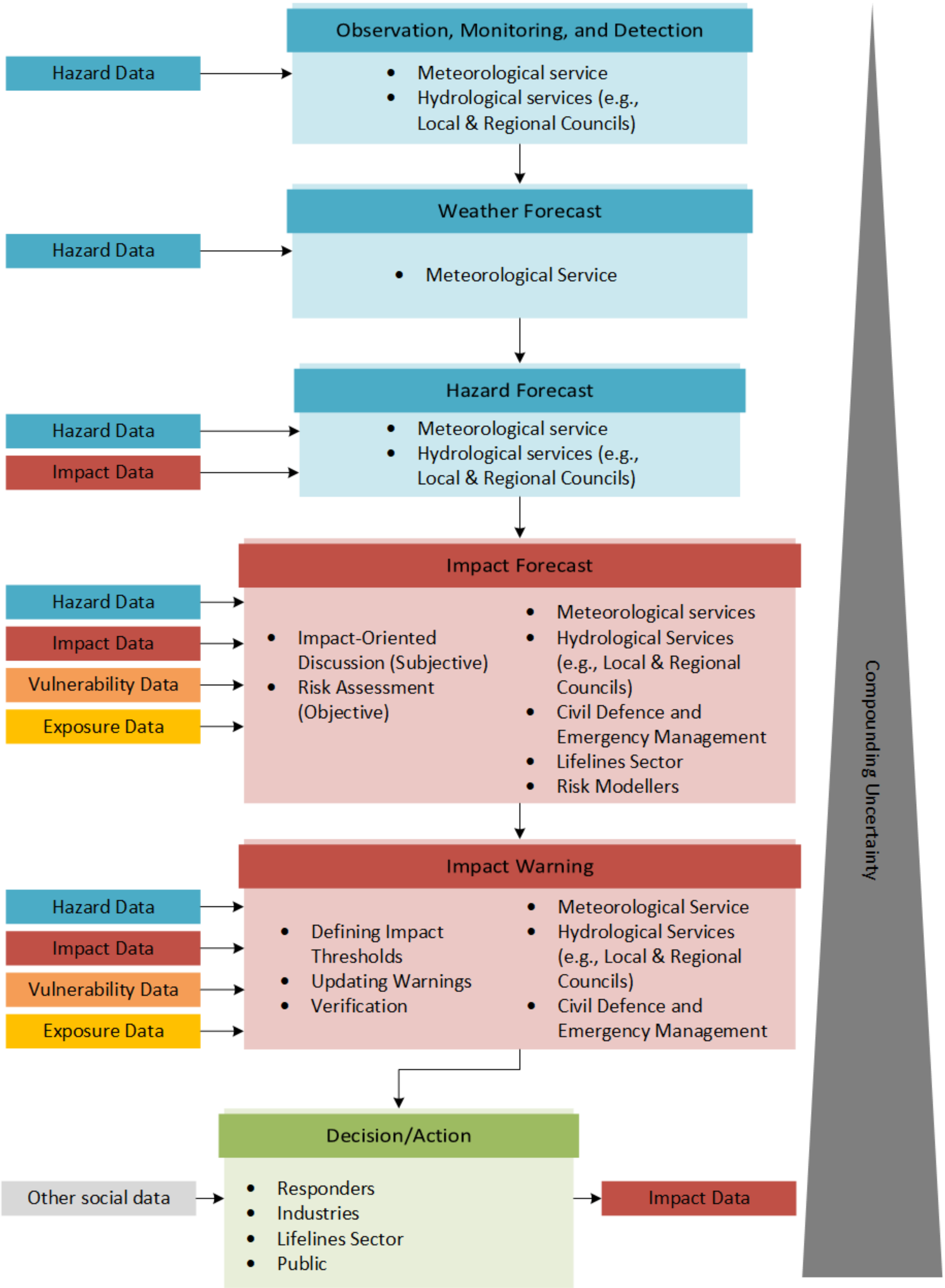

Figure 6.6. This figure represents the Warning Value Chain and the associated data inputs and outputs for each component, along with the activities and actors for each value chain component. Uncertainty compounds at every stage of the chain and is represented by the compounding uncertainty wedge.

Each component links together to complete the Impact Forecasting and warning Value Chain. Figure 6.6 provides a visual representation of the connected chain, starting with Observation, Monitoring, and Detection, where meteorological services and hydrological services use raw observational hazard data. These observational hazard data are then used to formulate Weather Forecasts in the next component. Weather Forecast data and raw observational data are then used to produce hazard forecasts, in conjunction with impact data if available. These hazard forecasts can then be combined with impact, vulnerability, and exposure data to produce impact forecasts, using models, impact-oriented discussions, or both. After an impact forecast is produced, the meteorological, hydrological, and EM services must decide on the appropriate impact warning level to issue to the appropriate audiences. Hazard, impact, vulnerability, and exposure data are all utilised to define the warning thresholds, update the warnings, and verify the warnings. Once a warning is issued, the warning audiences must decide on the appropriate action to take (if any). These actions (or lack thereof) may then result in forecasted or un-forecasted impacts. Uncertainty begins at the beginning of the value chain with weather forecasts. From there, the uncertainty compounds, as demonstrated by the compounding uncertainty wedge, which can influence warning audiences' decisions to act.

6.4.2 Need for more understanding on different types of impacts

Ranges of impacts occur from hydrometeorological hazards that can be physical (e.g., damage to infrastructure and the built environment), economic (e.g., financial losses), social/societal/cultural (e.g., traffic delays, disruptions to large events, educational services, health services), or environmental (e.g., pollution spills, wildlife endangerment). The impacts can be direct (e.g., injuries, casualties, building damage) or indirect (e.g., job loss, displacement, illness) (Lindell et al., 2006). Discussions with participants revealed a gap in modelling, forecasting, and communicating some indirect and social impacts.

6.4.2.1 Social Impacts

When considering the impacts of severe weather, the initial thinking is towards direct, physical impacts, and financial and economic impacts/losses. Examples of the IFWs provided in the WMO Guidelines appear to have a heavier focus on direct and physical impacts (e.g., wind damage to trees and power lines), with some social impacts considered such as traffic delays. However, all types of possible impacts must be considered. For example, in Argentina a severe weather warning created major impacts due to a soccer match, a culturally significant event:

> ... here in Argentina, football, soccer ... it's very, very important ... And there were (sic) South American final soccer cup here, and the final soccer cup was between the two most important soccer clubs, and everybody was very crazy. There was a very, very heavy storm and the match had to be postponed. You cannot imagine how was (sic) that day for us, and it was just a soccer game, you know. [High-level authorities were] calling my boss to 'tell me what's going on, what

> do we have to do' you know, because people really got very, very angry. They blame us, on the match. So, what can I do? (Met. Int. D).

This example indicates the importance of identifying cultural impacts from hydrometeorological hazards and including this in communications. Further, messaging needs to be more culturally sensitive/aware and empathetic. As highlighted by Ayeb-Karlsson et al. (2019), several cultural and social limitations exist in disaster preparedness, particularly warning response, and there is a need to understand the cultural contexts influencing preparedness. Doing so would further align with the concept of people-centred EWSs (Basher, 2006).

A shift is occurring in the NZ risk modelling space towards social impact assessments in response to needs identified by the EM sector. A NZ-based risk modeller described the importance of considering social impacts beyond just the direct, physical impacts, to provide a fuller picture (Risk Modelling NZ. B). For example, direct impacts such as power and other critical service outages may cause population displacement, which is often not modelled.

Indeed, an official from NZ's National Emergency Management Agency (NEMA) echoed the need for documenting indirect impacts (EM. Gov. NZ. Nat. G). While NEMA collects impact and loss data for the Sendai Framework (UNDRR, 2015b), the face value of the impact/loss data lacks the deeper meaning of the indirect, potentially longer-term, impacts because "recording a road outages as a 1 or a 0, you know it was out or it wasn't out, doesn't give you any scale of duration, the impact, lost productivity, stress on people's lives" (EM. Gov. NZ. Nat. G).

Following flood events in NZ, risk modellers and other researchers have disseminated post-event surveys to the affected people. Challenges arose around collecting and using social impact data for modelling purposes (Risk Modelling NZ. C). A range of physical and non-physical impacts occurred after the initial event, such as injuries (physical), and anxiety and stress (non-physical). While they were able to capture some of this information, data collection was not well planned, thus it did not result in a high-quality dataset useful for modelling (Risk Modelling NZ. C). Conducting well-planned longitudinal surveys in collaboration with more experts such as social scientists were suggested to increase the usefulness of the surveys (Risk Modelling NZ. C). Furthermore, this participant suggested that risk modellers may not be the best suited for this type of social impact modelling as their expertise lies in modelling buildings and infrastructure. This highlights the need for multidisciplinary work for IFWs (Merz et al., 2020).

6.4.2.2 Health Impacts

Health impacts appear to also have gone largely unnoticed in the IFW literature, aside from the health impacts of extreme heat (Harrowsmith et al., 2020; Pascal et al., 2006; WMO, 2015). Recent events have brought the risk of thunderstorm-induced asthma attacks to light in Australia and New Zealand (Sabih et al., 2020; Thien et al., 2018). Before the 2016 Melbourne epidemic thunderstorm asthma event, this risk was not forecasted or warned for. Following this event recommendations included developing an epidemic thunderstorm asthma forecast (Hew et al., 2017; Thien et al., 2018), which is now provided by the Australian Bureau of Meteorology (Met. Int. B; Bannister et al., 2021). A similar event occurred on a smaller scale in Waikato, NZ in 2017 with no advanced warning (Health NZ Reg. A; Sabih et al., 2020). There has thus been a push to capture such severe weather health impacts (Aitsi-Selmi & Murray, 2016), which must then be integrated into IFWs. Health impacts from poor air quality due to pollution (Gao et al., 2015), wildfires (Cisneros & Schweizer, 2018), etc., are also increasingly important and must be considered when designing IFWs.

6.4.2.3 Urban and Rural Impacts

The difference between urban and rural impacts introduces another challenge when communicating impact information, as meteorological hazard impacts differ between these. For example, urban heavy rainfall may create more impacts due to surface flooding and traffic delays (Met. NZ. E). However, equivalent rural heavy rainfall in locations exposed to such rain often (e.g., West Coast, NZ) may experience fewer impacts on the resident population, with minimal flooding (Met. NZ. E), and in some habitually dry regions, the heavy rainfall may be welcomed. In contrast, a tramper/hiker or hunter on the Department of Conservation tracks may need forewarning due to rapid river rising, posing a life safety risk (Met. NZ. E). This conundrum echoes the findings of Potter et al. (2021), who questioned whether IFWs are designed for individuals or society. This key question must be addressed and was raised by participants (Met. NZ. F, K), as exemplified by a NZ-based meteorologist:

> … exposure and vulnerability are the two key questions and for some warnings, a short lead time is fine, but for others, it's not, and it very much depends on the user. A farmer for a snow warning is going to need a lot more time to get stock down out of the high country than you as an individual getting a wind warning and needing to go down and tie up the trampoline, right? So if you want to tie down the trampoline, you can do that in a couple hours when you get home, but you know, if you're a farmer, you might need to know that there's snow coming the day after tomorrow to move the stock (Met. NZ. K).

This relates to the need for vulnerability and exposure to be included in IFWs and the identification of appropriate audiences' relevant trigger points (or thresholds) (Zhang et al., 2021). It is not enough to collect only past event impact data and expect the impacts to be the same for future events or different populations. However, as Potter et al. (2021) found, vulnerability and exposure are often overlooked when designing EWSs. This may be due to challenges in capturing the dynamic nature of vulnerability and exposure, discussed next.

6.4.2.4 Dynamic Exposure and Vulnerability

Exposure and vulnerability change over space and time (The World Bank, 2014). Thus, up-to-date datasets for this information are critical for accurately representing the level of risk (Met. Int. A, D; Met. NZ. F, K). If exposure data is not current, the risk assessment will be inaccurate, resulting in improper warning buoyancy (i.e., over-warning or under-warning will occur) (Met. Int. A, B). Thus, a UK-based meteorological risk specialist hopes "we all recognise the importance of updated vulnerability and exposure data" (Met. Int. A). However, gathering and integrating dynamic vulnerability and exposure data is a challenge for participating NMSs, such as the UK MetOffice who are determining how best to maintain up-to-date data and integrate it into an IFW system (Met. Int. A).

In recent years, research has emerged investigating the dynamic nature of exposure and vulnerability (Terti et al., 2015) and methodologies for integrating dynamic exposure and vulnerability into risk analyses (Gallina et al., 2016; Shabou et al., 2017; Wilhelmi & Morss, 2013). Our findings echo those from Merz et al. (2020) regarding the role of dynamic exposure and vulnerability in impact forecasting, and the need to integrate dynamic exposure and vulnerability into models through collaboration across sectors (e.g., social science, engineering, and natural sciences). Other options commonly used include visual overlays for integrated multi-hazard decision support platforms supporting impact-oriented discussions. There is a need to identify the potential sources, creators, and custodians of dynamic exposure and vulnerability data and investigate how it can be accessed and used for IFWs.

6.5 Conclusions

This exploratory study identified the uses and gaps for hazard, impact, exposure, and vulnerability data for implementing severe weather IFW systems within the Warning Value Chain framework presented by Golding et al. (2019). The qualitative nature of data collection and analysis herein limits the generalisability of results beyond the participants. However, the qualitative approach offers an in-depth understanding of a problem not readily available from quantitative approaches (Blumer, 1969; Miles & Huberman, 1994; Patton, 2002).

Our findings support existing research pointing to the need for creating, gathering, and using impact, vulnerability, and exposure data for IFW systems. This study builds on existing research by identifying where each data type (hazard, impact, vulnerability, and exposure) can be used for each Warning Value Chain component and offers examples of alternative approaches for impact forecasting and for defining impact thresholds. For example, models provide an objective approach while impact-oriented discussions provide subjective and flexible approaches. These approaches should be used complementarily.

Findings from this research provide new insight into a growing need to identify, model, and warn for social and health impacts, which have typically taken a back seat to modelling and forecasting for physical and infrastructure impacts. The type of impacts to be forecasted and warned for depends on the intended audiences of the warnings.

While this study identified the uses and gaps for hazard, impact, vulnerability, and exposure data, questions remain around who collects, creates, stores and manages these data (particularly impact, exposure, and vulnerability). Future research should explore mapping the various sources, creators, users, and custodians of the relevant data needed for IFWs.

This study has a heavy focus on hydrometeorological hazards and impacts due to the experiences of most of the research participants. Floods are the most frequent and costly hazard in NZ (Rouse, 2011), and thus were the most common examples that NZ participants drew from during interviews. Further research should verify the findings of this research against other hydrometeorological hazards both within and outside of New Zealand.

Position of the reader

Part 1	Chapter One Introduction
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Part 2	Chapter Three Research Design
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Part 4	Chapter Ten Discussion and Conclusion

Chapter Seven: **'Where oh where is the data?': Identifying data sources for hydrometeorological impact forecasts and warnings in Aotearoa New Zealand**

This chapter presents the third manuscript of this doctoral study prepared for publication. The focus of this manuscript is to identify existing and potential sources of hazard, impact, vulnerability, and exposure data to support IFWs in New Zealand. After developing an understanding of the flow of information along the IFW Warning Value Chain and identifying gaps in supporting data, as presented in the previous chapter, identifying the sources of data to address those gaps was the next objective. This paper aimed to achieve Objective 3.1 Identify the creators, collectors, and users of HIVE data that is relevant to severe weather IFWs; and Objective 3.2 Identify the inhibitors of and facilitators to collecting and using HIVE data to support the implementation of an IFW system in New Zealand for severe weather hazards.

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The published form is available in Appendix L.

Chapter 7: 'Where oh where is the data?: Identifying data sources for hydrometeorological impact forecasts and warnings in Aotearoa New Zealand

7.1 Abstract

Early Warning Systems are a key component to building preparedness and response capacities to hydrometeorological hazards that continue to affect people worldwide. Notable historic events have revealed gaps in current hazard-based warning systems. Impact Forecasts and Warnings (IFWs) have been proposed to fill these communication gaps by re-centring the warning thresholds and language around the consequences, or impacts, of the hazard(s), rather than just the physical characteristics. However, research has shown that implementing IFWs requires not just hazard data, but also data on impacts, vulnerability, and exposure to understand the risk of impacts.

Using Grounded Theory Methodology, we conducted a series of interviews with users and creators of hazard, impact, vulnerability, and exposure (HIVE) data to identify data sources and understand how these data collected and created to support the implementation of IFWs. We focus the study on the New Zealand context to support the country's efforts towards implementing IFWs.

Our findings indicate that many sources for HIVE data exist that are collected for other uses (such as for response efforts for disaster and emergency events, and for research) and have relevant application for IFWs. Our findings further suggest that priorities, motivation, and interest within organisations influence how well data is collected. Moreover, agencies tend to prefer official data, but official data has limitations that unofficial data may address, such as timeliness. To that end, a tension exists between the timeliness and trustworthiness of data needed for emergency response and warnings.

7.2 Introduction

The last two decades have seen a paradigm shift in disaster risk reduction from reactive post-disaster response and recovery to proactive preparedness and mitigation. Early Warning Systems (EWS) are a key component for better preparedness (UNDRR, 2015b). Past severe weather events exposed major communication gaps between meteorologists and warning services and target audiences, resulting in widespread losses including death, injuries, and damage. For example, following Typhoon Haiyan, which resulted in over 6,293 deaths, 28,689 injuries, and 1,061 missing people in the Philippines (McPherson et al., 2015), it was found that 88% of warning recipients did not understand messages about 'storm surge' and 95% of warning recipients did not evacuate because they did not expect the storm to be so catastrophic (Ching et al., 2015). It was recommended that "warning messages … should be conveyed in terms understood by the population at risk" (Ching et al., 2015, p. 34).

This communication gap is a result of both technical failings and human behaviour. The World Meteorological Organization (WMO) posited that meteorologists and warning services do not typically consider the warning audiences' current state of vulnerability and exposure at the time of the warning or at the expected time of impact (WMO, 2015). Furthermore, warning audiences fail to understand and respond to the warnings effectively due to ambiguous terminology (Ching et al., 2015), lack of trust in the warning system and service provider (Taylor et al., 2018), and warning fatigue (Mackie, 2013). As such, EWSs continue to evolve in attempts to reduce the effects of these factors.

In the hydrometeorological space, Impact Forecasts and Warning (IFW) systems are an advancement of traditional hazard-based EWSs. IFW systems provide an opportunity to integrate knowledge and understanding of exposure, vulnerability, and impacts into an EWS to build new warning thresholds that better align with the position, needs, and capabilities of target audiences (Harrison et al., 2022). However, challenges have been identified around identifying and accessing the required data sources for IFWs (Hemingway & Robbins, 2019). Harrison et al. (2022) identified the specific needs and uses for hazard, impact, vulnerability, and exposure (HIVE) data in an IFW system. We continue this work by identifying sources for these required datasets. We next present a review of existing HIVE data sources from the literature, identifying data gaps that we explore further through a series of key-informant interviews.

7.3 Impact Forecasting and Warning Data Gaps and Sources

Warning agencies and meteorologists are challenged with accessing appropriate data to support the decision-making required for IFW systems (Harrison et al., 2014). The lack of impact, vulnerability, and exposure data is a major obstacle to implementing IFWs (Potter et al., 2021). Beyond IFWs, these data are also needed for enhancing our understanding of disaster risks and subsequent mitigation and reduction, as per the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015b).

The following literature review identifies some existing sources of HIVE data for IFWs. These data sources and datasets are summarised in Table 7.1 and described further in the following sections.

7.3.1 Hazards

For this study, hazard data refers to meteorological, hydrological, and hydrogeological data. For example, windspeeds and rainfall amounts may be considered meteorological hazard data, while river levels would be hydrological hazard data, and slope data are useful for landslide hazards (i.e., hydrogeological hazards).

Understanding of severe weather hazards primarily comes from hydrometeorological observations and measurements usually gathered quantitatively through specialised equipment, such as rain gauges, river gauges, and remote sensing. This information helps to estimate the timing, direction, and magnitude of the hazard for forecasts (Heinselman et al., 2015).

Forecasts are another form of hazard data. Multiple Numerical Weather Prediction (NWP) models are run using observational data to determine probabilities of future weather patterns based on running multiple simulations (Gneiting & Raftery, 2005). This probabilistic forecasting approach allows for the calculation of likelihoods of the weather phenomena to occur, and thus an overall confidence level of the forecast (Gneiting & Raftery, 2005). More observational data can increase the confidence of weather forecasts; however, this confidence decreases as forecast lead time increases (Hirschberg et al., 2011).

In places where hydrometeorological monitoring network coverage is limited or lacking, crowdsourcing and citizen science projects have been used to fill these gaps (e.g. Fava et al., 2014). Eyewitness accounts and storm spotter reports also contribute to an understanding of severe weather hazards and phenomena (Krennert, Pistotnik, et al., 2018).

7.3.2 Impacts

Impacts are the effects, outcomes, or consequences of hazardous events. During a severe weather event, Kox, Lüder, et al. (2018) identified impact information sources to include media coverage, fire stations upstream of a storm track that have already been affected, emergency calls, scout reports and ground-truthing, and emergency vehicle occupancy, to determine if enough capacities are on hand. Social media (Harrison et al., 2015), crowdsourcing (Sadler et al., 2018), and volunteered geographic information (Harrison et al., 2020) are other near real-time sources of impact information. Near real-time impact data is usually collected by local emergency management (EM) agencies to produce situational reports which contain all available information about the developments and impacts of an event (Kox, Lüder, et al., 2018).

Table 7.1. Summary of data sources and datasets for hazard, impact, vulnerability, and exposure data identified from the literature review.

Data Type	Description	Data Sources	Datasets
Hazard	Hydrometeorological observations and measurements to formulate warnings.	Meteorological services, hydrological services, Law enforcement, Storm spotters, Responders, social media (Twitter, Facebook, Seina Webo, Flickr, Instagram, SnapChat), the public, online databases, crowdsourcing and citizen science projects.	Meteorological and hydrological observations (e.g., rain gauges, river gauges), satellite and radar imagery, aerial imagery, Natural Hazards Assessment Network (NATHAN), European Severe Weather Database, US Storm Database, public surveys, historic warning records, eyewitness interviews, public surveys, photos and videos.
Impact	Building situational awareness and informs situational assessments for response planning. After an event, impact/damage assessments are conducted to link radar signatures of upcoming or unfolding hazards with a historical database and formulate impact-based warnings based on the historic impacts of similar events. Feeds into vulnerability models and fragility functions for impact modelling.	Media reports, law enforcement, fire stations upstream already affected, the public, emergency responders, engineers, social media (Twitter, Facebook, Seina Webo, Flickr, Instagram, SnapChat), crowdsourcing applications, Google, hydrological services and flood managers, public health agencies, insurance industry, online databases, flood databases, research institutions, environmental protection agencies, storm spotters, emergency services, personal contacts, risk modelling.	Ground-truthing, in-situ observations, reports and emergency calls, situational reports, eye-witness interviews, photos/videos, commentary, incident reports, situational reports, hotline records, loss claims, Emergency Events Database (EM-DA), Natural Hazards Assessment Network (NATHAN), flood databases, digital mapping (e.g. Humanitarian OpenStreetMap, MissingMaps), Google Alerts, Google Analytics Records, technical reports, European Severe Weather Database, public surveys, eyewitness interviews, risk modelling outputs.
Exposure	Highly specific and small-scale nature, usually at the individual, activity, or community level, (e.g., Ferry routes and the locations of large trees overhanging power lines).	Government departments, land and resource management agencies, flood managers, mapping agencies/organisations, crowdsourcing, OpenStreetMap, Google Maps, infrastructure industry, risk model.	Census data (for population counts and density), transportation routes and schedules, infrastructure databases/datasets, land-use spatial layers, building/asset footprints, road network spatial layers, Digital Elevation Models, time-varying population data, river network spatial data, risk modelling outputs.
Vulnerability	Conveys the vulnerability of people, livelihood, and property and typically includes information about infrastructure, buildings, land-use, census data, ecological data, and economic data; feeds into vulnerability models and fragility functions for impact modelling.	Research Institutions, public health agencies, engineers, risk specialists, insurance industry.	Vulnerability assessments, Pacific Risk Information System (PacRIS), vulnerability functions/fragility curves, vulnerability indices, asset characteristics (e.g., building structure information), public surveys.

Post-event damage information is collected in the aftermath of an event in the form of damage surveys. Post-event data such as damage surveys allows forecasters to correlate damage levels produced from certain hazards, such as tornadoes, with the storm radar signature (Harrison et al., 2015). If this impact information is stored in a historic database, forecasters can refer to the database to compare past storm radar signatures with current radar signatures and understand the level of damage and impacts the current storm may produce, allowing the forecaster to formulate impact-based warnings (Harrison et al., 2015).

Impact data is also produced from risk/impact models for pre-impact, rapid-impact, and post-impact assessments. Data sources can include hazard, exposure and vulnerability information, geo-located social media data (Smith et al., 2017), satellite data (Cervone et al., 2017), crowdsourced impact reports (Sadler et al., 2018), and normalised damage functions (Crompton & McAneney, 2008).

Challenges still exist with collecting enough systematic, in-situ data (i.e., observed impacts) to build empirical models (Panteli et al., 2017) and to validate models (Hemingway & Robbins, 2019). Furthermore, existing impact databases have been created with varying responsibility for which agency collects information, and the methods and purposes of collection (Robbins & Titley, 2018). This limits the databases' use, particularly for analysis and verification. Classifying impacts appears to be subjectively done (Doocy et al., 2013), proving it difficult to use datasets outside of the original purpose for which they were created.

7.3.3 Vulnerability

Vulnerability information is usually created through conducting vulnerability assessments (Sai et al., 2018). This involves combining information about infrastructure, buildings, land-use, census data, ecological data (Poolman, 2014), and socio-economic data (Terti et al., 2015). These vulnerability assessments are typically presented as spatial maps (McCallum et al., 2016).

Vulnerability assessments have traditionally focused on physical vulnerability, such as buildings and infrastructure, with less focus on social vulnerability (McCallum et al., 2016). Studies that have looked at social vulnerability tended to focus on physical impacts such as loss of life or physical injuries (Enarson, 2007), and less so on nuanced social impacts resulting from less quantifiable social vulnerability factors such as "poor biophysical, social, and/or financial capital" in communities (Terti et al., 2015, p. 1482). This is because these vulnerability factors are easier to quantify (McCallum et al., 2016). To address these gaps, Terti et al. (2015) identified a range of underlying social vulnerability factors resulting from human behaviour and demonstrated the highly dynamic nature of social vulnerability, such as risk governance, land use, and individuals' status, all of which change over space and time.

In New Zealand, Mason et al. (2021) developed social vulnerability indicators for flooding using national Census population data. These indicators are based on social vulnerability dimensions such as exposure, age, health and disability status, financial security, social connectedness, knowledge of natural hazards, housing conditions, food and water security, and decision-making and participation (Mason et al., 2021). Health indicators relating to certain health conditions such as cardiovascular disease, respiratory disease, and mental health issues were not completed due to time constraints (Mason et al., 2021). The results of their study provide an opportunity for decision-makers to consider additional factors beyond economic impacts when planning mitigative actions towards flooding (Mason et al., 2021).

Vulnerability information may be obtained through partnerships with the insurance industry who conducts vulnerability assessments for insurance schemes (Rogers et al., 2017). Additionally, the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) created the Pacific Risk Information System (PacRIS), which houses historical hazard data, and risk profiles for Pacific Island countries (Rogers et al., 2017).

7.3.4 Exposure

The highly specific and small-scale nature of exposure makes it difficult to systematically collect and incorporate into an IFW system with the current tools and data available (GFDRR, 2016; WMO, 2015). An example of one form of general exposure information is population counts of people living in areas where hazards frequently occur (e.g. population data overlaid onto floodplains data) (Poolman, 2014). Exposure data is typically created by mapping the locations of assets, such as buildings and infrastructure in proximity to a hazard (McCallum et al., 2016).

Ferry routes and the locations of large trees overhanging power lines are other examples of exposure data that would be important to consider during a high wind event (WMO, 2015). Building footprints (i.e., a spatial layer of building polygons) is another example of exposure if the building footprints layer is overlaid with a hazard layer (e.g., Paulik et al., 2020). However, even national- or global-scale exposure datasets can be expensive (McCallum et al., 2016), and remain difficult to create and use due to lack of detailed asset information (Lin et al., 2020).

7.4 Data Characteristics for Early Warning Systems

Data usability in disaster response is determined by many factors. For the purposes of this study, we focused on two factors: reliability and timeliness. These appear to be two of the most important factors for choosing data sources for disaster response (Mansourian et al., 2006). The requirements for reliable and timely data for disaster response can also apply to EWSs, as warnings must be timely and accurate to incite early and appropriate action (WMO, 2018; Zhang et al., 2002).

Data is perceived as more reliable if it comes from a trusted source and/or it can be vetted (Harrison & Johnson, 2019). As such, there is a preference for official sources, such as emergency call centre reports, intel from responders themselves, etc. (Kox, Lüder, et al., 2018). For this study, official data refers to data created by recognised officials involved in local disaster response management practices where the disaster is occurring, such as police and fire services, engineers, helicopter pilots, local and regional councils, as well as meteorological and hydrological agencies, and science agencies. Unofficial data refers to data created by external parties of the disaster management practices, such as social media users, contributors to OpenStreetMap, private external corporations (e.g., Google Maps), and media agencies.

This section identified various sources of HIVE data. These components (hazard, impact, vulnerability, and exposure, or HIVE) form the conceptual basis of severe weather IFWs. Meteorologists do not typically possess knowledge of impacts, vulnerability, and exposure (Kaltenberger et al., 2020). As such, sources of these data need to be identified for IFWs (Harrison et al., 2022; Potter et al., 2021). Furthermore, understanding the characteristics of the available data sources in terms of reliability and timeliness will assist data users in determining appropriate datasets for their purposes.

The objectives of this research are to identify sources for HIVE data, and to understand the inhibitors and facilitators to collecting and using these data, to support the implementation of an IFW system in New Zealand for severe weather hazards. We chose to focus on the New Zealand context to support the country's efforts for fulfilling both the WMO's objectives and Sendai Framework priorities for improved documenting of disaster risk and loss data; a need identified in previous research (Crawford et al., 2018; Potter et al., 2021). We employed Grounded Theory (Strauss & Corbin, 1990) to meet the research objectives, described next.

7.5 Research Methods

We used a qualitative approach to address the research question, specifically employing the Evolved-Straussian Grounded Theory research strategy (ES-GT) for data collection and analysis. Interviews and workshops were the primary data collection methods. From November 2018 to April 2021, the lead author interviewed thirty-nine (n=39) experts in weather forecasting, warning, response, risk modelling, and data collection and management, as shown in Table 7.2. Three virtual workshops were held in New Zealand (NZ). Two of these workshops involved EM practitioners, weather forecasters, communication and data specialists, and hydrologists, from Auckland Region (n=4) and Southland Region (n=5). The third workshop involved a portion of the NZ risk and hazard science community based at GNS Science (n=11). Thus, in total 59 people participated in this research.

Table 7.2. Participant Codes. All participants remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by the area of expertise and/or practice, industry, location, or governance level[14].

Interview Code	Position	Classification	Location	Government Level
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ	National
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ	National
Data Management Private NZ. B	Geospatial Specialist	Data Management	NZ	
Data Management Research NZ. C	GIS Specialist	Data Management	NZ	
Data Management Private NZ. D	GIS Specialist	Data Management	NZ	
Data Management Gov. NZ. Nat. E	Head of Data	Data Management; Governance	NZ	National
EM. NZ. Reg. A	Director	Emergency Management	NZ	Regional
EM. NZ. Reg. B	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. C	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ	Regional
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ	Regional
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ	National
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Nat. I	First Responder	Emergency Management	NZ	National
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ	National

[14] The acronyms and abbreviations in Table 7.2 are as follow: Meteorological (Met.), Emergency Management (EM), New Zealand (NZ), Geographic Information Systems (GIS), Regional (Reg), Government (Gov.), Early Warning System (EWS), International (Int.).

Interview Code	Position	Classification	Location	Government Level
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ	Regional
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ	Regional
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ	Regional
Hyd. Gov. NZ. Reg. A	Flood EWS Programme manager	Hydrology; Governance	NZ	Regional
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ	Regional
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ	
Met. Int. A	Science Manager	Meteorology	International	National
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	International	National
Met. Int. C	Senior Policy Officer	Meteorology	International	National
Met. Int. D	Senior Social Scientist	Meteorology	International	National
Met. Int. E	Consultant Meteorologist	Meteorology	International	National
Met. NZ. F	Senior Meteorologist	Meteorology	NZ	National
Met. NZ. G	Communications	Meteorology	NZ	National
Met. NZ. H	Public Relations	Meteorology	NZ	National
Met. Int. I	Division Chief/Meteorologist	Meteorology	International	National
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ	National
Met. NZ. K	Senior Meteorologist	Meteorology	NZ	National
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ	
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ	National

Interview questions and workshop activities focused on IFW data needs and sources. We asked for participants' general thoughts on IFWs; what impact, vulnerability, and/or exposure data they use or need, why, and how; the life path of the data; experienced and/or perceived challenges obtaining data required for IFWs and other uses; and thoughts on collecting and using alternative data sources (e.g. social media and crowdsourcing). Herein we report on data sources, collection, and creation.

This research was conducted under a 'low risk' ethics notification with the Massey University Human Ethics Committee prior to data collection in 2018. All interviewees remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by area of expertise and/or practice, industry, location, or governance level (Table 7.2). Interviews were audio-recorded and transcribed verbatim.

Following ES-GT, we analysed the interview and workshop data using open coding and axial coding, supported by memo-writing and diagramming (Corbin & Strauss, 2015), in Nvivo 12 (Bergin, 2011). The coding paradigm introduced by Strauss and Corbin (1990) supported the axial coding stage whereby the codes created from open coding were related back to the coding paradigm dimensions (Table 7.3) for increased density and precision.

Table 7.3. Summary of the coding paradigm dimensions that supported the axial coding analysis in this study.

Coding Paradigm Dimension	Description
Causal Conditions	A set of events that influence the phenomena or result in the appearance or development of a phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Phenomena	The subject or object under study (Strauss & Corbin, 1990).
Contextual Conditions	The specific set of conditions and characteristics surrounding the phenomena and resulting in action/interaction strategies taken to address the phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Intervening Conditions	Unexpected events or factors leading to action/interaction strategies (e.g., time, space, culture, socioeconomic status, technological status, history) (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Action/Interaction Strategies	Purposeful and deliberate acts taken to address the phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Consequences	Predictable or unpredictable, intended or unintended outcomes of the action/interaction strategies (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).

7.6 Findings and Discussion

This section will first present data sources for HIVE data as identified by the participants, followed by an investigation into the causal conditions, intervening conditions, and subsequent action/interaction strategies for collecting the HIVE data.

7.6.1 Data Sources

The interviews and workshops identified several sources for hazard, impact, vulnerability, and exposure data. These data sources are described next. The following sections are organised by data type (hazard, impact, vulnerability, and exposure). Herein, each section will provide an overview, with accompanying summary tables, of the data sources and their characteristics related to IFWs. The accompanying tables present the data or dataset (e.g., weather stations, radar data), whether the data is official or unofficial, who collects or creates the data (e.g., the creator may be a member of the public by posting a report on social media, and the collector may be an EM agency who collects social media posts for situational awareness), the timescale of the data (e.g., "[Near] real-time" is data collected in real-time or near real-time, such as observational data, social media reports, etc.; "Current" is data that is static in time, was created prior to the event, but has been maintained and kept up-to-date; "Forecasted" is data created from forecasting models; and "Historic" is data created after an event and is not kept up-to-date), the type of hazard and/or impact (e.g., meteorological, hydrological, hydrogeological, social, infrastructural, urban, rural, environmental, health, property, built environment), and uses within and outside of the Impact Forecasting and Warning Value Chain (Chapter Six; Harrison et al., 2022).

7.6.1.1 Hazard Data

Hazard data refers to meteorological, hydrological, and hydrogeological data. Table 7.4 provides a summary of the hazard data sources identified by our participants. With regards to uses in the Warning Value Chain, each hazard data source listed in Table 7.4 was found to be used for Observation, Monitoring, and Detecting; Hazard Forecasting; Impact Forecasting; Impact Warning.

Our findings indicate that hazard data is quite systematically collected, documented, and used in New Zealand for many purposes by a select group of official agencies (see Table 7.4). For example, meteorological data, such as rainfall, windspeed, radar data, and forecast data are mostly produced, used, and housed by the Meteorological Service of New Zealand (herein referred to as the NZ MetService) and the National Institute of Water and Atmospheric Research (NIWA). The NZ MetService is NZ's appointed National Meteorological Service (NMS) (Williamson, 1998), and NIWA is NZ's Crown Research Institute (CRI) [15] for atmospheric and oceanic science (Steiner et al., 1997). NIWA maintains the national climate database with all the rainfall records and hydrological databases. Fire and Emergency New Zealand

[15] Crown Research Institutes (CRIs) are government owned companies that conduct scientific research in New Zealand (MBIE, 2021).

(FENZ) was also found to collect observational meteorological data for their own operations, which helps them plan responses to wildfires and other weather-related emergencies (EM. NZ. Nat. I).

The NZ MetService has made some of their observation and satellite data freely available (MetService, 2021a; Met. Private NZ. L) for commercial use by private weather forecasting companies, and for stakeholder agencies and researchers to conduct their own analyses, such as risk modelling. Following an impactful event on the Wellington South Coast where large swells and waves damaged houses and evacuations of five properties, arrangements have been made for the NZ MetService and their oceanographic branch (the MetOcean), and NIWA, to provide swell data, wave data, and wave forecast data to the regional EM office for a Significant Wave Warning programme (EM. NZ. Reg. L; WREMO, 2021).

Findings from our interviews indicate that hydrological data is collected, created, and used primarily by local and regional councils in New Zealand. This aligns with the mandated role of local and regional councils under the Resource Management Act 1991, the National Civil Defence Emergency Management Plan 2015, and the Local Government Act 2012, wherein local and regional councils are assigned the responsibility of managing, monitoring, forecasting, and warning for flood hazards, with support from NIWA, the MetService, and EM Groups (Rouse, 2011). Hydrological data includes river height and flow gauges, river camera feeds, river network and watershed data (e.g., spatial shapefiles of rivers, floodplain footprints), overland flow paths, river flow and flood forecast models, etc.

The MetService also forecasts pollen counts for those with allergies. Pollen data is desirable for the public health sector (Health NZ. Reg. A), because pollen was found to play a significant factor in thunderstorm-related asthma attacks (D'Amato et al., 2016). While the MetService provides qualitative pollen forecasts (e.g., "Pollen Levels: Moderate, Type is Plantain"), a public health official from the Waikato Region in NZ expressed a need for quantitative pollen data to model the risk of asthmatic attacks due to pollen and spring thunderstorms (Health NZ Reg. A; Harrison et al., 2022). This need was echoed by a NZ-based pollen scientist for climate change risk assessments (see Sharpe, 2020).

Our interviews identified other creators of relevant hazard data alongside the MetService, NIWA, local/regional councils, and FENZ. Land Information New Zealand (LINZ), the public service department charged with handling geographic information in New Zealand, collects sea level data from float gauges (as do port companies), which is useful for coastal flood hazards (Data Management Gov. NZ. Nat. A); and holds slope data, useful for landslide hazard management and mitigation (Data Management Gov. NZ. Nat. A). LINZ and the Ministry for Environment (MfE) also hold river network data.

Table 7.4. Summary of hazard data sources in New Zealand, identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, type of hazard, and non-IFW uses[16].

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	Type of Hazard	Non-IFW Uses
Weather stations (rain gauges, anemometers, etc.)	Official and unofficial	MetService, FENZ, NIWA, councils, volunteers	[Near] real-time	Meteorological	Research
Radar data	Official	MetService, NIWA, Private industry	[Near] real-time	Meteorological	Research
Satellite imagery & observations	Official	MetService, NIWA, LINZ	[Near] real-time	Meteorological	Research
River height and flow gauges	Official	Regional councils, NIWA	[Near] real-time	Hydrological (e.g. flood)	Research
Float gauges/Sea level data	Official	LINZ, port companies, regional councils, NIWA	[Near] real-time	Hydrological (e.g. flood)	Research
River networks	Official	NIWA, LINZ, Ministry for the Environment, Councils	[Near] real-time	Hydrological (e.g. flood)	Research
Vertical Rain Radar	Official	MetService, Private industry, Healthy Waters Auckland Council	[Near] real-time	Meteorological	Research
Regionwide floodplains footprints/shapefiles	Official	Councils	[Near] real-time	Hydrological (e.g. flood)	Research
Overland flow paths	Official	Councils	Current	Hydrological (e.g. flood)	Research
Coastal inundation maps	Official	Councils	Forecasted	Hydrological (e.g. flood)	Research

[16] The acronyms and abbreviations in Table 7.4 are as follows: Fire and Emergency New Zealand (FENZ), National Institute of Water and Atmospheric Research Ltd (NIWA), Land Information New Zealand (LINZ), New Zealand Meteorological Service (MetService), New Zealand Transport Agency (NZTA), Emergency Management (EM), New Zealand Geographic Information Systems for Emergency Management (NZGIS4EM), MetOcean Solutions (MetOcean).

Data	**Official or Unofficial**	**Data Creators and/or Collectors**	**Timescale**	**Type of Hazard**	**Non-IFW Uses**
Pollen counts	Official	MetService	Forecasted	Health	Research; Response: Preparedness
Slope	Official	LINZ, Councils	Current	Hydrogeological (e.g. landslide)	Research
Camera feeds	Official	Councils, NZTA, Ski fields, Police	Real-time	Meteorological, Hydrological, Hydrogeological (e.g. landslide)	Response; Preparedness; Public Awareness
Social media (Tweets, Facebook post comments)	Unofficial	Creators: public / social media users Collectors: MetService, EM, Researchers, Councils, NZGIS4EM	[Near] real-time	Meteorological, Hydrological, Hydrogeological	Research; Response; Situational Awareness
Crowdsourcing (e.g., volunteer rain gauges, NZ Flood Pics, mPing, WeatheX, European Weather Observer)	Unofficial	Creators: public / social media users Collectors: EM, Researchers, Councils, NZGIS4EM, Volunteers (e.g., NZ Flood Pics)	[Near] real-time	Meteorological, Hydrological, Hydrogeological	Research; Response; Situational Awareness
Forecast data	Official	MetService, MetOcean, NIWA, Councils	Forecasted	Meteorological, Hydrological, Marine/Coastal	Research; Response: Preparedness
National Climate Database	Official	NIWA	Historical	Meteorological, Hydrological	Research

Unofficial data sources were also identified by participants for monitoring hydrometeorological hazards and building situational awareness. For example, the MetService, Civil Defence and Emergency Management (CDEM) Groups, and Local/Regional Councils monitor social media for reports or observations of hydrometeorological hazards (Met. Int. E; EM. NZ. Reg. B, C). From our interviews, we found that none of our participating agencies collect or store social media data for future analysis, citing resource limitations as a key barrier (Met. NZ. F, G, H; EM. NZ. Reg. A, E). Rather, the social media platforms are monitored onscreen for staff to pick up posts or events of interest for further investigation (Met. Int. E; EM. NZ. Reg. B, C). Additionally, one CDEM Group described how they actively request social media users to verify impacts if they can safely do so (EM. NZ. Reg. A). Notable posts may be captured and included in situational reports, but the data usually does not have a use beyond that (EM. NZ. Reg. A, C).

Crowdsourced data was found to be collected through specially designed applications and platforms. In NZ, the West Coast CDEM Group crowdsourced hazard and impact reports using the Esri Story Maps platform (EM. NZ. Reg. C, F). Similarly, the NZ Flood Pics Esri Story Map[17] was set up by a volunteer to collect flood and impact photos during flood events in Auckland and has since been expanded to the rest of NZ (Data Management Private NZ. D). In the USA, the meteorological service collects precipitation data and associated impacts through the mobile application mPing[18] (Met. Int. I). Similarly, in Austria and Australia, the European Weather Observer[19] (Met. Int. E) and WeatheX[20] (Met. Int. B, C) applications respectively are used to collect severe weather reports. These applications gather hazard (and some impact) reports from the public, who have not received any training. The Story Map data usually contains photos with an optional description for the CDEM Group to build their situational awareness (EM. NZ. Reg. F). Alternatively, the specialised applications used in the USA, Austria, and Australia collect more structured data using reporting forms (Met. Int. B, C, E, I). The benefits of the crowdsourced data are that it is timely (Met. Int. E), it may fill in sensor gaps (Met. Int. I), and the applications may increase public awareness and engagement in severe weather hazards (Met. Int. B, C, I). However, maintaining engagement is a challenge and agencies may struggle with receiving reports once contributors have lost interest (Met. Int. E). A gamification element is being considered to maintain interest for contributors of the European Weather Observer (Met. Int. E). Other challenges include quality control and getting buy-in from scientists on the validity of crowdsourced data (Met. Int. E, I).

Meteorological services in the USA and Austria regularly collect reports from storm spotters. The storm spotters can receive training from the meteorological services to increase their credibility. In Austria, the meteorological services offer training and certificates with identification numbers for storm spotters to then register and receive a quality control rating for their reports based on their level of training

[17] http://www.nzfloodpics.co.nz/
[18] https://mping.nssl.noaa.gov/
[19] https://www.essl.org/cms/european-severe-weather-database/ewob/
[20] https://weathex.app/

(Met. Int. E). The meteorological service can then discern the trustworthiness of incoming spotter reports (Met. Int. E). This data is considered highly credible among scientists (Met. Int. E). Furthermore, engagement and awareness are quite high with the "weather enthusiasts" (Met. Int. E). However, connecting with spotters for training remains a challenge (Met. Int. E). The data is also limited in its application for warnings because it is not real-time, thus it cannot be used for real-time warning verification (Met. Int. E). Lastly, storm spotter reports may overlook meteorological phenomena that produce small impacts, a need identified by the US National Weather Service (Met. Int. I).

As reported in a related study (Harrison et al., 2022), much of these datasets are used for steps in the Value Chain for warnings, particularly hydrometeorological Observation, Monitoring, and Detection, Hazard Forecasting, and in some cases Impact Forecasting and Impact Warning. For example, the MetService uses radar and rainfall data to observe, monitor, and detect rainfall amounts, which is then used by regional and local councils to forecast flood hazards (Met. NZ. G). Flood forecasts may then be used to forecast the impacts of the flood, in a quantitative model-based approach, or in a qualitative discussion-based approach, or both (Harrison et al., 2022). Local/regional councils and CDEM Groups may then use these forecasts to inform their flood warning messages, wherein they might include impact-oriented messages (EM. NZ. Reg. H; Kaltenberger et al., 2020).

7.6.1.2 Impact Data

A plethora of impact data were identified in our interviews that are created, collected, and used by different groups for different purposes, as shown in Table 7.5. Impact data is available in a range of official and unofficial capacities.

Impact data is collected, created, and used in an official capacity by CDEM Groups, local/regional councils, FENZ, the lifelines sector (e.g., transportation, power, water/wastewater/stormwater services), the insurance sector (e.g., the Earthquake Commission (EQC), the Accident Compensation Corporation (ACC), the Insurance Council of NZ), and the research sector (e.g., GNS Science, NIWA). The primary purpose of collecting the impact data is not for severe weather forecasts and warnings, but for response, recovery, mitigation, and planning. Depending on the quality of the data, it could be used for additional purposes such as impact forecasting and warning. For example, emergency call centre (i.e., 111 calls in NZ) reports incite responses from the appropriate authorities (e.g., FENZ, police). Afterwards, weather-related emergency reports can be used for post-event analysis to verify and improve warnings (Met. NZ. G; Harrison & Johnson, 2016).

Insurance claims from property damage and injuries are used for recovery and produce rich datasets for future analysis such as risk/loss modelling (Loss Modelling Research NZ. A), which may inform impact forecasts. Likewise, impact assessments conducted by CDEM Groups are primarily used for building situational awareness to inform response efforts (EM. NZ. Reg. H; NEMA, 2020a) and can also be used for warning verification and warning updates in real-time (EM. NZ. Reg. H).

Table 7.5. Summary of impact data sources identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, uses in the IFW Value Chain, type of impact, and non-IFW uses[21].

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Tweets	Unofficial	Public / social media users	MetService, CDEM, Researchers, Councils, NZGIS4EM	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Facebook Post comments	Unofficial	Public / social media users	MetService, CDEM, Researchers, Councils, NZGIS4EM	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
SnapChat Heat Maps	Unofficial	Public / social media users	MetService, CDEM, Researchers, NZGIS4EM	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Crowdsourced Photos via Story Maps (e.g., NZ Flood Pics)	Unofficial	Public / social media users	MetService, CDEM, Researchers, Councils, NZGIS4EM, Volunteers (e.g., NZ Flood Pics)	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness

[21] The acronyms and abbreviations in Table 7.5 are as follows: Fire and Emergency New Zealand (FENZ), National Institute of Water and Atmospheric Research Ltd (NIWA), New Zealand Meteorological Service (MetService), New Zealand Transport Agency (NZTA), Emergency Management (EM), New Zealand Geographic Information Systems for Emergency Management (NZGIS4EM), Insurance Council of New Zealand (ICNZ), Accident Compensation Corporation (ACC), Institute of Geological and Nuclear Sciences Limited (GNS Science), Statistics New Zealand (Stats NZ), Earthquake Commission (EQC), National Emergency Management Agency (NEMA) Real-time Individual Asset Attribute Collection Tool (RiACT).

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Crowdsourcing / Public Reporting	Unofficial	Public	Councils, CDEM, Volunteers	Current, maybe near real-time	Observation, Monitoring, and Detecting; Hazard Forecasting; Impact Forecasting; Impact Warning	Built environment, infrastructure	Response; Situational Awareness; Recovery; Planning; Mitigation; Public Awareness / Engagement / Education
Red Cross Chained Crowdsourcing	Unofficial	Public	Red Cross	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Response; Situational Awareness
Emergency call centre reports	Official	Public	Police, FENZ	[Near] real-time & Historic?	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Community volunteer radio calls	Unofficial	Designated community volunteers	EM, Councils	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Response; Situational Awareness
Damage surveys (e.g. aerial surveys, building surveys via Survey123, QuickCapture, RiACT, Kobo 2, etc.)	Official	Councils, Researchers (NIWA, GNS Science, Universities), CDEM	Councils, Researchers (NIWA, GNS Science, Universities), CDEM	Historic	Impact Forecasting; Impact Warning	Urban, Rural, Infrastructural	Research; Response; Situational Awareness; Recovery; Mitigation; Land use planning and development policies

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Media reports	Unofficial	Media outlets	Councils, Researchers (NIWA, GNS Science), CDEM, MetService	[Near] real-time	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Tacit knowledge, experience, intuition	Official	Councils, CDEM, MetService	Councils, CDEM, MetService	Available in real-time, based on historic knowledge and experience	Impact Forecasting; Impact Warning	Urban, Rural, Environmental	Response; Situational Awareness
Health & Injury Data	Official	District Health Boards, ACC, Stats NZ	District Health Boards, ACC, Stats NZ	Historic	Impact Forecasting; Impact Warning	Health	Research; Response; Recovery; Planning and Mitigation
Wellbeing Surveys	Official	CDEM, Councils	EM, Councils	Historic	Impact Forecasting; Impact Warning	Social, Health, Property	Response; Situational Awareness; Recovery
Post-event interviews and surveys	Official	Researchers (e.g. NIWA, GNS Science, other), EM	Researchers (e.g. NIWA, GNS Science, other), EM	Historic	Impact Forecasting; Impact Warning	Social	Response; Mitigation; Preparation
Insurance claims	Official	Insurance companies, EQC, ICNZ	Insurance companies, EQC, ICNZ	Historic	Impact Forecasting; Impact Warning	Property, Health, Economic	Research; Recovery; Mitigation
"Boots on the ground"	Official	Councils, CDEM	Councils, CDEM	[Near] real-time	Impact Forecasting; Impact Warning	Urban, Rural, Environmental	Response; Situational Awareness

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Lifelines Sectors (e.g. power companies, NZTA)	Official	Lifelines Services (e.g., NZTA, Transpower, KiwiRail), councils, wastewater services	Lifelines Services (e.g., NZTA, Transpower, KiwiRail), councils, wastewater services	[Near] real-time	Impact Forecasting; Impact Warning	Infrastructural	Response; Situational Awareness; Recovery; Business As Usual; Research
Council Requests For Service (RFS)	Official	Public	Councils	[Near] real-time	Impact Forecasting; Impact Warning	Infrastructural; Property; Urban; Rural; Environmental	Situational Awareness; Response; Recovery
Situational Reports	Official	CDEM, Councils	CDEM, Councils	Current	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Built Environment	Response; Situational Awareness; Recovery; Research
Post-event reports	Official	NEMA, CDEM Groups, Councils	NEMA, CDEM Groups, Councils	Historic	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Built Environment	Recovery; Mitigation and Planning; Research
Operations Reports (Council)	Official	Councils	Councils	Historic	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Response; Situational Awareness; Recovery; Research
Flood event reporting	Official	Councils, Healthy Waters Auckland Council/Councils	Councils, Healthy Waters Auckland Council/Councils	Historic	Observation, Monitoring, and Detecting; Impact Warning	Infrastructural, Urban, Rural Environmental	Response; Situational Awareness; Research; Mitigation; Land use planning and development policies

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Injuries and fatalities (e.g., cause of death)	Official	ACC, Coronial Services of New Zealand, Stats NZ	ACC, Coronial Services of New Zealand, Stats NZ	Historic	Impact Forecasting; Impact Warning	Health	Response; Situational Awareness; Research; Mitigation
Cultural and heritage / historical impacts	Official	Councils	Councils	Historic	Impact Forecasting; Impact Warning	Social, Cultural	Research; Planning; Mitigation
Impact Model outputs	Official	GNS Science, NIWA, Researchers	GNS Science, NIWA, Researchers	Historic, Rapid	Hazard Forecasting; Impact Forecasting	Social, infrastructure, built environment, hydrological, hydrogeological, urban, rural, Property, Economic	Response; Research; Planning; Mitigation
NEMA National Loss Database	Official	CDEM Groups	NEMA	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Sendai Framework Reporting
NIWA NZ Historic Events Catalogue	Unofficial	Media outlets	NIWA	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Research; Mitigation
Local Council Databases	Official	Councils	Councils	Historic	Impact Forecasting; Impact Warning	Hydrological, Hydrogeological, Property, Urban, Rural, Infrastructural, Built Environment	Response; Situational Awareness; Recovery; Mitigation

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Storm Data (USA)	Official	Meteorological services, Responders, Emergency Services, Storm Spotters, media outlets	National Centers for Environmental Information	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Research; Mitigation
European Severe Weather Database	Official	Meteorological services, Responders, Emergency Services, Storm Spotters, media outlets	European Severe Storms Laboratory	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Research; Mitigation

Impact assessments for CDEM Groups in NZ have evolved with the advancements of GIS-based technology for improved data capture and management (EM. NZ. Reg. C, H, F; Data Management Private NZ. B). An overview of how GIS tools were used for a flood event in NZ's West Coast region was provided by Stowell (2020). Officials used rapid data collection tools such as Survey123[22] and QuickCapture[23] to collect impact information. QuickCapture was primarily used for collecting photos from aerial and ground assessments, while Survey123 was used to complete form-based assessments (Stowell, 2020). The value of these tools lies in the seamless integration process of the field data directly into a GIS layer for real-time viewing in an Emergency Operations Centre (EOC) (EM. NZ. Reg. C, H, F; Data Management Private NZ. B). However, the pitfalls of these collection methods are that information overload can occur with applications like QuickCapture if the trained staff take a large volume of photographs, and gaps in training can lead to errors in the data, which may skew datasets (EM. NZ. Reg. F).

Tacit knowledge and experience refer to knowledge held by official staff from past experiences who apply this knowledge when planning for or responding to events. NZ participants described how senior EM staff know from past events that certain river levels and peaks will lead to respective levels or types of impacts (EM. NZ. Reg. A, B). This knowledge is passed on verbally either just before or during an event to help with response planning and coordination (EM. NZ. Reg. A, B). The same was found to be true for the Lifelines sector, who "have a good amount of data but … more importantly …, their staff have a very good historical knowledge" (Lifelines NZ. Reg. A). This information is highly trusted as it is based on years of experience. It allows agencies to learn from past events and better prepare for current or future events (EM. NZ. Reg. B).

In many cases this tacit knowledge and experience is not formally documented and there is a risk of losing this knowledge when staff move on (EM. NZ. Reg. A, C; Lifelines NZ. Reg. A). As one participant identified: "[hazard and impact forecasting are] primarily based on history and knowledge. And with that comes the risk … if you have key people out of the equation or people move on … in life, then you have the knowledge gap until such time as that's filled" (EM. NZ. Reg. C). Upon identifying this vulnerability, this participant indicated that their agency has begun some historical cataloguing (EM. NZ. Reg. C).

[22] Survey123 is a location-based application developed by Esri (Esri, n.d.-b) that is used for completing assessment forms such as impact assessment forms, building assessment forms, and welfare needs assessment forms (EM. NZ. Reg. F).
[23] QuickCapture is another location-based field observation application developed by Esri (Esri, n.d.-a) that is particularly useful for taking photographs of damage/impacts and uploading in real-time to be viewed on a dashboard in the Emergency Operations Centre (EM. NZ. Reg. F).

Unofficial impact data/information also helps EMs "build a picture of what's happening" (EM. NZ. Reg. C). Unofficial data includes social media posts, crowdsourced and citizen science data, media reports, and community volunteer radio calls. Interviewees were found to obtain information from Facebook, Twitter, and SnapChat. In most cases, the interviewees indicated that they do not collect or store social media data, but only monitor it for situational awareness and real-time verification. The value of social media appears to lie in its ability to indicate potential hot spots early on in an event and building situational awareness (Met. Int. E; EM. NZ. Reg. C). Social media sentiment analysis can also help to understand the cultural impacts of severe weather and communicate the warnings better (Met. Int. D). However, interviewees use social media data with caution, indicating that while social media data is timely and quantitatively rich, it is difficult to verify (EM. NZ. Reg. B). Relying solely on social media risks missing or overlooking impacted people who are not on social media, such as areas without power or internet access (EM. NZ. Reg. B). Thus, social media data should be used complementarily with other data (Met. Int. D).

Impact databases were also found to exist or be under development. In NZ, the National Emergency Management Agency (NEMA) is developing a national loss database in fulfilment of the Sendai Framework priorities (UNDRR, 2015b). Data is pulled from EM impact assessments, situational reports, and post event reports (EM. Gov. NZ. Nat. G). NIWA hosts a catalogue of historic severe weather events in NZ using media reports (Met. Research NZ. J), primarily for research purposes. Storm Data in the USA and the European Severe Weather Database contain data sourced from storm spotters and impact assessments from storms in the USA and Europe (Met. Int. E, I). These American and European databases are highly credible as only vetted and trusted information goes in (Met. Int. E, I). Unfortunately, the databases are not updated in real-time due to the rigorous quality control measures and may have gaps for small impact events (Met. Int. E, I).

Most of the data sources described above capture direct and physical impacts such as damages to the built and natural environment and do not capture social human impacts or indirect impacts. This is a major gap identified in a previous study (Harrison et al., 2022). Wellbeing surveys and post-event surveys from research studies capture indirect impacts to people's health and social/cultural wellbeing (EM. NZ. Reg. F, H; Risk Modelling NZ. B, C). Wellbeing surveys (also referred to as Needs Assessments and Welfare surveys) are conducted by CDEM Groups and/or health agencies to understand the needs and impacts of people affected by an emergency (MCDEM, 2015; Nielsen, 2017). Furthermore, District Health Boards, ACC, and Stats NZ collect and house health, injury, and mortality data for their own purposes (EM. Gov. NZ. Nat. G; Loss Modelling Research NZ. A). In the context of severe weather IFWs, these data, along with the Wellbeing surveys conducted by EM/councils, could be useful for understanding indirect and social and cultural impacts to inform impact warning messages (EM. Gov. NZ Nat. G; Loss Modelling Research NZ. A; Harrison et al., 2022).

7.6.1.3 Vulnerability Data

Our participants identified some vulnerability data sources, as shown in Table 7.6. As stated in our literature review, vulnerability data is more difficult to obtain or create, as vulnerability changes over space and time. On their own, many of the identified data sources in Table 7.6 do not provide an indication of vulnerability. Rather, these data sources are inputs into vulnerability assessments and risk models. For example, census data and health data may be used to conduct a social vulnerability assessment, while building damage assessments are inputs into vulnerability functions for risk modelling (Harrison et al., 2022; Tarbotton et al., 2015). The results of the vulnerability assessment or risk model then help analysts identify vulnerable areas:

> Everything's built off the models … we've identified … issues with care homes and areas, hotspots in the community which could potentially … be at risk …We've got them in … behind the stop banks, bungalows, probably not the best place for them but they're there. So just being aware of those [vulnerable areas] (Hyd. Gov. NZ Reg. A).

Asset information refers to characteristics of the asset for which the vulnerability is being assessed. These can be people, buildings, roads, stop banks, the environment, etc. The asset information of buildings would include data on the age of the building, the construction material, and number of floors (Risk Modelling NZ. B). This information is collected through building assessments by building engineers (Risk Modelling NZ. B). Alternatively, asset information of people consists of demographic data, health data, socioeconomic data, etc. (Risk Modelling NZ; Terti et al., 2015), available from Stats NZ and the Ministry of Health. Asset information about stop banks includes age and condition and is held by local and regional councils (Hyd. Gov. NZ. Reg. A).

An additional challenge with using census data identified by our participants is the spatial scale. The NZ census data is at the meshblock[24] scale, but risk modellers want to model at the building scale. Participating risk modellers questioned how they can interpolate the census data with the building level (Risk Modelling NZ. A, B).

Health data is another indicator of human vulnerability. The impacts of severe weather events can exacerbate underlying health conditions. For example, people with asthma may experience exacerbated symptoms while cleaning up damaged and contaminated sites after a flood (Risk Modelling NZ. C), or during thunderstorms (Health NZ. Reg. A; Harrison et al., 2022). In NZ, District Health Boards (Health NZ. Reg. A) and the Ministry of Health house this data. The Ministry of Health conducts an annual national Health Survey of NZ.

[24] According to Stats NZ (2021), "[a] meshblock is defined by a geographic area, which can vary in size from part of a city block to a large area of rural land."

Table 7.6. Summary of vulnerability data sources identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, uses in the IFW Value Chain, type of impact, and non-IFW uses[25].

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	IFW Uses (from the Value Chain)	Type of Impact	Non-IFW Uses
Vulnerability Assessment and Risk Modelling Outputs	Official	Councils, Researchers (NIWA, GNS Science), CDEM, Hired contractors	Historic	Impact Forecasting; Impact Warning	Property, human, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Planning; Mitigation; Research
Asset Information	Official	Councils, Researchers (NIWA, GNS Science), CDEM, Hired contractors	Historic	Hazard Forecasting; Impact Forecasting; Impact Warning	Property, human, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Planning; Mitigation; Research
Building damage assessments	Official	Councils, Researchers (NIWA, GNS Science), CDEM, Hired contractors	Historic	Hazard Forecasting; Impact Forecasting; Impact Warning	Property	Response; Situational Awareness; Recovery; Research; Mitigation
Census data	Official	Stats NZ	Historic	Hazard Forecasting; Impact Forecasting	Human	Research; Business As Usual (BAU)

[25] The acronyms and abbreviations in Table 7.6 are as follows: National Institute of Water and Atmospheric Research Ltd (NIWA), Emergency Management (EM), Institute of Geological and Nuclear Sciences Limited (GNS Science), Statistics New Zealand (Stats NZ), Ministry of Health (MOH), District Health Boards (DHBs).

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	IFW Uses (from the Value Chain)	Type of Impact	Non-IFW Uses
Tacit knowledge, experience, intuition	Official	Councils, CDEM	Available in real-time, based on historic knowledge and experience	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Response; Situational Awareness; Preparedness; Mitigation; BAU
Lab-based experiments	Official	Researchers (NIWA, GNS Science, universities)	Historic	Hazard Forecasting; Impact Forecasting	Built environment	Research
Health Data, New Zealand Health Survey	Official	MOH, DHBs	Historic	Impact Forecasting. Impact Warning	Health	Research; Recovery
Infrastructure	Official	Councils, contractors	Historic	Hazard Forecasting; Impact Forecasting; Impact Warning	Built environment, infrastructure	Response; Situational Awareness; Recovery; Planning; Mitigation
Soil/land stability	Official	GNS Science	Historic?	Observation, Monitoring, and Detecting; Hazard Forecasting; Impact Forecasting	Hydrogeological; Built environment, infrastructure, Environment, Property	Planning; Mitigation; Research

Like impact data, vulnerability data is also present as tacit knowledge and experience. As previously mentioned, infrastructure engineers and other asset managers possess a wealth of knowledge and experience around the performance capacities of a building, levy, or other piece of infrastructure. In the risk modelling space, this tacit knowledge, or expert opinion is a valid resource for building vulnerability functions:

> If you are an asset manager and you know about your port or your wharf … and you just intuitively think about … if a six-meter wave came in what do you think would happen? … you can elicit information that way. And there's a lot of vulnerability functions out there that are done that way because you don't need an event to happen. And I guess there is a certain level of knowledge and intuition that can go into these things … So you can do some kind of estimate (Risk Modelling NZ. A).

CDEM Groups possess tacit knowledge around vulnerable areas, people, and communities within their jurisdiction (Hyd. Gov. NZ. Reg. A; Auckland Workshop), but our participants indicated that they still need to know "who is where and what their mobility/health/access considerations are" (Auckland Workshop). Some of this information is available through pre-existing networks with EM services that manage relationships with vulnerable communities, such as the "Caring for Communities" government work programme that was established in response to COVID-19[26], and through Welfare coordination groups (Auckland Workshop). However, there is a risk of missing people who are not "in the system" (Auckland Workshop). Furthermore, privacy concerns exist when considering alternative uses for the data beyond its initial purpose, which is usually to support response and recovery (Auckland Workshop; EM. NZ. Reg. H; EM. Gov. NZ. Nat. G). Yet, even this tacit knowledge can still help EM groups formulate their warning messages (EM. NZ. Reg. H).

All datasets listed in Table 7.6 are produced and housed in an official capacity. Our interviews did not find any instances where crowdsourcing or other unofficial methods were used for producing vulnerability data. Some research has been done to use crowdsourcing applications for capturing vulnerability. For example, in Kazakhstan Fdez-Arroyabe et al. (2018) developed mobile application (OxyAlert) where users can answer questions about their health status relative to their geographic location and atmospheric conditions to characterise individual vulnerability to meteorological changes. Hung and Chen (2013) presented a new participatory mapping methodology for incorporating stakeholder's participation, local knowledge, and locally spatial characteristics for vulnerability assessments of flood risk. These studies demonstrate the untapped opportunity to use crowdsourcing and other engagement activities to produce localised or individualised vulnerability assessments.

[26] https://ipanz.org.nz/Article?Action=View&Article_id=150258

7.6.1.4 Exposure Data

The dynamic nature of exposure data also makes it difficult to collect and maintain. However, our participants identified some existing and potential sources of exposure data for different uses and with different time scales, summarised in Table 7.7. Most of the data sources are classified as official, as they are produced by official agencies.

Asset footprints refer to the geographical location of assets, such as buildings, historically and culturally significant sites, etc. These data are officially produced by local/regional councils, LINZ, and FENZ. They are also available on unofficial platforms like Google Maps and OpenStreetMap[27]. This location-based data helps EMs and researchers identify assets that are potentially exposed to a hazard.

Exposure is typically determined by overlaying the asset information with hazard information (Risk Modelling NZ. C). This is common practice for disaster and climate change mitigation. For example, Paulik et al. (2020) created a national-scale built environment exposure model to extreme sea level rise for NZ by overlaying buildings, infrastructure, and built land area with a Digital Elevation Model and coastal flood maps. Similarly, Bell et al. (2016) compared urban and rural exposure to coastal hazards using demographic data overlaid with building, infrastructure, and land assets. Their results provided counts of people, building, infrastructure, and land assets located in areas exposed to coastal hazards. While these exposure models and their outputs help to locate and quantify exposed people and assets to a given hazard, the results of these models represent one point in time. Thus, they do not accurately represent the dynamic nature of exposure.

Other data sources can capture dynamic exposure, such as live traffic flows from transportation agencies (e.g., the New Zealand Transport Agency) (Data Management Gov. NZ. Nat. A; Met. NZ. K). Cell phone data was also discussed for capturing population shifts (Risk Modelling NZ. A; Data Management Gov. NZ. Nat. E). For example, Data Ventures, a commercial data brokerage branch of Stats NZ, used cell phone data to produce population densities at the Statistical Area 2 level (a higher scale than the Meshblock level) for a given time range[28].

[27] OpenStreetMap is a form of geographic crowdsourcing in which volunteers digitize features of the earth onto an online map of the world. This data is produced under a Creative Commons license, thus making it open-source and freely available for download.
[28] See https://population-density.dataventures.nz/explorer2/help/index.html for more.

Table 7.7. Summary of exposure data sources identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, uses in the IFW Value Chain, type of impact, and non-IFW uses[29].

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	IFW Uses (from the Value Chain)	Type of Impact	Non-IFW Uses
Asset footprints (e.g., building, cultural and historical site locations)	Official and unofficial	Councils, Google Maps, OpenStreetMap, LINZ, FENZ, Heritage NZ, Iwi	Historic	Hazard Forecasting; Impact Forecasting	Property, Cultural, Social	Response; Research; BAU; Mitigation
Infrastructure networks, e.g., transportation networks, traffic flows, power & water supplies	Official	Lifelines Services (e.g., NZTA, Transpower, KiwiRail), local & regional councils	Current	Hazard Forecasting; Impact Forecasting	Infrastructural	Response; Situational Awareness; BAU
Census data	Official	Stats NZ	Historic	Hazard Forecasting; Impact Forecasting	Human	Research; BAU
Population movement via cell phone data	Official	DataVentures / Stats NZ	Historic and [Near] real-time?	Hazard Forecasting; Impact Forecasting; Impact Warning	Human	Research

[29] The acronyms and abbreviations in Table 7.7 are as follows: Fire and Emergency New Zealand (FENZ), National Institute of Water and Atmospheric Research Ltd (NIWA), New Zealand Transport Agency (NZTA), Institute of Geological and Nuclear Sciences Limited (GNS Science), Statistics New Zealand (Stats NZ), Ministry of Business, Innovation, and Employment (MBIE).

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	IFW Uses (from the Value Chain)	Type of Impact	Non-IFW Uses
Tacit knowledge, experience, intuition	Official	Councils, CDEM	Available in real-time, based on historic knowledge and experience	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Response; Situational Awareness; Preparedness; Mitigation; BAU
Topographical data, e.g., digital elevation models	Official	LINZ, Landcare Research, Universities, GNS Science, NIWA	Historic	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Rural, Urban, Environmental	Response; Situational Awareness; Research; BAU
Land-use	Official	Councils, LINZ	Historic	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Rural, Urban, Environmental	Response; Situational Awareness; Research; BAU
Community events	Official	MBIE, Stats NZ, Local and regional cultural and tourism agencies (e.g., Auckland Unlimited)	[Near] real-time	Hazard Forecasting; Impact Forecasting; Impact Warning	Cultural, Social	Response; Situational Awareness; BAU

This product became useful in the COVID-19 response where Data Ventures provided near real-time population movements to the National Crisis Management Centre which "provided [a] very close to real time view of whether or not people were following the advice" (Data Management Gov. NZ. Nat. E), which informed advice to the Prime Minister's COVID-19 advisory group "about whether or not we move or shift down levels of lockdown" (Data Management Gov. NZ. Nat. E). Through this, they were also able to determine "whether or not people were moving from one region to another because that's really how you have that wider contagion risk" (Data Management Gov. NZ. Nat. E). This has potential application in an IFW system for identifying the "catchment of individuals" (Data Management Gov. NZ. Nat. E) in near real-time for more contextualised warnings. However, this data alone does not provide an overall risk indication; "you have to put other layers of information to go 'well if it's a … category 5 [ex-tropical cyclone] then are the buildings of a particular standard and … how many people are in the areas that those buildings are present in'" (Data Management Gov. NZ. Nat. E). Hence the need for vulnerability information as previously discussed.

Knowledge of dynamic human exposure can also come from knowing about community events (Auckland Workshop). A regional EM official in NZ identified the need for "real-time understanding of what is going on in the community (i.e., sports events, hotel capacity, etc.)" (Auckland Workshop). In this case, the regional council's economic and cultural department possesses this knowledge and information (Auckland Workshop) and should be shared with the EMs and other agencies such as the MetService who would need to be aware of events if severe weather were to occur.

7.6.2 Data Creation, Collection, and Use

Discussions with participants revealed several inhibitors and facilitators to collecting, creating, and using the data. Using the ES-GT coding paradigm, we identified the causal conditions driving data collection, creation, and use, intervening conditions to this phenomenon, and actions and strategies that have been used to address those intervening conditions (Figure 7.1). The causal conditions are presented next.

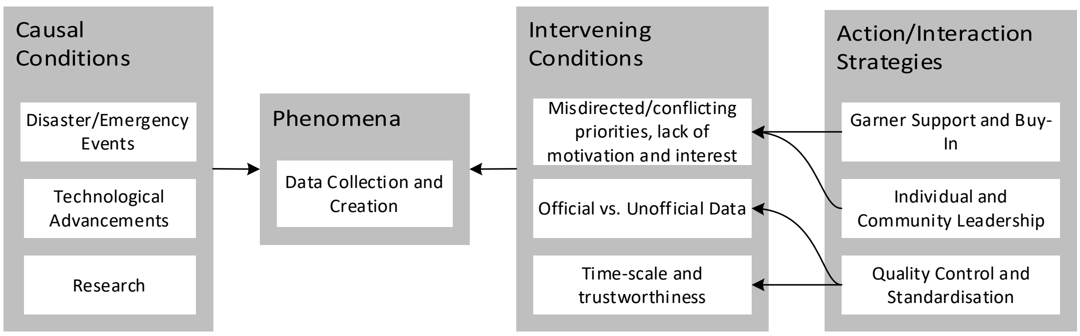

Figure 7.1. Results of applying the coding paradigmto understand the causal conditions, intervening conditions, and action/interaction strategies for HIVE data creation, collection, and use phenomenon as defined in Table 7.3. Causal conditions are the drivers of the phenomena. Intervening conditions inhibit or facilitate the phenomena. Action/interactions strategies were identified to address the intervening conditions.

7.6.2.1 Causal Conditions

Causal conditions were identified as drivers for agencies collecting and using HIVE data in general for different purposes and via different methods. The main causal conditions identified by participants are: (1) Disaster/emergency events, (2) technological advancements, and (3) Research.

Other factors can also be attributed to HIVE data collection, such as existing policies and plans (e.g., the National Disaster Resilience Strategy) within NZ, and international initiatives such as the Sendai Framework. For the purposes of this study, we have decided to focus these current findings on the causal conditions that participants identified more directly.

Disaster/Emergency Events

Our participants gave examples of how the creation, collection, and use of HIVE data has been driven by past disaster/emergency events. Following the 2010-2011 Canterbury earthquake sequence there was a need for data on the damaged buildings, such as their age, construction material, and level of damage to inform recovery (Risk Modelling NZ. B). At the time, no database existed for building characteristics (e.g., history, age, construction material) (Risk Modelling NZ. B). Consequently, engineers had to "go through one by one to record the location and age … of the material" before they could conduct the damage assessments (Risk Modelling NZ. B). This experience, where decision-makers were caught scrambling for data, revealed a need for building up databases for future events (Risk Modelling NZ. B; EM. NZ. Reg. H).

This and other major events resulted in the formation of a Technical Advisory Group (TAG) by the Ministry of Civil Defence and Emergency Management (now the National Emergency Management Agency or NEMA), in 2017 (Treadgold et al., 2018). The TAG conducted a Ministerial Review and provided several recommendations for better intelligence gathering (i.e., data collection) (Technical Advisory Group, 2017). A participating regional EM official cited this review as a driver for their council and EM Group attempting to improve their data collection efforts for disaster response (EM. NZ. Reg. H). Additionally, in response to two back-to-back ex-tropical cyclones that resulted in disastrous flooding, the Bay of Plenty region EM Group now updates exposure maps for tropical cyclone hazards annually (EM. NZ. Reg. A).

Technological Advancements

Technological advancements, particularly the implementation of geospatial technologies such as Geographic Information Systems (GIS), cloud-based services, and the proliferation of mobile devices with cameras and an internet connection have also driven efforts for better collection of HIVE data. For example, one participant described Esri's ArcGIS Online product as the "catalyst" for using geospatial technologies for emergency response (EM. NZ. Reg. H). The cloud-based aspect of the ArcGIS Online product supports rapid development and sharing of maps and other geospatial applications, which is seen as the most valuable feature for emergency response (EM. NZ. Reg. H). As such, "the strength of the NZGIS4EM [New Zealand Geographic for Emergency Management] community really … is built upon that. And … there's … been continual growth with event after event" (EM. NZ. Reg. H). Furthermore, this cloud-based technology used in combination with mobile devices using applications like QuickCapture and Survey123 allowed for the redevelopment of how rapid impact assessments conducted for more efficient and timely data collection. For example, with Survey123, "the fieldworker hits submit, that assessment will instantly show up on the map [in the Emergency Operations Centre]" to display the level of damage and safety of the buildings (EM. NZ. Reg. H).

Research

Research has also driven the collection of HIVE data. For example, NIWA's NZ Historic Events Catalogue[30] was initially developed for research interests, where "people realised that it would be really good to have this database for people and researchers, and just sort of give an idea of what historically has happened ... And I think it's been quite useful" (Met. Research NZ. J). Other HIVE data has been collected to support the research and development of risk models (Risk Modelling NZ. B).

7.6.2.2 Intervening Conditions for Data Creation, Collection, and Use

Intervening conditions were found to affect whether HIVE data is collected, and the choice for which data source is used. Herein we focus on three intervening conditions: (1) Priorities, motivation, and interest; (2) Official and unofficial data; (3) Timescale and trustworthiness.

Priorities, motivation, and interest

Conflicting priorities and a lack of motivation or interest in data creation and maintenance was a barrier identified by several participants for gathering HIVE data (EM. Gov. NZ. Nat. G; Data Management Gov. NZ. Nat. A; Data Management Private NZ. B; Data Management Research NZ. C; EM. NZ. Reg. D). Management priorities and the personal interests of key staff within an organisation appear to either inhibit or enable data collection and creation, as one NZ risk modeller summarised: "it just depends on who's here and who's leading the team" (Risk Modelling NZ. A).

The National Emergency Management Agency (NEMA) for New Zealand reports losses and impact to the UNDRR in fulfilment of Sendai Framework priorities. Their goal is to develop a national loss and impact database (EM. Gov. NZ. Nat. G). However, progress on this front is slow as NEMA is continuously busy responding to other events and so is unable to direct resources towards developing a national loss and impact database (EM. Gov. NZ. Nat. G). This may be due to the reactive nature of the EM sector (Kox, Lüder, et al., 2018), where agencies lack the time or resources to establish proper data collection and management practices (EM. Gov. NZ. Nat. G; Loss Modelling Research NZ. A; EM. NZ. Reg. A, B, H; Data Management Private NZ. B; Hyd. Gov. NZ. Reg. A).

[30] https://hwe.niwa.co.nz/

Official and unofficial data

The leading mandate of many of the participating agencies is to preserve life and property, be it through designing and issuing warnings (e.g., NMSs, warning services) or coordinating emergency response plans and actions (EM agencies). A key role for these agencies is providing the voice of truth during a severe weather event. These agencies must maintain a high level of credibility and trustworthiness amongst the public and stakeholders to ensure that their messages are heeded (NMS. Int. C, D, E; NMS. NZ). Since these agencies use a plethora of data to communicate critical information and alerts to the public, trust in the supporting information underpinned all discussions with participants.

Official and unofficial datasets and sources were discussed and compared with interviewees. Interviewees showed a preference for official datasets and sources because of their role as an authoritative voice in saying "this is what happened" or may happen (NMS. Int. C). However, collecting and using official data is not always possible. For example, agencies who possess the data may be unable or unwilling to share (NMS. Int. C), or agencies may need real-time data, which is rarely official or trusted (NMS. Int. D). In these cases, agencies may need to turn to unofficial data sources such as crowdsourcing and social media (NMS. Int. C).

Time scale and trustworthiness

Forecasting impacts in real-time or near real-time for early warning is an operational goal (Aldridge et al., 2016; Hemingway & Robbins, 2019). Thus, our participants identified a need for real-time or near real-time data (Met. Int. E; EM. NZ. Reg. H; Risk Modelling NZ. C, D; Data Management Private NZ. B). Potential real-time data sources that were identified are crowdsourcing, social media, and mobile tracking data. Aside from the mobile tracking data these sources are unofficial data sources, resulting in decreased perceptions of trust and credibility in the data (Met. NZ. H; Met. Int. D, I). As such, our results indicate trustworthiness, and the timescale needs appear to be two intervening conditions in the choice and use of a data source. A tension appears to exist between these two conditions, as officials (e.g., warning agencies, emergency managers, responders) have a need for both timely and trustworthy data, but often have to compromise on either factor (Mehta et al., 2017).

Distrust is a critical obstacle to warning adherence (Covello & Sandman, 2001). Thus, it is not surprising that trust in the data and in the sources to support IFWs is a primary driver in deciding which impact, exposure, and vulnerability dataset/source to use. It is important that warning officials perceive the data as trustworthy (Terti et al., 2019), as this will ensure that public trust in the agency and in the warnings is maintained. Different uses of impact, exposure, and vulnerability data require varying levels of trustworthiness.

The timescale needed also determines the most appropriate dataset. We found that some data sources, like crowdsourcing and social media, fill a gap in the need for real-time or near real-time data for verification, situational awareness, and response. This finding supports those of a recent survey of European NMSs (Kaltenberger et al., 2020). However, these data may be less useful for defining impact thresholds and informing impact/risk models due to the perceived limited quality and trustworthiness. For example, social media data appeared to be less trustworthy amongst participants because it is difficult to vet and lacks structure needed for forecasting and modelling (Met. NZ. G, H). However, social media remains useful for building situational awareness quickly and updating alerts (EM NZ Reg. C; Harrison & Johnson, 2016).

7.6.2.3 Action/Interaction Strategies

Action/interaction strategies were found to address the intervening conditions previously identified. The three strategies we focused on here are: (1) Garnering support and buy-in, (2) Individual and community leadership, and (3) Quality control and standardisation.

Garnering support and buy-in

Garnering support and buy-in was found to be an action/interaction strategy for overcoming conflicting management priorities or a lack of motivation and interest. One regional EM official has been pushing for a GIS-based approach for improved intelligence gathering, management, sharing, etc., but has faced resourcing challenges. The first "informal" (EM. NZ. Reg. H) stage of this project "didn't turn out to be sustainable because we had a lot of issues with trying to carve out time from people to actually contribute to it" (EM. NZ. Reg. H). As such, they developed a "more formal" (EM. NZ. Reg. H) strategy to approach decision-makers for support for resource allocation across regional stakeholders/agencies (EM. NZ. Reg. H). Efforts for garnering support are still underway (EM. NZ. Reg. H).

Individual and community leadership

Individual and community leadership was found to be another action/interaction strategy for overcoming misdirected management priorities and lack of motivation or interest. Some regional agencies have improved their own data collection practices based on the leadership of their in-house GIS and EM experts. For example, the West Coast CDEM Group regularly develops innovative ways for using GIS-based technology to carry out impact assessments (EM. NZ. Reg. C, F; see Stowell, 2020). Furthermore, the emergence of the NZGIS4EM[31] group has been identified by participants as a major driver for technological advancement and for pushing the needle forwards on creating, sharing, and accessing geospatial data and tools for emergency response

[31] NZ Geographic Information Systems for Emergency Management (NZGIS4EM) is a grassroots community of GIS specialists and EM practitioners in NZ that began working together in the mid-2010's to identify how they could build and use geospatial tools for better emergency response (EM. NZ. Reg. H).

(EM. NZ. Reg. H; Data Management Gov. NZ. Nat. A; Data Management Private NZ. B; EM. NZ. Reg. D).

This innovative GIS-based work is credited to specific individuals within the sector who possess a passion and expertise to drive these efforts (Data Management Private NZ. B; EM. NZ. Reg. B, F). Furthermore, the innovation may also be due to available resources and support from management. Our findings align with the Policy Capacity Framework (Wu et al., 2018) which outlines three levels of capacity development and implementation: individual, organisation, and systemic; and three dimensions: analytical, managerial, and political. The individuals accredited with driving the GIS4EM movement in NZ appear to possess analytical, managerial, and political acumen capacity at the individual level by possessing analytical, technical, communication, and leadership skills to drive technological innovation within their sector. Agencies like the West Coast CDEM Group possess technical and administrative capacity at the organisational level by providing and coordinating the resources needed to allow the individuals to implement their innovative solutions. More investigation is needed to understand the policy capacities at the systemic level and political dimension within the NZ EM and severe weather warning space. However, it appears that the GIS movement within NZ's EM sector has reached central government decision-makers with the recent release of the *Impact Assessments Director's Guideline for Civil Defence Emergency Management Groups [DGL 22/20]* by NEMA (2020a). This guidance document outlines the role of GIS and supporting spatial tools for undertaking impact assessments.

Quality control and standardisation

Participating agencies emphasised the importance of applying quality control measures to increase perceived trustworthiness of the data. Some quality control measures that came up in the conversations included vetting the source(s) of the data, training storm spotters, cross-validating between sources for accuracy, timing, and location. For example, the NMSs in the USA and Austria train and vet storm spotters so that they can trust incoming ground observations (Met. Int. E, I; Kaltenberger et al., 2020; Krennert, Kaltenberger, et al., 2018). Standardised post-event damage/impact assessments collected by those trained to, and entered into a database for further analysis, may be more suitable for needs that do not require real-time data (Kaltenberger et al., 2020).

7.7 Conclusions and Limitations

Documenting hazard, impact, vulnerability, and exposure data fulfils needs for IFWs, and meets Sendai Framework priorities for improved understanding of disaster risks and subsequent mitigation and reduction. The New Zealand focus of this research further supports an identified need for better risk data for modelling and natural hazard management in New Zealand.

In this exploratory study we identified sources for hazard, impact, vulnerability, and exposure data for implementing severe weather IFW systems. Our findings indicate that many sources for hazard and impact data exist that are collected for other uses (such as for response efforts for disaster and emergency events, and for research) and have relevant application for IFWs. Furthermore, underlying datasets for vulnerability and exposure exist and are available. Technological advancements have also enabled the collection and creation of HIVE data, such as GIS-based tools and mobile devices.

We also identified intervening conditions, and action/interaction strategies for collecting HIVE data, as shown in Figure 7.1. Our findings suggest that priorities, motivation, and interest within organisations influence how well data is collected and used. Furthermore, agencies tend to prefer official data, but official data has limitations that unofficial data can sometimes address, such as timeliness. To that end, a tension exists between the timeliness and trustworthiness of data needed for emergency response and warnings.

To address these intervening conditions, we identified some action/interaction strategies using Grounded Theory. Garnering support and buy-in from decision-makers and upper management within an agency can redirect priorities and increase motivation and interest in collecting HIVE data. Individual and community leadership within the field of practice also provides a bottom-up approach for driving industry priorities and practices for collecting HIVE data. Furthermore, measures for quality control and data standardisation may improve the perceived trustworthiness of the data.

The qualitative nature of data collection and analysis herein limits the generalisability of results beyond the interviewees. However, the qualitative approach offers in-depth understanding of a problem not readily available from quantitative approaches (Blumer, 1969; Miles & Huberman, 1994; Patton, 2002). Furthermore, participant recruitment and data collection methods were affected by the COVID-19 pandemic response, as many individuals and agencies targeted for recruitment were involved in the response. As such, some perspectives may be missing from the qualitative dataset.

Discussions with colleagues in the field pointed towards the value of mātauranga Māori (Māori knowledge) in understanding disaster risk and impacts in New Zealand. Considerations about cultural ownership of such knowledge and its use in an impact forecasting and warning system is thus an important area for future research.

Findings from this research provide insight into the drivers and barriers for collecting hazard, impact, vulnerability, and exposure data in New Zealand. Sources of such data were identified such that practitioners and researchers may seek out these datasets if so desired. Further questions remain around how the data can be accessed and acquired for use in an IFW system. Future research should explore the data acquisition process for these datasets.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Eight: **'Sharing is caring': A socio-technical analysis of the sharing and governing of hydrometeorological impact data in Aotearoa New Zealand**

This chapter presents the fourth manuscript for this doctoral study prepared for publication. The focus of this paper is on accessing and managing hazard, impact, vulnerability, and exposure data for severe weather hazards. Following discussions with participants, and during the Grounded Theory analysis process (Strauss & Corbin, 1990), data governance, management, access, and sharing emerged as important themes that influence the use of hazard, impact, vulnerability, and exposure (HIVE) data.

From Chapter Seven we now know that many sources of HIVE data exist and have identified the need to investigate governance and accessibility of these data. To that end, this chapter focusses on the following objectives of this doctoral thesis: 4.1 Identify and understand the governance and access and sharing processes of HIVE data for severe weather hazards in New Zealand; 4.2 To support efforts to fulfil the Sendai Framework priorities around disaster data access; and 4.3 To support the implementation of a severe weather IFW system.

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The published form is available in Appendix M.

Chapter 8: 'Sharing is caring': A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand

8.1 Abstract

There has been a growing recognition of the need to collect disaster and risk data over the last two decades. Accordingly, better collection and management of disaster data was identified as a priority of the Sendai Framework for Disaster Risk Reduction. The introduction and implementation of Impact Forecasts and Warnings (IFWs) have further highlighted this need to collect and access hazard, impact, vulnerability, and exposure (HIVE) data. However, challenges have been met with reporting and using disaster data, which have resulted in an identified need to establish principles for data collection, recording, reporting, exchange/sharing, and comparability. This introduces the concept of data governance and management for disaster data, particularly with regards to data custodianship, stewardship, and sharing. Using Grounded Theory, a series of interviews were conducted with users and creators of HIVE data to develop further understanding around managing and accessing it for severe weather hazards in New Zealand. A socio-technical lens guided the analysis to identify the organisational and technical intervening conditions and action/interaction strategies for accessing and sharing HIVE data in NZ.

Findings indicated that there is a need to establish data governance principles for HIVE data. An additional need was identified for nurturing partnerships to continue building trust between stakeholders for sharing data. Furthermore, integration challenges continue to interfere with the use of various sources of HIVE data for effective risk and impact assessments for IFWs and beyond. Systematic and standardised data collection approaches using GIS-based tools can support integration. Introduction

8.2 Introduction

There has been a growing need to collect disaster and risk data over the last two decades (e.g., Guha-Sapir & Below, 2000). Accordingly, better collection and management of disaster data was identified as a priority of the Sendai Framework for Disaster Risk Reduction (UNDRR, 2015b). In response, global initiatives now exist with the objective of developing technical guidance for building up disaster and risk data, such as the Integrated Research on Disaster Risk (IRDR) programme and subsequent workshops (Clarke et al., 2018; Fakhruddin et al., 2017). The introduction and implementation of Impact Forecasts and Warnings (IFWs) for hydrometeorological hazards (e.g., WMO, 2015) has further highlighted the need to collect and access relevant disaster data for mitigation and prevention; namely hazard, impact, vulnerability, and exposure (HIVE) data (Harrison et al., 2022; Potter et al., 2021). However, challenges have been met with reporting and using disaster data, such as the fact that many stakeholders are involved in the collection, creation, and use of disaster data, making it difficult to integrate different data sources and perform comparative analyses (Díaz & Ferrer, 2018). These challenges have resulted in an identified need to establish principles and standards for data collection, recording, reporting, exchange/sharing, and comparability (Fakhruddin et al., 2017). This introduces the concept of data governance for disaster data (Clarke et al., 2018; Li et al., 2019; Migliorini et al., 2019), particularly with regards to data custodianship, stewardship, and sharing (Plotkin, 2020; Zaidi, 2012).

Building on recent research where we identified the data needs, uses, and sources of HIVE data for implementing hydrometeorological IFW systems in Aotearoa-New Zealand (see Harrison et al., 2021; Harrison et al., 2022), we aim to develop further understanding around managing and accessing these data sources. We begin by presenting background on data governance and management, and data access and sharing, where data accessibility can affect data sharing (OECD, 2019).

8.2.1 Data Governance

Data governance is an emerging field of research, with no agreed-upon definition (Al-Ruithe et al., 2018). We adopt the definition provided by Benfeldt et al. (2019, p. 299) where "data governance refers to the organisation and implementation of rules and responsibilities, which enforce decision making and accountabilities regarding an organisation's data assets." This is different from data management, which focuses on defining the data element, and how it is stored, structured, and moved (Al-Ruithe et al., 2018). Thus, data governance is argued to be a higher level of "planning and control over data management" (Al-Ruithe et al., 2018, p. 841).

There has been little mention of governance for disaster loss data in the disaster risk reduction (DRR) literature, except when it is pointed to as a need to improve data quality, access, sharing, and interoperability (e.g., Clarke et al., 2018; Li et al., 2019; Migliorini et al., 2019). Clarke et al. (2018, p. 4) proposed that data governance and independence be established for "strengthening and protecting data quality through national statistical offices that are functionally autonomous from other government agencies." Migliorini et al. (2019) identified a lack of appropriate data governance arrangements to be impeding data access for DRR. Similarly, Li et al. (2019) identified issues around data governance when using population health data for disaster risk research. In NZ, Crawford et al. (2018) identified challenges with risk data collection due to unclear roles and responsibilities for doing so. Beyond these examples, we could not find studies that specifically investigated disaster data governance, despite the apparent need to establish appropriate data governance measures for improved data quality, sharing, and integration.

One element of data governance involves assigning roles and responsibilities, including decision rights and accountabilities, around how the data is managed, secured, validated, and made available (Al-Ruithe et al., 2018; Alhassan et al., 2019; Benfeldt et al., 2019). Two such roles are data stewardship and data custodianship (Zaidi, 2012). Often these roles may be confused or merged, however, they have distinct roles and responsibilities, discussed next.

8.2.1.1 Data stewardship and custodianship

Data stewardship and data custodianship relate to roles for managing data. In the context of health data, data stewardship consists of developing methods for "acquisition, storage, aggregation, deidentification, and procedures for data release and use" (Rosenbaum, 2010, p. 1444). Similarly, the NZ Government defines a data steward as an agency that operates at the systems and strategic level and promotes good practice to manage the data over its lifecycle, including planning and adjusting for technological obsolescence and long-term preservation and access (LINZ, 2014b; Secretary of Cabinet, 2011). Related, but distinct roles, are data custodians. For NZ government data these custodians are agencies that implement the data management practices stipulated by data stewards in daily practice (Secretary of Cabinet, 2011) to ensure the quality and accessibility of the data (LINZ, 2014b).

In NZ, several agencies have a data stewardship and/or custodianship role. Toitū Te Whenua Land Information New Zealand (LINZ; the government agency responsible for managing land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, etc.) provided a *Steward and Custodian Framework for New Zealand Fundamental Geospatial Themes and Dataset*s, to outline the responsibilities and expectations of appointed custodians and stewards of fundamental geospatial data (see LINZ, 2014b). LINZ also provided a partner document outlining the process of identifying and selecting fundamental geospatial data (see LINZ, 2014a). In summary, datasets are proposed to the New Zealand Geospatial Office for evaluation against a set of criteria to classify it as a fundamental geospatial dataset (LINZ, 2014a). Fundamental geospatial datasets are "datasets that provide the minimum core set of nationally-significant data that are critical to the effective running of [NZ], and work together to help support growth in the economy" (LINZ, 2014a, p. 4). Most of these fundamental geospatial datasets are not considered disaster datasets as they do not convey disaster losses, impacts, or risks. However, much of these underlying datasets can inform vulnerability and risk assessments when used in risk models and overlaid with hazard data to determine exposure (see Harrison et al., 2021).

The fundamental geospatial datasets identified by LINZ are labelled as either Suggested (i.e., the agency suggested by LINZ has not yet agreed to the role and may not have been approached yet), Proposed (i.e., the suggested agency has agreed to the role but the commitment has not yet been formalised), Appointed (i.e., the proposed agency has formally committed to the role), or Not Evaluated (i.e., the datasets were proposed as fundamental datasets but were not yet evaluated to determine their status) (LINZ, 2014a). For example, the Waka Kotahi NZ Transport Agency (NZTA) is the proposed custodian for the leadership and delivery of the national road network, while local government and territorial authorities are the suggested respective leadership and delivery custodians for council roads. Leadership Custodians ensure that appropriate data management policies and standards are developed while Delivery Custodians are "responsible for the continued physical existence, availability, and integrity of the dataset" for as long as is required by the leadership custodian (LINZ, 2014b, p. 25).

Like disaster data governance, there is little mention of the stewardship of disaster data in the literature. This gap has been identified by Fakhruddin, Murray, et al. (2019) who identified the need for building capacity in data collection and stewardship to support reporting to the Sendai Framework, an international accord outlining global priorities for disaster risk reduction (DRR) (UNDRR, 2015b). Another challenge faced in DRR is accessing and sharing the required data (Fakhruddin, Chu, et al., 2019) for emergency/disaster response, risk analysis (e.g., risk modelling and risk assessments), vulnerability assessments, and supporting IFWs (Harrison et al., 2021).

8.2.2 Data Access and Sharing

Many stakeholders are involved with DRR who collect, produce, and manage their datasets. Access to and sharing of these datasets is necessary for DRR (Fakhruddin, Murray, et al., 2019). For example, in places like Europe with many countries sharing borders, it is important to be able to share data across borders (De Groeve, 2015). Within a country, sharing data is important since, in many cases, disaster and risk data are collected by different agencies (Harrison et al., 2021). Data access refers to the retrieval and storage of data provided by the data holder and may be subject to technical, legal, and/or organisation requirements (OECD, 2019). Data sharing is the voluntary provision of data by the data holder, including commercial and non-commercial conditional data sharing agreements (OECD, 2019). Data accessibility is a spectrum, ranging from closed data to open data, and affects data shareability (OECD, 2019). Data sharing is a socio-technical activity as it involves various parties forming data-sharing partnerships and technical systems to support integrating multiple datasets.

8.2.2.1 Organisational Aspects of Data Access and Sharing

Sharing disaster and risk data requires building partnerships between data stakeholders (Fakhruddin, Chu, et al., 2019). The Natural Hazards Partnership (NHP) is an example of a formal partnership developed in the UK between public agencies to improve disaster management across the country, including sharing data between the various agencies (Hemingway & Gunawan, 2018). Building the NHP required extensive time, coordination, communication, and interaction between agencies (Hemingway & Gunawan, 2018).

Multi-organisational collaboration is wrought with challenges (Sonnenwald, 2007). Building trust and increasing the willingness of organisations to participate is the first hurdle to overcome (Sonnenwald, 2007). After this, new challenges include mutually identifying goals and objectives and agreeing on timelines, uses of differing terminology and epistemologies, legal issues around intellectual property, and developing workflows and communication standards (Sonnenwald, 2007). These early stages of scouting and building trust can take years (Sonnenwald, 2007). Sustaining collaboration (e.g., maintaining interest and securing funding sources) remains an ongoing challenge (Hemingway & Gunawan, 2018; Sonnenwald, 2007). In addition to building partnerships to share data, technical solutions are needed to enable data integration.

8.2.2.2 Technical Aspects of Data Access and Sharing

Data integration and interoperability are important, yet challenging, technical factors that support data sharing for DRR (Fakhruddin, Chu, et al., 2019). Disaster and risk data are available in countless formats, making integration difficult (Horita et al., 2017). Thus there is a need to understand the various data sources and how they can be effectively and efficiently used (Horita et al., 2017).

Interoperability is a familiar challenge for both EWSs and data sharing and integration (Botterell, 2006; Horita et al., 2015). Interoperability issues for EWSs emerged as technological advancements led to a plethora of warning delivery mechanisms (Botterell, 2006). The Common Alerting Protocol (CAP) was proposed to set standards for warning design and delivery (Botterell, 2006). The CAP relies on standardising warning data for sharing across platforms (OASIS, 2010; Rebelo Moreira et al., 2018). The introduction of IFWs further adds to the challenge of standardised data exchanges (Kaltenberger et al., 2020; Potter et al. 2020).

In NZ the Canterbury earthquakes from 2010-2011 laid bare gaps in interoperability for data sharing during and after the disaster, and the need for standards-based interoperability for improved information and data management (Treadgold et al., 2018). Furthermore, the NZ Civil Defence and Emergency Management (CDEM) sector is striving towards a Common Operating Picture (COP) in which all agencies and stakeholders involved in an event can access and view the same information (Department of the Prime Minister and Cabinet, 2018). This involves developing standards and capabilities for enabling access to and sharing of datasets (Treadgold et al., 2018).

Harrison et al. (2021) identified and reported the various sources for HIVE data for hydrometeorological hazards in New Zealand (NZ). While the data sources were identified, more understanding is needed around managing and accessing these data both for IFW systems and for general DRR (Harrison et al., 2021).

The objectives of this research are to identify and understand the governance and acquisition process for hazard, impact, vulnerability, and exposure (HIVE) data for hydrometeorological hazards in NZ, to support efforts to fulfil the Sendai Framework priorities around disaster data access and to support the implementation of a hydrometeorological IFW system.

8.3 Research Methods

We used a qualitative approach to address the research question, specifically employing the Evolved-Straussian Grounded Theory (ES-GT) research strategy for data collection and analysis (Corbin & Strauss, 2015). Interviews, workshops, and key documents were the primary data sources. Between November 2018 and April 2021, the lead author interviewed thirty-nine (n=39) experts in weather forecasting, warning, emergency management, risk modelling, and data collection and management (see Harrison et al., 2022 for more information on the participant details). Three virtual workshops were held in NZ. Two of these workshops involved Emergency Management (EM) practitioners, weather forecasters, communication and data specialists, and hydrologists from the Auckland (n=4) and Southland (n=5) Regions. The third workshop involved a portion of the NZ risk and hazard science community based at GNS Science (n=11). Thus, 59 people participated in this research.

Interview questions and workshop activities focused on themes regarding IFW data needs and sources. We asked for participants' general thoughts on IFWs; what impact, vulnerability, and/or exposure data they use or need, why, and how; the life path of the data; experienced and/or perceived challenges obtaining data required for IFWs and other uses; and thoughts on collecting and using alternative data sources (e.g., social media and crowdsourcing). Findings around data governance and acquisition are reported in this paper.

This research was collected under a 'low risk' ethics notification with the Massey University Human Ethics Committee. All interviewees remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by the area of expertise and/or practice, industry, location, or governance level (Table 8.1). Interviews were audio-recorded and transcribed verbatim, and qualitative analysis (including coding and memo-writing) followed the axial coding paradigm according to the ES-GTM (Corbin & Strauss, 2015), using NVivo 12 qualitative analysis software (Bergin, 2011).

Table 8.1. Interviewee Codes.

Interview Code	Position	Classification	Location	Government Level
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ	National
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ	National
Data Management Private NZ. B	Geospatial Specialist	Data Management	NZ	Private
Data Management Research NZ. C	GIS Specialist	Data Management	NZ	Private
Data Management Private NZ. D	GIS Specialist	Data Management	NZ	Private
Data Management Gov. NZ. Nat. E	Head of Data	Data Management; Governance	NZ	National
EM. NZ. Reg. A	Director	Emergency Management	NZ	Regional
EM. NZ. Reg. B	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. C	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ	Regional
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ	Regional
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ	National
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Nat. I	First Responder	Emergency Management	NZ	National
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ	National
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ	Regional
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ	Regional
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ	Regional
Hyd. Gov. NZ. Reg. A	Flood EWS Programme manager	Hydrology; Governance	NZ	Regional

Interview Code	Position	Classification	Location	Government Level
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ	Regional
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ	Private
Met. Int. A	Science Manager	Meteorology	International	National
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	International	National
Met. Int. C	Senior Policy Officer	Meteorology	International	National
Met. Int. D	Senior Social Scientist	Meteorology	International	National
Met. Int. E	Consultant Meteorologist	Meteorology	International	National
Met. NZ. F	Senior Meteorologist	Meteorology	NZ	National
Met. NZ. G	Communications	Meteorology	NZ	National
Met. NZ. H	Public Relations	Meteorology	NZ	National
Met. Int. I	Division Chief/Meteorologist	Meteorology	International	National
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ	National
Met. NZ. K	Senior Meteorologist	Meteorology	NZ	National
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ	Private
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ	National

Per ES-GT, analysis of the interviews, workshops, and documents followed the open coding (assigning concepts and categories to an instance of the data by line or by word), axial coding (relating categories to each other with option guidance from the coding paradigm), and selective coding (relating all categories to a core category) stages (Strauss & Corbin, 1990). The coding paradigm introduced by Strauss and Corbin (1990) supported the axial coding stage whereby the codes created from the open coding stage were related to the coding paradigm dimensions (Table 8.2) for increased density and precision.

Additional techniques were used to support the ES-GT analysis, including regular memo-writing, diagramming, and constant comparison (Glaser & Strauss, 1967). When the lead author noticed common themes in the interview and workshop data, a memo was written to identify the theme and discuss its relation to other concepts or themes (i.e. constant comparison) (Corbin & Strauss, 2015; Glaser & Strauss, 1967). Diagramming was used to draw out linkages or relationships between the emerging themes. This was an iterative process that occurred during the data collection and analysis.

Table 8.2. Coding paradigm summary (from Harrison et al., 2022).

Coding Paradigm Dimension	Description
Causal Conditions	A set of events that influence the phenomena or result in the appearance or development of a phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Phenomena	The subject or object under study (Strauss & Corbin, 1990).
Contextual Conditions	The specific set of conditions and characteristics surrounding the phenomena and resulting in action/interaction strategies taken to address the phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Intervening Conditions	Unexpected events or factors leading to action/interaction strategies (e.g., time, space, culture, socioeconomic status, technological status, history) (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Action/Interaction Strategies	Purposeful and deliberate acts taken to address the phenomena (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).
Consequences	Predictable or unpredictable, intended or unintended outcomes of the action/interaction strategies (Strauss & Corbin, 1990; Vollstedt & Rezat, 2019).

From the axial coding process (summarised in Table 8.2), two phenomena related to data management and acquisition of hazard, impact, vulnerability, and exposure data were identified. Phenomena are the subjects or objects under study (Strauss & Corbin, 1990). Impact forecasts and warnings and HIVE data were identified as the overarching phenomena being studied in this research. As data collection and analysis progressed, the two phenomena that became the focal point of this manuscript were identified from the themes that emerged in the interviews, memo-writing, diagramming, and constant comparison techniques previously described.

These two phenomena are: (1) The Roles and Responsibilities of Data Custodianship, and (2) Data Access and Sharing. These are discussed next.

8.4 Findings and Discussion

Through ES-GT two key themes (or phenomena) related to data management and acquisition for hazard, impact, vulnerability, and exposure data were identified: (1) The Roles and Responsibilities of Data Custodianship, and (2) Data Access and Sharing. These themes were succinctly summarised by an NZ-based risk modeller, who said:

I think it really comes down to … sharing and collaboration … and I think there are good efforts, but … often things get snagged in … a privacy or confidentiality or legal issues with the datasets, who owns them, who maintains them, how can you rely on them ... And the amount of work that is required to produce and maintain a reliable dataset is massive, it's just so much work that people don't want to do it. It costs money, it costs time, and … being a custodian of a dataset is not really an enviable position, necessarily. I think that's probably one of the biggest barriers (Risk Modelling NZ. A). These two phenomena (the roles and responsibilities of data custodianship, and data access and sharing) will each be discussed in turn.

8.4.1 The Roles and Responsibilities of Data Custodianship

Amongst participating agencies and countries, it remains unclear as to who is responsible for maintaining datasets for IFWs:

> … it's a little bit about our traditional remits just being on the hazards information and so insurance companies and other areas are associated with damage and loss. And now … the challenge is accessibility to the data. So, we don't necessarily need to or want to become custodians of new data sets, we're just keen, if someone's got it organised and has it, to be able to … bring it together with our hazard information and our forecasting capability (Met. Int. B).

The responsibility and cost of collecting and storing HIVE data were concerns for participants. Many of the agencies' remits do not include data custodianship, and it would be a costly undertaking, with the uncertainty of maintaining funding (Met. Int. B; Met. NZ. F).

While the literature has pointed to EM agencies for collecting impact information (e.g., Kox, Lüder, et al., 2018; Potter et al., 2021), we found that the participating NZ-based CDEM Groups indeed collect impact information, but they often do not systematically collect it or store it (EM. NZ. Reg. A, B). These findings corroborate those of Crawford et al. (2018), who found that EM agencies and councils in NZ were not clear on who was responsible for collecting risk data. For example, regarding the NZ National Loss Database under development by the National Emergency Management Agency in NZ (NEMA), our participant indicated that NEMA is not a designated data custodian in NZ, and as such, they have been grappling with learning proper data management protocols (EM. Gov. NZ. Nat. G). This raises questions around who is most suitable for managing and acting as the steward and/or custodian of the data.

Several data custodians were identified in passing during our interviews, which align with some that have been identified by LINZ (2014a), such as LINZ, the NZTA, and local councils. For example, a risk modeller who was involved in collecting building asset information for the 2011 Canterbury earthquake recovery described how maintenance responsibilities for these data were transferred to LINZ due to privacy concerns:

> because there's some personal information in the database … that we didn't pay attention [to] previously … but to protect us from now on, we say 'okay this is the data we give [to] LINZ, you guys take the data … and you … decide if you want to share the data or not' (Risk Modelling NZ. B).

Similarly, for the development and management of the NZ National Loss Database, NEMA has turned to Statistics New Zealand (typically referred to as Stats NZ, New Zealand's national statistics agency) for guidance on proper data management protocols:

> Stats NZ … have helped us think about this, but it's their business. So, for example, we talked about data management, and they talked about, 'okay if you're holding that data then you need to run an integrity test, that your data hasn't become corrupted, and you do that every [so often]. And you've got enough backups and all that … but we haven't got an explicit data management policy around ensuring it's not corrupt, its integrity … change controls, and all that tracking; that's not what we do (EM. Gov. NZ. Nat. G).

In addition to being the national statistics agency for NZ, Stats NZ also became the lead agency for government-held data in 2017 (Stats NZ, 2019). In this leadership role Stats NZ acts as a facilitator to support government agencies in building their capabilities and data management practices (Stats NZ, 2019). Thus, their help in guiding NEMA towards proper data management practices for the National Loss Database aligns with their role as the lead for government data. The Stats NZ website[32] provides further guidance on principles for safe and effective use of data and analytics, data stewardship, data standards, open data, etc.

Several of the HIVE datasets that were identified by Harrison et al. (2021) have been classed as fundamental geospatial datasets by LINZ and have an appointed, proposed, or suggested data custodian and steward. Table 8.3 presents the Suggested (S), Proposed (P), or Appointed (A) Stewards and Custodians of the HIVE data sets identified by Harrison et al. (2021) from our interviews as designated by LINZ (2014a) The results in Table 8.3 are based on an analysis of two LINZ documents regarding data custodianship (see LINZ, 2014a, 2014b).

[32] https://www.stats.govt.nz/about-us/data-leadership. Accessed 7 July 2021.

Table 8.3. Suggested (S), Proposed (P), or Appointed (A) Stewards and Custodians of the HIVE data sets identified by Harrison et al. (2021) from our interviews as designated by LINZ (2014a)[33]. N/A is used for datasets that were not proposed as fundamental datasets (note that any person or agency can propose a fundamental geospatial dataset (LINZ, 2014a)), and thus a steward and custodian was not identified. The number of N/A entries demonstrates a lack of direction for managing impact data.

	Dataset	*Status*	*Steward*	*Leadership Custodian*	*Delivery Custodian*
Hazard Data	Weather stations (rain gauges, anemometers, etc.)	N/A	N/A	N/A	N/A
	Radar data	N/A	N/A	N/A	N/A
	Satellite imagery & observations	Fundamental, Not evaluated	LINZ (A)	LINZ (S), NZDF (S), TAs (S), Police (S)	LINZ, NZDF, TAs, Police, MfE, Landcare (S)
	River height and flow gauges	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S)	RCs (S)
	Float gauges/Sea level data	N/A	N/A	N/A	N/A
	River networks	Fundamental	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S)
	Vertical Rain Radar	N/A	N/A	N/A	N/A
	Regionwide floodplains	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S), GNS (S), RCs (S), TAs (S)
	Overland flow paths	N/A	N/A	N/A	N/A
	Coastal inundation Maps / Hazards	Not evaluated	Steward Committee (S) or MPI (S), DoC (S)	MfE (S)	RCs (S), GNS (S)
	Pollen Counts	N/A	N/A	N/A	N/A
	Slope	N/A	N/A	N/A	N/A
	Camera feeds	N/A	N/A	N/A	N/A
	Social media (Tweets, Facebook post comments)	N/A	N/A	N/A	N/A
	Crowdsourcing (e.g., volunteer rain gauges, NZ Flood Pics)	N/A	N/A	N/A	N/A

[33] The acronyms in Table 8.3 are as follows: Land Information New Zealand (LINZ), New Zealand Defence Force (NZDF), Territorial Authorities (TAs), Ministry for the Environment (MfE), National Institute of Water and Atmospheric Research Ltd (NIWA), Ministry of Primary Industries (MPI), Institute of Geological and Nuclear Sciences Limited (GNS Science), Regional Councils (RCs), Department of Conservation (DoC), Ministry of Business, Innovation and Employment (MBIE), Local Government New Zealand (LGNZ), Statistics New Zealand (Stats NZ), New Zealand Transport Agency (NZTA), National Emergency Management Agency (NEMA, formerly MCDEM), Local Government Geospatial Alliance (LGGA).

	Dataset	*Status*	*Steward*	*Leadership Custodian*	*Delivery Custodian*
Impact Data	Social media (Tweets, Facebook post comments, SnapChat)	N/A	N/A	N/A	N/A
	Crowdsourced Photos via Story Maps (e.g., NZ Flood Pics)	N/A	N/A	N/A	N/A
	Crowdsourcing / Public Reporting	N/A	N/A	N/A	N/A
	Red Cross Chained Crowdsourcing	N/A	N/A	N/A	N/A
	Emergency call centre reports	N/A	N/A	N/A	N/A
	Community volunteer radio calls	N/A	N/A	N/A	N/A
	Damage surveys	N/A	N/A	N/A	N/A
	Media reports	N/A	N/A	N/A	N/A
	Tacit knowledge, experience, intuition	N/A	N/A	N/A	N/A
	Health & Injury Data	N/A	N/A	N/A	N/A
	Wellbeing Surveys	N/A	N/A	N/A	N/A
	Post-event interviews and surveys	N/A	N/A	N/A	N/A
	Insurance claims	N/A	N/A	N/A	N/A
	"Boots on the ground"	N/A	N/A	N/A	N/A
	Lifelines Sectors (e.g., power companies, NZTA)	N/A	N/A	N/A	N/A
	Situational Reports	N/A	N/A	N/A	N/A
	Post-event reports	N/A	N/A	N/A	N/A
	Operations Reports (Council)	N/A	N/A	N/A	N/A
	Flood event reporting	N/A	N/A	N/A	N/A
	Injuries and fatalities (e.g., cause of death)	N/A	N/A	N/A	N/A
	Cultural and heritage / historical impacts	N/A	N/A	N/A	N/A
	Impact Model outputs	N/A	N/A	N/A	N/A
	NZ National Loss Database	N/A	N/A	N/A	N/A

	Dataset	*Status*	*Steward*	*Leadership Custodian*	*Delivery Custodian*
Vulnerability Data	Vulnerability Assessment and Risk Modelling Outputs	N/A	N/A	N/A	N/A
	Asset information - Building footprints	Fundamental	LINZ (A)	MBIE (S)	TAs (S), NZFS (S), MBIE (S)
	Asset information - Historically and Culturally Significant Sites	Not evaluated	Steward Committee (S) consisting of LINZ (S), LGNZ (S), Emergency Services (S)	LINZ (S), LGNZ (S)	LINZ (S), TAs (S), Private Sector (S)
	Building damage assessments		N/A		
	Census data - meshblocks	Fundamental	Stats NZ	Stats NZ	Stats NZ
	Tacit knowledge, experience, intuition	N/A	N/A	N/A	N/A
	Lab-based experiments	N/A	N/A	N/A	N/A
	Health Data, New Zealand Health Survey	N/A	N/A	N/A	N/A
	Soil/land stability	Fundamental	No Steward	LINZ (S), GNS (S), Landcare (S)	LINZ (S), GNS (S), Landcare (S)
	Infrastructure - NZ Road Network	Not evaluated	Ministry of Transport	NZTA (P)	NZTA (P)
	Infrastructure - Council roads	Not evaluated	Ministry of Transport	LGNZ (S)	TAs (S)
	Infrastructure - Water	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S), LINZ (S), RCs (S), TAs (S)

	Dataset	*Status*	*Steward*	*Leadership Custodian*	*Delivery Custodian*
Exposure Data	Asset information - Building footprints	Fundamental	LINZ (A)	MBIE (S)	TAs (S), NZFS (S), MBIE (S)
	Asset information - Historically and Culturally Significant Sites	Not evaluated	Steward Committee (S) consisting of LINZ (S), LGNZ (S), Emergency Services (S)	LINZ (S), LGNZ (S)	LINZ (S), TAs (S), Private Sector (S)
	Infrastructure - NZ Road Network	Not evaluated	Ministry of Transport	NZTA (P)	NZTA (P)
	Infrastructure - Council roads	Fundamental	Ministry of Transport	LGNZ (S)	TAs (S)
	Infrastructure - Power - Electricity	Not evaluated	No Steward	Transpower (S)	Transpower, Lines Companies
	Infrastructure - Utility Networks	Not evaluated	No Steward	MCDEM/NEMA (S)	Utility Companies (S)
	Infrastructure - Water	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S), LINZ (S), RCs (S), TAs (S)
	Census data - meshblocks	Fundamental	Stats NZ	Stats NZ	Stats NZ
	Population movement via cell phone data	N/A	N/A	N/A	N/A
	Tacit knowledge, experience, intuition	N/A	N/A	N/A	N/A
	Topographical data, e.g. digital elevation models	Not evaluated	No Steward	MfE (S), LINZ (S)	Landcare (S), LINZ (S)
	Land-use and planning zones	Not evaluated	No Steward	LGGA (S), LGNZ (S)	TAs (S), RCs (S)
	Land-use maps	Fundamental	No Steward	MfE (S)	MfE (S)
	Community events	N/A	N/A	N/A	N/A

The results in Table 8.3 show that stewardship/custodianship for most of the underlying datasets for hazards, vulnerability, and exposure have been identified by LINZ and are either Suggested (S), Proposed (P), or Appointed (A), while there is a clear a gap in the stewardship/custodianship of impact data, as shown by the number of 'N/A' entries for these datasets. This, in conjunction with our interviews, shows the need for establishing data management protocols and practices for impact data, including identifying potential data stewards and custodians for these data, such that the data can be accessed by and shared with other relevant users.

8.4.2 Data Access and Sharing

Data access and sharing was the next key theme or phenomena identified in our data analysis. The ES-GT coding paradigm was applied to understand the causal and intervening conditions, and action/interaction strategies for data access and sharing, as shown in Figure 8.1.

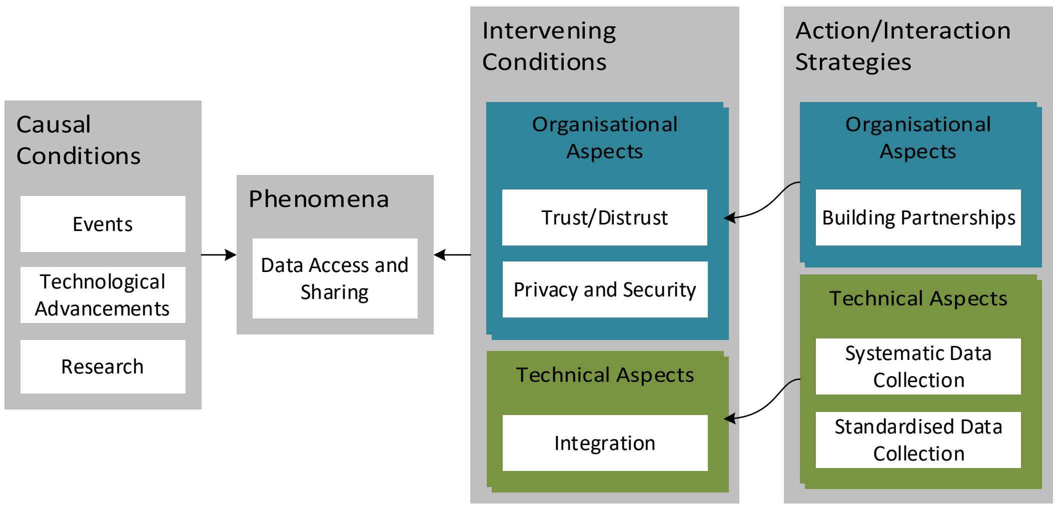

Figure 8.1. Summary of findings relating to the causal conditions, intervening conditions, and action/interaction strategies relating to data access and sharing, identified using the ES-GTM coding paradigm. Blue boxes represent organisation aspects and green boxes represent technical aspects.

As discussed by Harrison et al. (2021)[34], disaster/emergency events, technological advancements, and research were identified as the causal conditions to data collection and data access and sharing. For example, sharing data was required for the response to the 2019 Pigeon Valley fires in Nelson, NZ, yet organisational and technical issues impeded the data sharing process (Data Management Gov. NZ. Nat. A). However, as shown in Figure 8.1, intervening conditions can inhibit data sharing and access while several action/interaction strategies have been identified as capable of addressing these intervening conditions. These conditions and strategies will be discussed next.

8.4.2.1 Organisational Aspects of Data Access and Sharing

Trust and distrust, and privacy and security were identified as organisational intervening conditions affecting data sharing. Building partnerships was identified as an organisational action/interaction strategy to address these intervening conditions. These will be discussed next.

Trust and Distrust as Intervening Conditions

Trust is a key element to data use and access. While Harrison et al. (2021) identified the importance of trust in the data for IFWs, here we found the need for trust between agencies to be an important condition for data access and sharing, as summarised by a NZ risk and data specialist:

> There's a lot of suspicion between institutions in New Zealand as to what people are doing things for and why and with this comes patch protection. This is an important point and that it inhibits risk awareness, collaboration and our risk management as a country (Data Management Private NZ. D).

The management of the NZ Flood Pics[35] crowdsourcing platform and access to its resulting data is an example of an initiative established to avoid suspicion and lack of institutional trust, according to one of our interviewees (Data Management Private NZ. D). They described that NZ Flood Pics was developed independently from any institutions, and there is an aversion to tying the platform to any single institution even though that would make available the resources needed to sustain the platform. This aversion stems from the need for the data to remain open and separate from any "ulterior motives" (Data Management Private NZ. D). They indicated that institutionalising the platform may give the impression that there is an agenda with the use of the data, which could make people wary to contribute to it. At the time of conducting this interview, the costs and resources needed to sustain the platform

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[34] The results of Harrison et al. (2021) are presented in a similar fashion using the ES-GTM Coding Paradigm to analyse the causal conditions, intervening conditions, and action/interaction strategies pertaining to the Data Collection phenomenon. As such, a similar figure is presented here, but pertaining instead to the Data Access and Sharing phenomenon.

[35] www.nzfloodpics.co.nz. Accessed 7 July 2021.

remained such that the participant was seeking collaborating support and buy-in from multiple sectors with the requirement of keeping the data openly accessible. An update has since been provided by this participant that NZ Flood Pics is now in the process of being institutionalised with NIWA with an agreed set of principles for how the data will remain open and accessible for "anybody to add value" (Data Management Private NZ. D).

Institutional involvement and open access to and sharing of citizen science data are growing areas of interest in citizen science research. The type of organisation involved in citizen science projects appears to influence people's willingness to participate and contribute their data (Anhalt-Depies et al., 2019). For example, Martin et al. (2016) found that contributors to a marine citizen science project in Australia showed a very high willingness to share data with research organisations, but less so with private research companies or consultants. Additionally, contributors seem to care about how the data they contribute is shared: Ganzevoort et al. (2017) found that surveyed citizen scientists do not support unconditional data sharing, rather their acceptability of sharing the data with third parties depends on the goals of the data user. Moreover, Groom et al. (2017) argue that the motivations of citizen scientists to contribute their data should align with the accessibility of the data for other uses. Thus, it is important to invest in data policies and transparency efforts to protect the interests of the contributors and ensure their continued engagement (Anhalt-Depies et al., 2019).

Participants indicated that some agencies who collect impact data were also found to be averse to sharing the data due to its sensitive nature and distrust in how such data could be used (Met. Int. D; Risk Modelling NZ. A; Loss Modelling Research NZ. A). As one loss modelling participant from NZ outlined, not all agencies are willing to publicly share their data, such as a public insurance group that formed after the 2010-2011 Canterbury earthquake sequence (Loss Modelling Research NZ. A). As such, there is no guarantee that government/public organisations will want to, or can, make any of their data publicly available (Loss Modelling Research NZ. A).

This could be due to the sensitive nature of the data (Met. Int. D; Risk Modelling NZ. A). Certainly, in NZ there are concerns around how releasing impact information could influence property values (Risk Modelling NZ. A). In Argentina, our participant described how a provincial government would not share their impact data with the National Meteorological Service (NMS) because of the political nature of the data:

> I was working with the province of [redacted] … and we implement[ed] this [data collection] form as a final project, and when I [said] 'okay, I want the data' they [told] me 'okay, we will give you the infrastructure data but no data about deaths' ... And I was like 'hey, no. That's not fair.' Why? Because it's political data! Who live and who die during a storm: that's political data, because it has to do with vulnerability and people here [are] very vulnerable. That's why I say that impact data is political data (Met. Int. D).

This finding aligns with those from Harrison and Johnson (2019), where Canadian emergency managers showed concern about displaying heavily damaged areas online via crowdsourcing platforms for emergency response. However, as shown in the above quote, the political nature by which the impact data in Argentina is perceived adds another layer beyond simply showing concern for the privacy and security of people and assets during an emergency. Viewing impact data as a threat to how government response agencies and their response capabilities are perceived indeed introduces a political element that inhibits the global movement for open and collaborative data sharing for improved DRR.

The consequences of restrictive data access and lack of information sharing for DRR can lead to disastrous consequences, as was seen in the USA following the landfall of Hurricane Katrina in 2005 (Peled, 2011). Yet, our findings show that data creators and users remain reluctant to share critical information. In addition to the concerns around the political nature of the data as described above, this aversion to sharing may be due to inter-agency competition over resources, influence, and autonomy (Peled, 2011), and/or loss of control over the datasets (Barry & Bannister, 2014).

Trust is an essential factor in multi-agency collaboration and data sharing, especially for disaster response (Doyle & Paton, 2017). Our findings further illustrate the importance of trust to facilitate data access and sharing through interagency collaboration for DRR (Kapucu, 2006). The importance and value of opening and sharing disaster-related data cannot be denied, and it is possible to establish open data access and sharing for DRR. For example, local, provincial, and national agencies, and regional and national academic and research institutions in Argentina worked together to establish an open data platform for flood impact reduction, "with a view to socializing knowledge for early alerts" (De Giusti et al., 2016, p. 86). Thus, agencies must continue to build and nurture trust between each other to facilitate data and information sharing.

Traditional media outlets may be one party not tied to the political influence and privacy and security concerns of sharing data and play a major role in disseminating information during a disaster (Greenberg & Scanlon, 2016; Nair, 2010). For example, in Aotearoa-NZ, the MetService usually has "a conversation with media" about their official warning message and provides examples of impacts along with the warning message to add meaning and context to the warning. The media then passes on this information to the public (Met. NZ. G, K).

Media outlets and reports can be a timely data stream for information during a disaster (Nair, 2010). They can even provide new information that might not otherwise be picked up or observed elsewhere. For example,

> there might be a report of … a motorcyclist blown off a piece of road or something. But there might not be any weather observations for miles in any direction that support that. So, then you have to go and look for corroborating evidence somewhere else, and how much do you trust the source? (Met. NZ. K)

However, as this example suggests, while media reports can bring new information to light, the new information still needs to be verified, as it might not always be accurate or true. Media outlets are both heavily reliant and influential on perceptions of trust and distrust during disasters (Miles & Morse, 2007). In another example, a regional EM agency in Aotearoa-NZ received crowdsourced reports on their public online story map of a van "stuck in the centre of the Hokitika River" (EM. NZ. Reg. F). The media picked up this report and publicised that "there's people trapped" (EM. NZ. Reg. F). The van was empty, and the EM agency had to re-upload the report themselves to include a note that the van was empty (EM. NZ. Reg. F).

The literature indicates that agencies elsewhere have reported difficulties with communicating with media outlets e (Anzur, 2000; Nair, 2010). In Aotearoa-NZ, the continuous conversations between the NZ MetService and the media described above exemplify a working relationship that ensures a unified message for informing people. In another example, the media provided "quite active and quite positive support" in the response and evacuation of a large-scale flood in Edgecumbe, Bay of Plenty by providing ample media coverage of the event and of the messages issued by the EM agency (EM. NZ. Reg. A). For media outlets and their resulting reports to be effectively used by their audiences, it is thus critical for them to build trusted relationships with those audiences, including members of the public, hydrometeorological services, and EM agencies. This could include developing a process or protocols for sharing data and information effectively.

Building Partnerships as an Action/Interaction Strategy

While NMSs are not typically responsible for collecting non-meteorological data, EM and flood management agencies, amongst others, collect or produce various types of impact data for their own purposes. Findings from the interviews, in support of existing literature (e.g., Hemingway & Gunawan, 2018; WMO, 2015), suggest that either formal or informal partnerships support data sharing for DRR. Continued collaboration to build and nurture partnerships has a positive relationship with trust (Kapucu, 2006), an important factor for sharing data. The NHP is an example of a formal partnership developed in the UK between public agencies to improve disaster management across the country (Hemingway & Gunawan, 2018). This partnership allowed the UK MetOffice to access useful datasets such as traffic count data from the transportation agency, for their impact models (Met. Int. A; Harrison et al., 2022).

In New Zealand and other participating countries, no such formal partnership was found to exist that is comparable to the NHP in the UK. However, evidence of informal partnerships was found in NZ and Australia. In both NZ and Australia, NMS and EM officials frequently contact each other informally during an event to exchange more targeted forecasting information such as levels of uncertainty, and worst-case scenarios to help with planning responses (Met. Int. B; Met. NZ. F, K; EM. NZ. Reg. A, B, C, D, E, F; Harrison et al., 2022). For example, as reported by Harrison et al. (2022), the NZ MetService works together with local and regional EM groups and hydrologists to determine the most appropriate warning level. These informal partnerships are particularly useful for information-sharing and decision-making on the fly during an event.

A need remains for more formal partnerships to facilitate data sharing after response events (Risk Modelling NZ. A). However, progress in this space will be slow:

> there's lots of talk about data sharing and I think there's a general attitude in New Zealand moving towards greater collaboration, greater sharing. [But] a sort of central repository for any of this stuff within the next decade is absolutely not going to happen, or if ever … It's hard to get people to work together (Risk Modelling NZ. A).

The participant listed data ownership and proprietary licensing as key limitations to sharing data. Perhaps in the context of sharing HIVE data via a central repository as mentioned by the risk modeller (Risk Modelling NZ. A), progress will indeed be slow as this requires more in-depth understanding and legal groundwork to establish data ownership rights and protection of proprietary data (e.g., Clark & Guiffault, 2018; Risk Modelling NZ. A). However, like the informal partnerships between the MetService and EM groups and council hydrologists to share hydrometeorological information for warnings, another informal partnership has been established to fill a gap in EM practice in NZ, the NZ Geographic Information Systems for Emergency Management (NZGIS4EM) group.

The NZGIS4EM group formed in the mid-2010s to boost the use of geospatial tools, such as Geographic Information Systems (GIS) within the EM sector (EM. NZ. Reg. H; Harrison et al., 2021). NZGIS4EM is a grassroots community of GIS specialists and EM practitioners in NZ that work together to share data and tools during responses and to innovate the use of geospatial technologies for EM (EM. NZ. Reg. H; Data Management Private NZ. B; Harrison et al., 2021). The community was formed from the leadership of one skilful individual who identified the need for geospatial innovation in the NZ EM sector, to enhance practices from relying on paper maps to using modern tools and technology (Data Management Private NZ. B).

The NZGIS4EM is credited with fostering a community of practice within the EM and GIS sectors, where relationships across agencies have been built and strengthened for a more coordinated disaster response effort (EM. NZ. Reg. H; Data Management Private NZ. B). In turn, this has driven innovation, knowledge sharing, and data sharing across NZ (EM. NZ. Reg. H; Data Management Private NZ. B). Direct outcomes of this group's work are seen in the recent *Director's Guideline for Civil Defence Emergency Management Groups [DGL 22/20]* (NEMA, 2020a) and *Technical Standard [TS05/20] National Impact Assessments Data Set and Dictionary* (NEMA, 2020c), published by NEMA. In these documents, the use of GIS is heavily referenced, and NZGIS4EM aided in defining the standards presented in the *Technical Standard [TS05/20] National Impact Assessments Data Set and Dictionary* (NEMA, 2020c; Data Management Private NZ. B).

Our findings suggest that informal partnerships are developed to fulfil an immediate need, such as communicating hydrometeorological information for warning decision-making or building a community of practice for coordinated disaster response. This finding aligns with the ad hoc informal partnerships that formed in the response and recovery to the 2010-2011 Queensland floods, where such partnerships formed between public and private agencies for information sharing (Bajracharya & Hastings, 2015). Furthermore, interorganisational networks facilitated by groups like the NZGIS4EM can be voluntary or mandated (Kapucu & Demiroz, 2017); in the case of the NZGIS4EM group, it is a voluntary effort. Success factors of such networks have been identified as effective communication, trust and social capital, and learning and adaptation (Kapucu & Demiroz, 2017).

Formal partnerships appear to be less common, and not as easy to establish, as indicated previously (Risk Modelling NZ. A), particularly for severe weather hazards. However, formal partnerships have been developed in NZ in the form of science advisory panels for natural hazard perils, such as the New Zealand Volcanic Science Advisory Panel (NEMA, 2020b), and the New Zealand Tsunami Advisory Group. The New Zealand Volcanic Science Advisory Panel works with area-specific volcanic advisory groups to coordinate planning for volcanic activity (NEMA, 2020b). These groups were formed from a specific need that was either identified from local/national or international events (EM. Gov. NZ. Nat. J), to better communicate science advice by bringing the expertise from various scientific agencies together (Doyle et al., 2014). For example, the New Zealand Tsunami Advisory Group was established in response to the 2011 Tōhoku and 2004 Indian Ocean earthquakes and tsunami (EM. Gov. NZ. Nat. J). These groups differ from the UK NHP in that practitioners are not formally included in them and some of the groups' roles in response and providing formal advice are unclear. Partnerships and multi-agency collaboration are not new concepts in the EM literature (e.g., Owen et al., 2013). It is promising to see these growing examples of successful partnerships both within and outside of NZ, be it formal and informal. However, more clarity is needed to establish the roles of these NZ-based groups in response and formal advice.

Strategies for building and nurturing partnerships and collaboration include networking (EM. Gov. NZ. Nat. J), professional development (EM. NZ. Reg. K; Doyle & Paton, 2017), cohabitation (Hemingway & Gunawan, 2018), and multi-disciplinary collaboration (Risk Modelling NZ. C; Ge et al., 2021), which may or may not be supported by funding and top-down mandates (EM. Gov. NZ. Nat. J; Peek et al., 2021). Participants indicated that a mix of both bottom-up and top-down approaches to building and nurturing partnerships is applicable in the Aotearoa-New Zealand context (EM. Gov. NZ. Nat. J). For example, cohabitation between agencies like the MetService, CDEM Groups, and local/regional councils can be organised from the bottom-up between the agencies in question. However, some political direction such as a national mandate might be more effective at inciting nation-wide cohabitation practices (EM. Gov. NZ. Nat. J). Further exploration of these strategies will be explored in future research.

Privacy and Security as an Intervening Condition

When it comes to sharing data for emergency response purposes, our participant from Fire and Emergency New Zealand (FENZ) identified the importance of protecting the response data. Much of their response data comes from NZ Police, who have very structured and careful security systems protecting their information (EM. NZ. Nat. I). As such, parties are working with the Privacy Commissioner to show that they can ensure the appropriate controls to protect the information, and in turn, there are also cultural challenges around the views of sharing information (EM. NZ. Nat. I). Our FENZ participant indicated that it is a matter of knowing staff members' behaviours and educating staff on why it is important to keep the data safe, while also safely sharing the information for effective response.

Safe and secure mechanisms for sharing the data are needed but are not always feasible. For example, our participant from Argentina indicated that they set up a Google Form to facilitate standardised data collection and sharing between the NMS and local government agencies, but they "have concerns … because … it is sensitive data [and] I don't trust … sending information through Google" (Met. Int. D). However, Google Forms was the most easily accessible tool that the local government agencies could handle (Met. Int. D). This demonstrates the need to have controls in place to maintain privacy and ensure data security.

8.4.2.2 Technical Aspects of Data Access and Sharing

Challenges around data integration were identified as a technical intervening condition affecting data sharing. Systematic Data Collection and Standardised Data Collection were identified as technical action/interaction strategies to address this intervening condition. These will be discussed next.

Data Integration as an Intervening Condition

Sharing data is only successful when the data can be integrated seamlessly into existing systems and practices (Migliorini et al., 2019). Findings from Harrison et al. (2021) show that a wide variety of HIVE data for severe weather events exists. In many cases, the challenge lies not in identifying the data sources but in integrating all sources and types of data in a meaningful way (NMS. Int. A, E; NMS. NZ; EM. NZ Regional. A, B, E). This is summarised by a NZ risk modeller, "although we all complain about a lack of data, a lot of the time, there is quite a bit of data out there that could be used and isn't being used very well" (Risk Modelling NZ. A). For example, this participant identified struggles with integrating building data, which is typically stored as spatial point data, with meshblock data, which is stored as spatial polygons. They stated that matching these point and polygon data together

> can be the bigger barrier than the fact that the data does or doesn't exist. Because … it turns out it's really not easy to put those points in a polygon because … there's no basic way of doing that, it's complicated (Risk Modelling NZ. A).

Furthermore, our UK-based participant described how they would like to see

> an integration of different approaches [like] the use of satellite, the use of social media, the use of citizen science, the use of media, and the integration of media to help understand better the differences and the causes for different types of impact (NMS. Int. A).

Some data integration methods have been successfully implemented. For example, the NZ MetService receive council rainfall data and share warning data files to integrate into hydrological models. In NZ, the West Coast CDEM Group primarily works online so they can share information in near-real-time with other agencies. But this is not standard practice across the country; gaps still exist in developing formal systems for data sharing and integration. A regional EM official elaborated on their challenges of linking up and integrating various data sources:

> I would like to see … some research in understanding what are the tools and systems that can be used for this? Because on one hand … if you sit around and everyone goes 'yeah, … we must share data' and … if we're going to plan for the future and everyone, different agencies hold different data about the same event, but how we're sharing that data? So, what is the system to do that? (EM. NZ Regional. A).

The Common Operating Picture (COP) is another example of a solution currently under development in NZ to allow cross-agency intelligence and data sharing during a response. The COP, a recommendation made following the 2010-2011 Canterbury earthquakes and other notable events (see Technical Advisory Group, 2017), is based on the idea of "everyone contributing to the scenario so that they've got to share, so that everyone's got access to that information" (EM. NZ. Reg. A); in other words, it is "a graphical visualisation of all the data available to make a decision" (Data Management Private NZ. B).

Phase one of the NZ COP programme began in late 2019 led by NEMA, when agencies involved identified the core national datasets needed for EM, and brainstormed how some of those datasets are shared, particularly geospatial datasets (EM. NZ. Reg. H). This required agencies to collaborate to identify different needs, highlighting the need for building trust and partnerships between agencies to facilitate data sharing.

Other solutions have been proposed and developed for improving data interoperability for integration. Horita et al. (2015) developed a spatial decision support system (DSS) to integrate official and unofficial data for flood risk management in Brazil, showing that integration "provides more complete, accurate and updated information about the situation in the affected areas" (Horita et al., 2015, p. 91).

Impact-based decision support systems (IDSS) offer a way for warning services to make effective decisions. An IDSS is "the provision of relevant information and interpretative services that enable partners to prepare for and respond, as planned, to extreme weather, water, and climate events for the protection of lives and livelihoods" (Uccellini & Ten Hoeve, 2019, p. 1928). In a case study comparison of two historic severe winter weather events in the USA with and without a formal IDSS, the IDSS was found to enable quicker and more complete forecast updates, such that emergency managers could relay information to appropriate agencies to take mitigative actions (Hosterman et al., 2019). The IDSS also allowed for improved crafting of public and partner messaging, and for preparing public officials to decide to shut down infrastructure.

Similarly, an integrated analysis of social vulnerability to extreme precipitation in Colorado was carried out by Wilhelmi and Morss (2013) using Geographic Information Systems (GIS). The process involved integrating radar-derived rainfall data and watershed boundaries with national census data and historical impact data. Challenges were faced with the differences in spatial-temporal scales between meteorological and social datasets, as well as the various formats in which the meteorological data were available (Wilhelmi & Morss, 2013).

Systematic Data Collection as an Action/Interaction Strategy

Systematic data collection is a need highlighted by many participants as an action/interaction strategy for better data sharing and integration. Non-systematic data collection occurs when data is collected in various formats and stored in different places (e.g., Massagrande, 1995). Thus, we refer to systematic data collection as having a system in place to process data from raw state to a usable format and storing the data in one place for easy access.

Our participants indicated that systematic data collection would support evidence-based planning and decision-making for warnings and planning (Met. Int. A; Met. NZ. F; EM. NZ. Reg. B). For example, our participating UK-based NMS official highlighted the need for systematic impact, exposure, and vulnerability data collection to be able to understand the causes of impacts with empirical evidence and to be able to compare different impact models (Met. Int. A). In NZ, a lack of systematic data collection severely impacted the organisation of intelligence and data gathered from event responses. For example, "back in 2011 [Canterbury earthquakes] … the capture of the data was so unstructured" (Data Management Gov. NZ. Nat. A); photos of buildings and letterboxes were not associated with dates or addresses, nor were they associated with damage and impact assessment forms used to capture information about the person and/or building (Data Management Gov. NZ. Nat. A). Consequently, an individual was "employed … for 18 months, just to take that photo and that building form and that welfare form and try to bring together a file on that family" (Data Management Gov. NZ. Nat. A). Had the data been collected in a more systematic way, "that information … would have been more informative at the time of the response and recovery" (Data Management Gov. NZ. Nat. A). Furthermore, systematic data collection would allow the sector to learn from past events and forecast potential future events by identifying impacts from events with similar meteorological signatures (Met. NZ. F; EM. NZ. Reg. B).

The COP previously mentioned provides a streamlined system for collecting, sharing, and managing impact data. However, much of this data does not have a shelf life beyond its initial purpose of building situational awareness for decision making during a response, because "from a Civil Defence perspective, whether it's local or regional, we don't need to keep the data, really. We'd probably keep it for two years and then say right, we're going to dispose of it because we don't need it" (EM. NZ. Reg. H). This also applies to welfare/wellbeing assessments, which are "very challenging, because there is a lot more private and personally identifiable information collected" (EM. NZ. Reg. H). As such, the CDEM Group will "probably … be even more aggressive about deleting that information once the event is over, to protect the people's privacy" (EM. NZ. Reg. H).

Standardised Data Collection as an Action/Interaction Strategy

Standardised collection of data was another need highlighted by many interviewees. Standardised data collection facilitates systematic data collection by providing a set of standards at which the raw data is collected such that it can be seamlessly integrated into a database with minimal processing (De Groeve, 2015; Ferrer et al., 2018). Standardised data collection would ensure all data is collected consistently for rigour and comparability (De Groeve, 2015; Ferrer et al., 2018). Our interviewees identified a need to be able to compare datasets and warnings across countries and regions, such as in Europe (Met. Int. E). Likewise, data collection practices within NZ, Argentina, and Australia differ regionally, making it difficult for regions to share data. In Australia, EM agencies collect post-event impact assessments, but the Australian NMS official indicated that this data lacks necessary fields for forecasting purposes (Met. Int. E). In Argentina, the NMS is working with EM agencies to build a process for collecting standardised impact data using Google Forms to benefit both agencies; the EM agencies will have trustworthy data, while the meteorological service will have data to support IFW implementation (Met. Int. D).

Our investigation into NZ practice showed that several types of standard data collection forms are available for different purposes, whereby the standards/forms were designed by different agencies for various uses. For example, in 2006, the Hawke's Bay Regional Council commissioned the development of *Template*s *for Consistent Hazard Event Reporting* (herein referred to as the *Template*) with a focus on capturing the impacts of the hazard for use by EM Groups for research, risk modelling, and developing a hazards and impacts database (EMS Limited, 2006). Standardised data collection provided from this template would better facilitate the organisation and storage of impact and hazard data for further use and analysis. However, it is unclear whether this form is used by CDEM Groups or councils across NZ, as no participants identified it as a resource that they use, yet it has potential for development going forward.

NEMA published an *Impact Assessments Director's Guideline for Civil Defence Emergency Management Groups* outlining the preparation requirements for conducting effective and efficient rapid impact assessments by response agencies to enable a coordinated approach across multiple agencies (see NEMA, 2020a). This document identifies the agencies responsible for conducting impact assessments for various purposes and at various phases. For example, CDEM Groups or local authorities are responsible for planning rapid impact assessments, while FENZ is "likely to be one of the first responding agencies to conduct a rapid impact assessment" (NEMA, 2020a, p. 15) due to their specialised capabilities for collecting and sharing field data (NEMA, 2020a). NEMA also provided forms for completing an initial situation overview, initial damage assessment, and impact report form. These assessments support response planning and coordination (EM. NZ. Reg. H). Furthermore, a companion document called the *Technical Standard [TS05/20] National Impact Assessments Data Set and Dictionary* (NEMA, 2020c) provides more technical information to support the consistent collection and recording of impact assessment data for easy cross-agency sharing and integration.

Our participants identified welfare needs assessments as another form of impact assessment (EM. Gov. NZ. Nat. G; EM. NZ. Reg. H; Data Management Gov. NZ. Nat. A; Data Management Private NZ. B), focusing on "understanding the needs of people affected by an emergency" (MCDEM, 2015, p. 1). Guidelines have been published outlining the welfare needs assessment process (see MCDEM, 2015). These guidelines indicate that data is collected using "customised CDEM Group/local authority forms" (MCDEM, 2015, p. 11).

For the built environment, the Ministry for Business, Innovation and Employment (MBIE) published field guides, assessment forms, and other learning resources for rapid building damage assessments for flooding, earthquakes, and geotechnical hazards such as landslips (see MBIE, 2018b). These resources are an outcome of lessons learned from the 2010–2011 Canterbury earthquake sequence, the 2011 Nelson storm, and the 2016 Hurunui/Kaikōura earthquake, and other international events (MBIE, 2018a). These assessments are primarily used by councils via contracted building engineers to assess the building and land safety and usability immediately after an earthquake or flood (Risk Modelling NZ. B; EM. NZ. Reg. H; MBIE, 2018b), but are not suitable for impact/risk modelling because they are not designed for this purpose and are not sufficiently comprehensive (Risk Modelling NZ. B).

Alternatively, our risk modelling participant indicated that developing a "master building database" containing building attribute data pre- and post-disaster would be "ideal" (Risk Modelling NZ. B). The participant envisions the database holding building data for all purposes, populated before an event, and updated with damage information to the respective buildings using a unique identifier post-disaster (Risk Modelling NZ. B). Efforts on this project are currently underway at GNS Science in NZ (see Lin et al., 2020).

The above assessments can be completed on paper, as has traditionally been done. However, a recent technological overhaul of the NZ CDEM sector (Data Management Private NZ. B) has introduced new tools for streamlining the collection and integration of these datasets (EM. NZ. Reg. F; EM. NZ. Reg. H; Data Management Private NZ. B). Much of the system has become location-based (Data Management Private NZ. B) using GIS technology (NEMA, 2020a). For example, the "welfare system [has] moved from being quite a database and table-based system to a location-based system" (Data Management Private NZ. B), and now utilises tools like Survey123[36] for welfare needs assessments (EM. NZ. Reg. H). The West Coast example outlined by Stowell (2020) provides more detail on how GIS has been used to streamline the CDEM impact assessment process.

Outside of impact data and the CDEM sector, other agencies have developed their own applications for conducting standardised information. For example, the Real-time Individual Asset Attribute Collection Tool (RiACT) was developed by risk modellers to capture real-time, geolocated, standardised asset information, such as building attributes (Risk Modelling NZ. B; Lin et al., 2014; Lin et al., 2020). The goal of this tool is to support an exposure data development framework whereby exposure data is systematically collected and stored for improved access, management, and use (Risk Modelling NZ. B; Lin et al., 2014; Lin et al., 2020).

While various standardised forms have been developed to capture hazard and impact data for various purposes, it would be beneficial to continue the systematic process of integrating the resulting data into a data repository for ease of access, sharing, and use beyond its initial purpose, depending on licensing and proprietary restrictions (e.g., Clark & Guiffault, 2018). Global efforts in the hydrometeorological hazard space are underway for building data repositories. For example, the HIWeather Value Chain Project under the World Weather Research Programme (WWRP) is currently building a catalogue of hydrometeorological events and their impacts to evaluate the end-to-end warning value chain (HIWeather, 2021). Additionally, the World Meteorological Organization (WMO) has established an initiative for cataloguing hazards and events through its members (Douris & Sopaheluwakan, 2019).

Strategies for building an integrated and multi-disciplinary data collection approach rely, again, on building and nurturing partnerships and collaboration. Collaboration allows data collectors and users from various disciplines to jointly define and scope problems for which the data is being collected, and identify the data types that are of interest to the problem (Ge et al., 2021). For example, Harrison et al. (2022) identified the need for including social scientists when designing post-impact assessments for risk modelling such that the modelling can extend into social and cultural impacts. For the aforementioned HIWeather Value Chain Project, an international multi-disciplinary task team of social scientists, meteorologists, and risk scientists was formed to co-develop the data collection template for the event catalogue (HIWeather, 2021). Consideration of emergent technology would also help

[36] https://survey123.arcgis.com. Accessed 7 July 2021.

with identifying efficient data collection and integration tools, such as GIS-based technology (e.g., Survey123), mobile devices, unmanned aerial vehicles (e.g., drones), etc. (Lin et al., 2019; Yu et al., 2018).

8.5 Conclusions and Limitations

This exploratory study built further understanding around the management, acquisition, and sharing of hazard, impact, vulnerability, and exposure (HIVE) data for severe weather hazards in New Zealand, towards supporting Sendai Framework priorities and implementing Impact Forecasts and Warnings (IFWs). While the qualitative nature of data collection and analysis herein limits the generalisability of results beyond the interviewees, this approach offers an in-depth understanding of a problem not readily available from quantitative approaches, which is appropriate for an exploratory study such as this (Blumer, 1969; Miles & Huberman, 1994; Patton, 2002).

We employed a socio-technical lens to our analysis to identify the organisational and technical intervening conditions and action/interaction strategies for accessing and sharing HIVE data in NZ. We found that there is a need for data governance of HIVE data. This involves identifying and appointing stewards and custodians of the relevant datasets such that the datasets can be maintained and available for further use beyond their initial purpose.

We also found a need for building and nurturing stronger partnerships to continue building trust between stakeholders for sharing data. Trust is an important factor for facilitating data sharing between agencies, and for people to share their data with hazards and impact monitoring crowdsourcing/citizen science projects.

Furthermore, integration challenges continue to interfere with the use of various sources of HIVE data for effective risk and impact assessments for IFWs and beyond. Systematic and standardised data collection approaches using GIS-based tools can support integration. Many templates for standardised data collection were found to exist in NZ but the resulting data has not been systematically collected into one place for easier access and use. Depending on licensing and proprietary restrictions, it may be beneficial to aggregate these data into a central repository for continued use.

This research provides empirical evidence supporting the need for establishing roles and practices for governing HIVE data in NZ. This is in support of both meeting the Sendai Framework priorities and implementing an IFW system for severe weather hazards in NZ. Building partnerships remains key to improving data collection, access, and sharing practices for DRR. Further research can investigate how these partnerships can be built and strengthened.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Nine: **Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use**

This chapter presents the core category found as result of the selective coding processed employed in this Grounded Theory research and integrates it into the broader context of this doctoral study. This chapter aims to address the question *"How can partnerships and collaboration better facilitate the collection, creation, and access to HIVE data for IFWs?"* by achieving the following objectives of this doctoral thesis: 5.1 To identify the required partnerships and collaborations required for IFW systems; 5.2 To identify existing partnerships and collaboration in NZ that can support IFW systems; 5.3 To outline a path forward for nurturing partnerships and collaboration for IFW systems.

The chapter is presented as follows. First, the core category of Partnerships and Collaboration is re-introduced in Section 9.1 from Chapter Four. This will provide an overview of the properties and dimensions of this core category (Section 9.2). Following this, a discussion of how the Partnerships and Collaboration core category threads through both the IFW System (Section 9.3) and HIVE data (Section 9.4) phenomena will be presented. These phenomena are the two subjects under study in this PhD research (see Chapter Four). A discussion will follow to integrate these findings together and with the literature (Section 9.5). A summary will conclude the chapter (Section 9.6).

9.1 Partnerships and Collaboration Core Category Defined

Following the ES-GT research strategy employed in this PhD study (see Chapter Four), the core category is that which all other categories and concepts relate to, and which "incorporates or supersedes other categories in explanatory importance" (Timonen et al., 2018, p. 7). The core category was identified through the selective coding process described in Chapter Three and Chapter Four. It was determined that the Partnerships and Collaboration category threads throughout the categories and sub-categories of this research and explains much of the conditions and action and interaction strategies of IFW Systems and HIVE data collection, use, access, and management. As such, Partnerships and Collaboration was identified as the core category. Examples of how Partnerships and Collaboration threads throughout the findings of this PhD research are listed in Table 9.1. This aligns with the literature, where partnerships and collaboration have been proven critical both in research and in practice for disaster preparedness, planning, and response (Ge et al., 2021; Johnson, 2021; Morss et al., 2021; Peek et al., 2021).

Based on the two phenomena under study in this doctoral research, and the properties and dimensions presented in the next section (9.2), the core category of Partnerships and Collaboration in this PhD study is defined as

> formal and informal, bottom-up or top-down approaches to establishing, building, and/or nurturing working relationships with stakeholders involved in the communication of and response to severe weather hazards, to allow for defining warning thresholds; creating consistent warning messages; sharing knowledge and data of hazards, impacts, vulnerability, and exposure; collecting appropriate and useful data; and managing said data towards the implementation of an impact forecasting and warning system.

The theoretical concepts, and thus the micro-theory, on which the above definition is based are represented visually in Figure 9.1, which places Partnerships and Collaboration in the middle of the figure, supported by its properties and dimensions (discussed next, in Section 9.2). Partnerships and Collaboration was found to play a key role in both the IFW System phenomenon and the HIVE data phenomenon, on which this PhD research is focused. This will be discussed in Sections 9.3 and 9.4, citing examples from the previous chapters and additional evidence in the interview and workshop data. Evidence from interviews is referenced using the interview codes previously presented in Table 3.6, for example 'Met. Research NZ. J' for participant J in the meteorological research field in New Zealand.

Table 9.1. Examples of themes relating to the Partnerships and Collaboration core category from the main results of each chapter.

Chapter	Key findings relating to Partnerships and Collaboration
Chapter Six	Partnerships and collaboration used throughout the Warning Value Chain: • Hazard forecasting (e.g., initial discussions with MetService and hydrologists), • Impact forecasting (e.g., sharing data between agencies to support impact modelling in the UK Natural Hazards Partnership (NHP), and conducting impact-oriented discussions across stakeholders such as when the Southland Red Warning was issued, and for forecasting the impacts of ex-TC Debbie and ex-TC Cook, • Impact warning (e.g., defining impact thresholds like the UK MetOffice co-producing an impact matrix with stakeholders and updating warnings based on feedback form the stakeholders,) • Co-design of an EWS with the target audiences. • Need for coordinated multi-disciplinary collection of human/social impact data. • Cross-sector collaboration for integrating dynamic exposure and vulnerability data.
Chapter Seven	Partnerships and collaboration are needed to: • Reduce unwillingness to share data, which may be due to a lack of trust between agencies. • Garner support and buy-in across regional stakeholders to allocate resources for better data collection. • Support community leadership to drive innovation.
Chapter Eight	Partnerships and collaboration help to: • Clarify roles and responsibilities, guidance in fulfilling tasks (e.g., Stats NZ helping NEMA manage their loss database). • Facilitate data sharing practices. • Develop integration strategies for seamless data sharing, e.g., developing the Common Operating Picture collaboratively to identify common needs and build trust and partnerships between agencies.

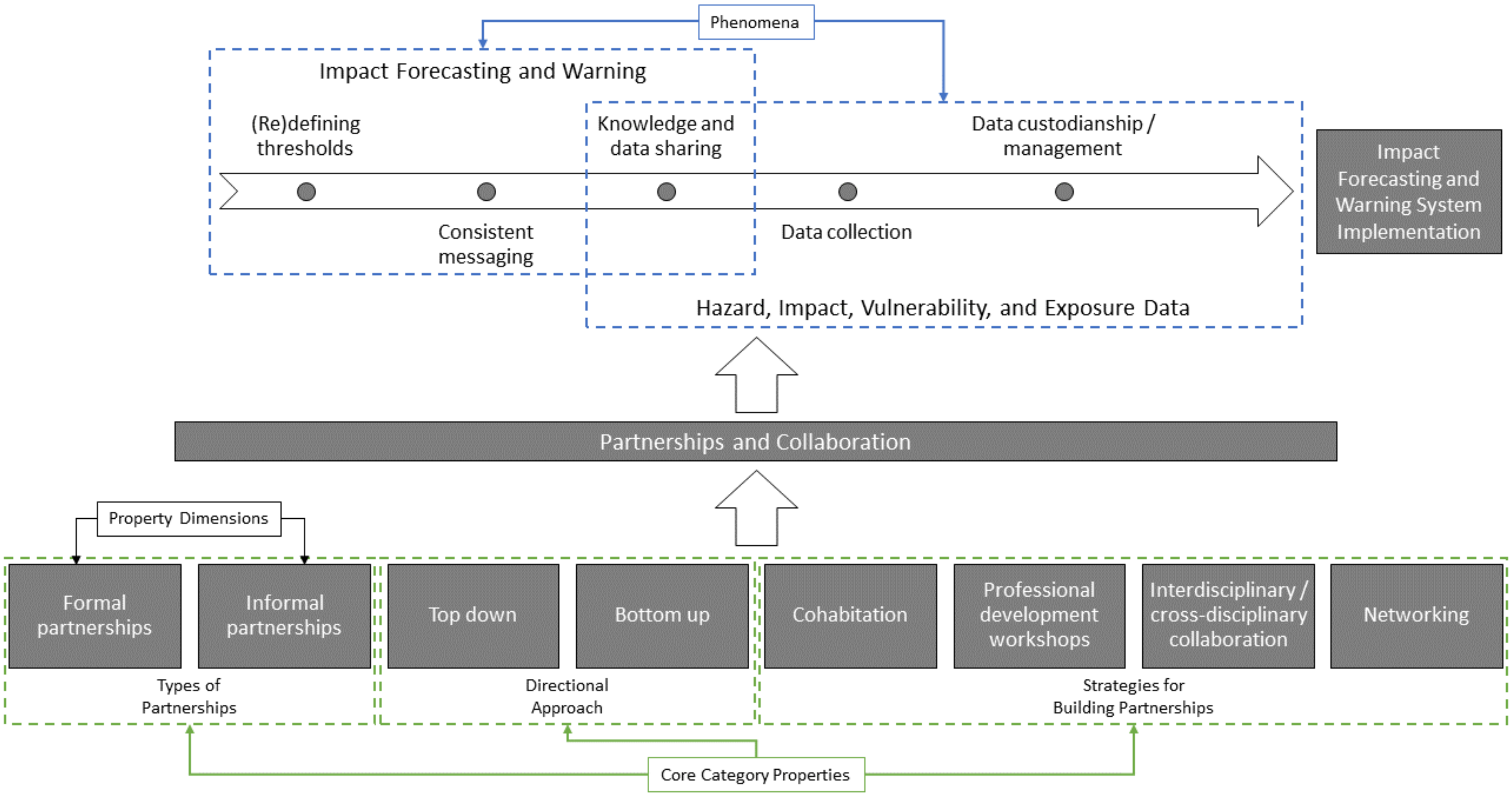

Figure 9.1. Integrative diagram of the micro-theory resulting from this doctoral research. The figure centres around core category of Partnerships and Collaboration for implementing an Impact Forecasting and Warning System. The two phenomena studied in this PhD thesis (Impact Forecasting and Warnings, and HIVE Data) are outlined in blue and labeled as such. The properties and their dimensions of the core category are outlined in green and labeled accordingly. The core category is presented in the middle, with arrows linking the properties and dimensions to the two phenomena.

9.2 Properties and Dimensions of the Core Category: Partnerships and Collaboration

The core category of Partnerships and Collaboration for IFW implementation and HIVE data collection, creation, and use consists of several properties and dimensions. Properties are "characteristics that define and describe concepts" (Corbin & Strauss, 2015, p. 220), and dimensions are variations within those properties (Corbin & Strauss, 2015, p. 220). Dimensions are represented as a continuum on which the properties lie, to provide range and specificity (Corbin & Strauss, 2015; Strauss & Corbin, 1990). Three properties were identified to make up the core category: types of partnerships, the directional approach to partnerships and collaboration, and strategies for building partnerships. Dimensions were identified for each of these properties. For example, formal and informal partnerships are the dimensions of the 'types of partnerships' property. These properties and their respective dimensions are summarised in Table 9.2 and will be discussed next, with direct references made to the findings reported in previous chapters and to additional interview and workshop data.

9.2.1 Types of partnerships

The first property of the Partnerships and Collaboration core category is types of partnerships and collaboration, incorporating the dimensions of formal and informal partnerships which represent the dimension of this property.

In the context of this research, a **formal partnership** is defined as a partnership that has been established with clear roles and responsibilities between partners and defined objectives for the partnership. Alternatively, an **informal partnership** is one that has formed rather spontaneously, typically in response to an event, to fill an immediate gap, and the roles and responsibilities are not mandated by an authoritative body or document. The NHP in the UK is an example of a formal partnership developed for providing authoritative and consistent hazard, impact, and risk information to responders and governments (Hemingway & Gunawan, 2018). This partnership consists of 17 UK public service agencies and was a result of a post-event review of the 2007 UK summer floods where the need for a national framework for reducing risks to delivering essential services from natural hazards was identified (Cabinet Office, 2008; Hemingway & Gunawan, 2018).

In NZ, no formal partnership like the UK NHP was identified over the course of this doctoral research. Instead, formal partnerships were found to exist in the form of science advice groups for non-hydrometeorological hazards, such as the New Zealand Volcanic Science Advisory Panel (NEMA, 2020b), and the New Zealand Tsunami Advisory Group, as described in Chapter Eight. These partnerships formed in response to gaps in services and communication that were observed during disasters that occurred both within and outside of NZ (Chapter Eight). The purpose of the NZ Volcanic Science Advisory Panel and associated members have been clearly identified in the Terms of Reference (see NEMA, 2020b), along with the roles and responsibilities for the members. While these groups and panels consist primarily of scientists who provide science advise to CDEM Groups, it is important to note that other groups must be included for response and operations planning. For example, during the 2012 Tongariro eruption crisis, several other sectors became involved in the response, even though they were not initially identified or included in practice scenarios leading up to the event (Leonard et al., 2014). These were the health, agriculture, and the veterinary sectors (Leonard et al., 2014).

Table 9.2. Summary of the properties and dimensions of the Partnerships and Collaboration core category.

Property	Dimensions	Description
Types of Partnerships	• Formal • Informal	Formal and informal partnerships exist for IFW implementation and for collecting, using, and managing HIVE data. A formal partnership is one that has been established with clear roles and responsibilities between partners and defined objectives for the partnership. An informal partnership is one that has formed rather spontaneously, typically in response to an event, to fill an immediate gap, and the roles and responsibilities are not mandated by an authoritative body or document.
Directional Approach	• Top-down • Bottom-up	The directional approach to form partnerships and collaborations refers to the motivation or drivers for the partnerships and collaboration. The top-down direction involves political guidance and a mandate to form the partnership and collaboration, while a bottom-up approach results in self-organised partnerships and collaboration.
Strategies for Building Partnerships	• Networking • Professional Development • Cohabitation • Multi-disciplinary collaboration	Four strategies were identified for strengthening and building relationships that can result in informal and formal partnerships and collaboration and can facilitate either a top-down or bottom-up approach.

No such science advice group has been formed for hydrometeorological hazards in NZ. However, the Resilience to Nature's Challenges Kia manawaroa – Ngā Ākina o Te Ao Tūroa (herein referred to as RNC) research programme offers a potential avenue for starting this conversation. RNC was launched in 2015 and is funded by the Ministry of Business, Innovation and Employment (MBIE, n.d.). The RNC programme is a successor to the former Natural Hazards Research Platform, which was a 10-year research programme that funded natural hazards research in NZ and "helped researchers and end-users work more closely together" (Natural Hazards Research Platform, 2020). A key objective of RNC is to promote innovative and collaborative research to build resilience to the natural hazards in NZ (RNC, 2018). The RNC programme is composed of eight themes: Rural, Urban, Matauranga Māori, Built Environment, Earthquake and Tsunami, Coastal, Volcano, and Weather and Wildfire. One participant in this doctoral research "always thought the [Natural Hazards

Research Platform] was a pretty good vehicle for encouraging collaboration" (Met. Research NZ. J). This participant further hopes "the [RNC] does the same", indicating that the leaders of the Weather and Wildfire theme "try to be as inclusive as possible in terms of people developing their plans" and act as a "coordination point" for researchers to align with them and with each other (Met. Research NZ. J). This is reflective of the identified need to build interdisciplinary research teams for rapid response disaster research (Ge et al., 2021; Peek et al., 2021). The RNC Weather and Wildfire theme, thus, may offer a potential mechanism for building both formal and informal partnerships for hydrometeorological hazard research and mitigation. Still, this may be difficult to implement in practice with no authoritative agency involvement, funding, or mandate (Peek et al., 2021).

While few formal partnerships were found to exist in NZ specifically for hydrometeorological hazards, informal partnerships do exist. One such example is between the MetService and regional hydrologists, as described in Chapter Six (Harrison et al., 2022), and Chapter Eight. This form of partnership and collaboration relies on the quality of the relationships between the MetService forecasters and meteorologists and the regional hydrologists, which can be influenced by staff turnover, training, or lack thereof, etc. This is considered an informal partnership because it has not been mandated and no guidance has been written to define roles and responsibilities (Jung et al., 2018; Olmos-Penuela et al., 2013). It is a practical strategy to support decision-making for forming and issuing hydrometeorological warnings. Closely related to the types of partnerships and collaboration identified here (formal and informal), is the directional approach to forming these partnerships.

9.2.2 Directional approach

The directional approach to form partnerships and collaborations refers to the motivation or drivers for the partnerships and collaboration. Top-down and bottom-up are the two directions (i.e., property dimensions) that were identified in the analysis of the interviews and workshops. The **top-down approach** would involve political guidance and a mandate to form the partnership and collaboration, while a bottom-up approach results in self-organised partnerships and collaboration (Kapucu & Demiroz, 2017). Thus, formal partnerships are usually formed using a top-down approach where a governing body has mandated the formation of a partnership, such as the NHP in the UK (Hemingway & Gunawan, 2018), and provided funding (Morss et al., 2021). Alternatively, informal partnerships usually arise from a **bottom-up approach** where potential partners might self-organise to meet a common need (Kapucu & Demiroz, 2017). The NZGIS4EM previously described in Chapter Eight is an example of a bottom-up approach to forming informal partnerships to facilitate effective collaboration and coordination during disaster response efforts, and eventually building a large network and community of practice for the GIS and EM sector in NZ. As noted in the previous section (9.2.1), a top-down approach in which mandates are established and funding is made available by authoritative, governing bodies, would further support the establishment of top-down partnerships that enable various groups to effectively collaborate with minimal barriers (Ge et al., 2021; Peek et al., 2021).

9.2.3 Strategies for building and strengthening partnerships and collaboration

Several strategies were identified during the interview and workshop data analysis for building and strengthening partnerships and collaboration for IFW implementation and HIVE data collection, creation, and use. These strategies (i.e., property dimensions) are **networking, professional development, cohabitation, and multi-disciplinary collaboration**.

Networking was identified in the interviews as a strategy for building and strengthening partnerships and collaboration (EM. Gov. NZ. Nat. J). A technical or science advisory group like the New Zealand Volcanic Science Advisory Panel and the New Zealand Tsunami Advisory Group may be useful for hydrometeorological hazards in New Zealand to enable further understanding and consistent communication of the risks and impacts of these hazards (EM. Gov. NZ. Nat. J). This may also facilitate more efficient data access and sharing practices (Ge et al., 2021). According to the research participants, forming such a group in NZ for severe weather and floods requires building and nurturing relationships by attending national conferences such as the National Emergency Management Agency (NEMA) Conference, NZ Meteorological Society Conference, NZ Hydrological Society Conference, etc., where attendees could test ideas amongst each other, garner support, and present it to higher-level decision- and policymakers (EM. Gov. NZ. Nat. J). For example, the MetService might register some of their staff to attend the NEMA conference, and CDEM Groups and councils might register their staff to attend the NZ Meteorological Society Conference and the NZ Hydrological Society Conference. This can be beneficial for making new connections, strengthening existing partnerships, and starting conversations.

Agencies that often work together, such as the MetService, councils (e.g., hydrologists), and CDEM Groups, can also nurture their working relationships by running **professional development** workshops together and hosting these workshops at their own agencies to allow other agencies to build an understanding of how each other operates (EM. NZ. Reg. K). One regional CDEM Group indicated that the NZ MetService used to host such visits with their group, which they found valuable for nurturing their relationship (EM. NZ. Reg. K). Past workshops held by researchers from CRIs were also seen as beneficial for keeping practitioners up to date on current research efforts and innovations (EM. NZ. Reg. K). These practices are akin to running scenario exercises to build relationships in advance of disaster events, for effective decision-making, communication, etc. (Doyle & Paton, 2017). Such exercises have proven highly beneficial for building and nurturing partnerships and collaboration for disaster risk reduction (Doyle et al., 2015; Hosterman et al., 2019; Leonard et al., 2014; Wein et al., 2016).

Cohabitation is a strategy that has been employed by the UK Met Office and Environment Agency to improve flood forecasting and warnings (Flood Forecasting Centre, n.d.; Hemingway & Gunawan, 2018). Cohabitation occurs when experts from different disciplines operate from the same location. When asked if cohabitation was an option in NZ for ease of communicating warnings, our NEMA participant (EM. Gov. NZ. Nat. J) indicated that it could be done in a bottom-up fashion where the MetService and CDEM Group(s) and council(s) make their own cohabitation arrangements. This has been done between the NZ MetService and Auckland council, where a MetService meteorologist sits in the Auckland Emergency Management office. Similarly, a supervisor of this PhD research is co-located with a regional CDEM Group. However, the participant indicated that it might be more effective if some political direction was given from the top, for example, if a bill (i.e., a proposed law) were introduced or an existing bill was appended to say that this should be done (EM. Gov. NZ. Nat. J). Doing so would be difficult due to agencies' internal politics, funding sources, operational practices, and governance structures (EM. Gov. NZ. Nat. J). Thus, a starting point would be to look at the governance arrangements of each agency, for example who governs the MetService, NEMA, CRIs, CDEM Groups, etc. and determine "how you would bring, and not bring, the organisations together, [put] some of their functions together or instruct them" to achieve something together (EM. Gov. NZ. Nat. J).

Collaboration between scientists from **different disciplines** (e.g., risk modellers and social scientists) was identified as a needed strategy for ensuring that data collection is comprehensive and accurate, and so that the risk and impact assessments of hydrometeorological hazards go beyond the built environment and extend into social human impacts (Chapter Six; Harrison et al., 2022). This further reflects proposals for building interdisciplinary teams for disaster response research (Ge et al., 2021) to support integrated transdisciplinary risk assessment and management processes (Johnson, 2021). Platforms like the RNC programme can enable this kind of collaboration by providing a channel for researchers to engage with each other. Doing so enables knowledge co-production to support collaborative, adaptive, and robust policies (Johnson, 2021).

The core category of Partnerships and Collaboration, consisting of the above properties and their respective dimensions, was found to thread through the two phenomena studied in this thesis (IFW Systems and HIVE Data). Examples of how Partnerships and Collaboration relates to IFW Systems and HIVE Data are discussed next.

9.3 Partnerships and collaboration in the Impact Forecasting and Warning Systems Phenomenon

Partnerships and collaboration thread throughout the IFW Systems phenomenon as an integral action/interaction strategy for implementing IFWs. Partnerships and Collaboration enable the important practice of sharing data and knowledge between agencies. Sharing of this data and knowledge through partnerships and collaboration can then facilitate the (re-)defining of impact thresholds for an IFW system and can ensure that messages are consistent across agencies. These actions of sharing data and knowledge, (re-)defining impact thresholds, and producing consistent warning messages emerged from codes relating to the IFW phenomenon as outlined in Chapter Four. Examples of how Partnerships and Collaboration enable these actions in the IFW phenomenon are provided next.

9.3.1 Sharing Data and Knowledge

Various agencies possess the knowledge and data needed for IFWs, as reported in Chapter Seven (Harrison et al., 2021), and listed in Table 7.4, Table 7.5, Table 7.6, Table 7.7. These various agencies and the associated data that they possess are visualised in a Venn diagram in Figure 9.2. This diagram displays the agencies that were identified by participants as those that possess HIVE data for hydrometeorological hazards and impacts in NZ, as reported in Chapter Seven (Harrison et al., 2021). Each leaf of the Venn diagram represents data partners for one of the four data types: hazard, impact, vulnerability, and exposure. Within each leaflet, the agencies identified in Table 7.4, Table 7.5, Table 7.6, and Table 7.7 for collecting or possessing datasets from each data type are placed in the Venn diagram. For example, the MetService was identified as possessing hazard, impact, and vulnerability knowledge and data in various forms: they continuously monitor and collect observational data on meteorological hazards, they monitor severe weather impacts reported in the media, and they possess tacit knowledge of regional vulnerabilities to certain meteorological hazards (e.g., knowing that Auckland is particularly vulnerable to winds coming from a northeast direction). They use this information to inform their decisions to issue a warning and how to emphasise and communicate the threats contained within. In another example, Data Ventures holds exposure information in the form of cell phone location data. This data was used recently, not for severe weather hazards, but to inform decision-making around alert level changes in response to the COVID-19 pandemic (Chapter Seven; Harrison et al., 2021). There is potential for this data to be useful for risk and impact modelling for hydrometeorological hazards (Chapter Seven; Harrison et al., 2021).

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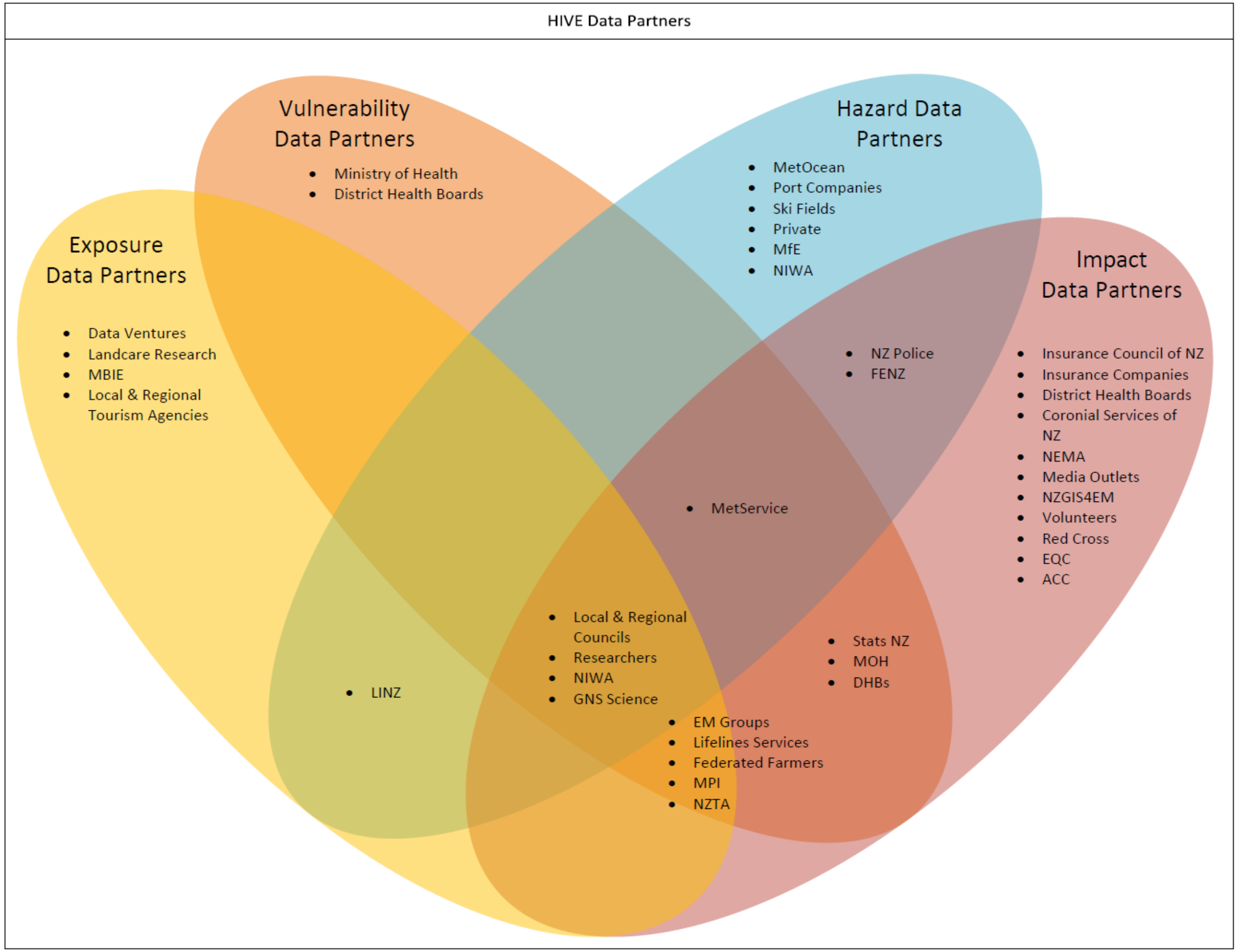

Figure 9.2. A Venn Diagram displaying agencies that possess HIVE data in New Zealand.

From the interviews, it appears that at least four groups in NZ possess all four types of data needed for IFWs: hazard, impact, vulnerability, and exposure. As shown in Figure 9.2, based on the results presented in Chapter Seven, these are local and regional councils, university and independent researchers, NIWA, and GNS Science. Local and regional councils possess data on flood hazards, such as river height and flow gauges, sea level data, river network, overland flow paths floodplain data, coastal inundation maps, slope data, and live camera feeds of river heights. In terms of impact data, councils have been found to use social media, crowdsourcing, and community volunteers to collect reports. Councils also have their staff and contractors conduct damage assessments, and often write post-event reports after a significant event for post-event analysis. Councils also possess data or information needed for vulnerability assessments, such as asset information (i.e., characteristics) and building damage assessments. Likewise, for exposure, councils have data on asset location and land-use zoning. Council staff also possess tacit knowledge of hazard, impacts, vulnerability, and exposure, and much of this tacit knowledge is undocumented.

Researchers were also found to possess various forms of HIVE data based on the interviews and workshops. Researchers often use social media and crowdsourcing to collect hazard and impact data for their own purposes. Researchers also collect data from media reports (indirectly), and directly from damage surveys and post-event interviews/surveys. Researchers also produce data from conducting risk and impact models.

From the interviews and workshops, NIWA and GNS Science were the third and fourth agencies found to possess HIVE data in various forms for hydrometeorological hazards. Like the MetService, NIWA collects observational data for hydrometeorological hazards, in addition to possessing data on river networks and sea levels in NZ. NIWA and GNS Science also conduct risk modelling for hydrometeorological and geological hazards using RiskScape, and thus collect and/or possess HIVE data to conduct these assessments. For example, NIWA officials conduct damage surveys following flood events to collect flood damage data for buildings and produce exposure layers based on overlaying spatial asset and hazard layers (Paulik et al., 2020). At GNS Science, efforts are underway to build a Pacific region exposure dataset for risk modelling (Lin et al., 2014; Lin et al., 2020)While one organisation might contain specific types of HIVE data (as shown in Figure 9.2), together they may not be able to be used for IFW. For example, GNS Science has landslide hazard data, but does not possess or collect rainfall data. Thus, the distribution of HIVE data across the various agencies represented in Figure 9.2 demonstrates the need to share data and knowledge between agencies for IFWs. This argument is supported in related IFW reports (e.g., Harrowsmith et al., 2020; WMO, 2015). The UK NHP is a prime example of how HIVE data can be shared between agencies to support IFWs. Interview findings from this thesis research (e.g., Chapter Six; Harrison et al., 2022), and recent literature (e.g., Hemingway & Gunawan, 2018), highlighted how this formal partnership enables the UK MetOffice to obtain key information for their IFWs, such as transportation data from the UK transport authority, to inform their Vehicle OverTurning Model, or population movement (i.e., exposure data) from the UK Health and Safety Executive.

Furthermore, as found in Chapter Six (Harrison et al., 2022), if an agency were to possess all of the required data for IFWs, if they do not have the mandate (i.e., roles and responsibilities) to issue IFWs, they cannot do it. Partnerships and collaboration thus are important for IFWs, to allow agencies who possess the required data for IFWs (such as NIWA, GNS Science, EM agencies, etc.) to work with the mandated warning services (such as the MetService and councils). Still, dynamic exposure and vulnerability, which were identified as important for IFWs in Chapter Six (Harrison et al., 2022), were found not to exist or be readily available in NZ.

9.3.2 Re-defining Warning Thresholds

While no formal partnership like the NHP was found to exist in NZ from the interviews and workshops, informal partnerships were found to exist between the MetService and EM Groups and hydrologists in New Zealand. These partnerships allow the MetService to (a) include CDEM Groups and hydrologists in their decision to issue a hazardous weather forecast, and (b) alert them to the fact that they have issued a hazardous forecast or warning so that they can prepare. They do this by 'phoning up' the hydrologists, and/or EM group to start the conversation(s), as shown in Figure 9.3, and as reported in Chapter Seven (Harrison et al., 2022).

Figure 9.3 provides a conceptual example of a severe weather warning chain in NZ and the partners involved in this chain. This figure is the result of diagramming and memo-writing following interviews with NZ MetService, CDEM Group officials, and hydrological participants (an early version of the diagram was previously presented in Chapter Four. The figure presented here is an updated version based on the iterative ES-GT analysis process). Starting with monitoring hydrometeorological hazards by the MetService and council hydrologists, when a potentially hazardous hydrometeorological phenomenon is identified (such as intense, heavy rainfall), the MetService reaches out to their hydrological and CDEM Group contacts in the region of interest to conduct a risk or impact assessment. This assessment can be discussion-based, model-based, or both (Chapter Six; Harrison et al., 2022). From there, both the MetService and council may choose to issue a watch or warning, which they disseminate to the respective CDEM Group(s), members of the public, lifelines sector, and other stakeholders.

Discussions with participants indicated that a result of risk or impact assessment is the decision to issue a warning (or not), and the level of warning. For example, the MetService could issue an Orange or Red Warning based on feedback from the CDEM Group and hydrologist(s), considering antecedent conditions and long-term forecasted conditions (Harrison et al., 2022). The council would also be responsible for issuing a flood warning if needed (Potter et al., 2021). The MetService also works with regions to adjust warning thresholds. For example, the MetService has worked with Auckland to adjust thresholds for damaging winds, as reported in Chapter Six (Harrison et al., 2022). They also lower thresholds if they know the antecedent conditions that might exacerbate the impacts by talking with the hydrologists and CDEM Groups to be aware of their current exposure, vulnerability, and response capacities (Harrison et al., 2022). This shows the importance of communicating and collaborating with stakeholders to define or redefine thresholds based on impacts for more effective warnings.

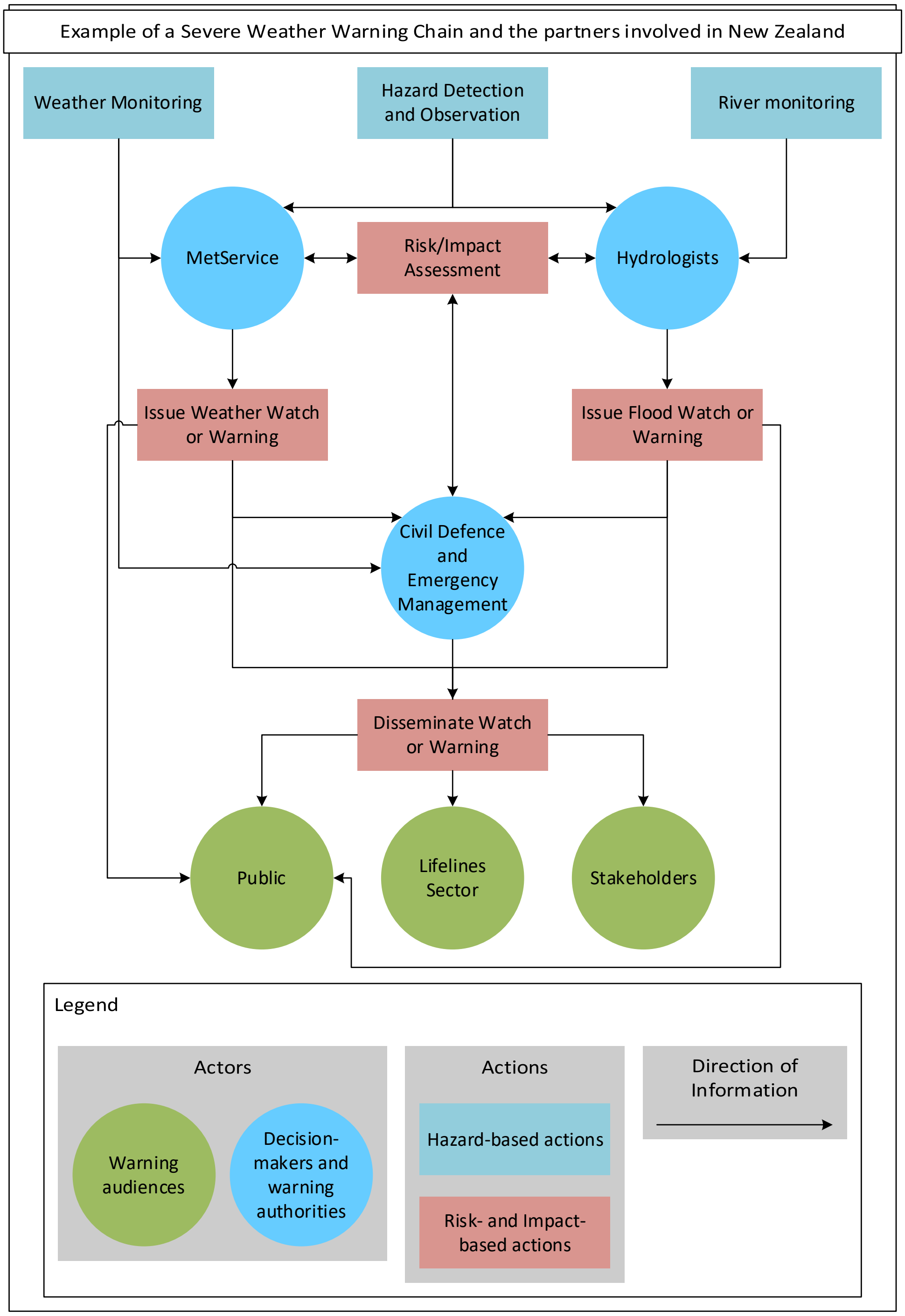

Figure 9.3. A conceptual example of a severe weather warning chain in NZ and the partners involved in this chain. The figure identifies the actors (warning audiences and decision-makers and warning authorities) involved in the warning chain and the actions of said actors. The actions are either hazard-based (such as monitoring and collecting observational data of hazards) or risk- and impact-based (where risk and impacts are considered in addition to the hazard information). The direction of information and communication is represented by arrows. Multi-directional arrows indicate that the actors such as the MetService, hydrologists, and CDEM Groups both contribute to the risk assessments and are informed by the risk assessment outputs for their warning messages.

9.3.3 Consistent Warning Messages

Consistency of warning messages has been deemed critical for effective risk communication (Williams & Eosco, 2021). Partnerships and collaboration are also important for ensuring that the warning messages and information is consistent across agencies and reaches target audiences. For this reason, Auckland Emergency Management works with the MetService to make sure that what they are putting out aligns with the forecasts and warnings from the MetService (Auckland Workshop). In another example, WeatherWatch, a private weather forecasting company in NZ, and the MetService have worked together over the years to strengthen their relationship such that they can ensure that they are putting out messages that are productive for the public to take action, rather than detract from each other (Met. Private NZ. L). The objective is to reach the targeted warning audiences with timely, accurate, and relevant information to aid preparedness and response actions (Basher, 2006). In a negative case[37] example, instances of conflicting weather forecasts have also occurred between hydrometeorological agencies in NZ where these conflicting forecasts were posted on social media channels (Gorman, 2016). Having multiple providers of (sometimes conflicting) weather forecasts and warnings in the media (and social media) may cause public confusion, leading to potential (or perceived) mistrust of the MetService and their role as the weather warning authority. Further research should verify these affects.

9.4 Partnerships and collaboration in the HIVE Data Phenomenon

Due to the distribution of HIVE data sources across these agencies and stakeholders, as previously shown in Figure 9.2, partnerships and collaboration are needed to open up access to these datasets and data sources for IFWs in order to reduce instances of repetition for data collection and creation. Within the HIVE Data phenomenon of this doctoral research, the category of partnerships and collaboration was found to affect the actions covered in Chapters Chapter Seven and Chapter Eight: data collection, data custodianship and management, and data access and sharing.

9.4.1 Data Collection

Many agencies collect and create various forms of HIVE data for various uses, as reported in Chapter Seven (Harrison et al., 2021). Interdisciplinary or cross-disciplinary collaboration has become increasingly important for disaster-related data collection (Ge et al., 2021). Findings from this doctoral thesis show the importance of this collaboration for creating templates for collecting data that can be used beyond its initial purpose, or so that the data collection is comprehensive. For example, in Chapter Six Harrison et al. (2022) found that to capture the social impacts of severe weather hazards, risk modellers who typically conduct post-damage assessments to calibrate their models should coordinate and collaborate with social scientists to ensure that the templates capture appropriate characteristics to inform social impact models as well, and to ensure that the data collection method itself is ethically sound.

[37] A negative case is a case that does not fit the pattern (Corbin & Strauss, 2015).

Such interdisciplinary collaboration has the potential to incorporate new and shared perspectives to a problem (Ge et al., 2021). Collaborators can thus jointly define and scope problems, and identify the data types that are of interest to these problems (Ge et al., 2021). The overall outcomes of this kind of 'data-driven' collaboration can be the production of "more holistic solutions that grow and evolve from the shared space" (Ge et al., 2021, p. 1146). Successful collaborations typically have the institutional support and have a foundation of long-term collaborations (Ge et al., 2021).

9.4.2 Data Governance, Access, and Sharing

Governance, access, and sharing of HIVE data, was also found to involve aspects of partnerships and collaboration. Data governance protocols help to establish authority and control over data by assigning clear roles and responsibilities (Benfeldt et al., 2019). Data governance also involves examining practices for data collection, management, accessibility, and use (Janssen et al., 2020). As reported in Chapter Eight, data governance became an important theme in discussions with participants about managing HIVE data. Furthermore, partnerships and collaboration were found to be important for agencies to learn from each other for best practices, particularly for agencies who have not traditionally been responsible for collecting such data in the past. For example, NEMA was working with Stats NZ to receive guidance on best practices for managing the national loss database currently in development for reporting under the Sendai Framework (see Chapter Eight). This example supports the notion that data governance depends on collaboration between the organisations and people of which the system comprises (Janssen et al., 2020). This includes establishing trusted frameworks for reliable and secure data sharing between organisations (Janssen et al., 2020).

Partnerships and collaboration were found to be an action/interaction strategy to enable access to and sharing of hydrometeorological HIVE data. Several examples of partnerships and collaboration were found to enable sharing data and knowledge for hydrometeorological hazards. The partnerships between the MetService and CDEM Groups and hydrologists were outlined in the previous section to inform severe weather warnings, as reported in Chapter Six (Harrison et al., 2021). In addition to that, interviews indicated that the MetService shares their data files (see Chapter Eight) with hydrologists to integrate with their flood models. In another example, the partnerships and collaboration formed in the NZGIS4EM community facilitates the sharing of data across agencies (see Chapter Eight).

The NZ MetService and WeatherWatch are also working together to form amicable data access and sharing arrangements (Met. Private NZ. L), however this is not necessarily the case with other agencies due to data sharing restrictions (Met. Private NZ. L). This has introduced a debate around which data should be made 'open' (Met. NZ. K). Global calls have been made to make hydrometeorological data openly accessible, citing various economic benefits (e.g., Rogers & Tsirkunov, 2021). However, a review of open access to weather data in New Zealand conducted by MBIE (MBIE, 2017) found that most data reuse principles are being met by the involved agencies, but access to observational weather data in NZ is more restricted than in other countries (MBIE, 2017). This is due to the State-Owned Enterprise (SOE) and CRI models under which the agencies operate; these models are based on earning commercial revenue to support data collection and cover operating costs (MBIE, 2017). The review determined that the costs to the NZ taxpayers of increasing open access to raw observation data would outweigh the benefits (MBIE, 2017).

While the MBIE review determined that the current accessibility of weather-related data is acceptable when considering the cost-benefit to NZ-taxpayers, this issue highlights the importance of forming functional partnerships such that data sharing agreements can be made between agencies (The World Bank, 2020). The Weather Enterprise in the USA is an example of a public-private-academic partnership formed across the various sectors involved in collecting, creating, using, and communicating weather information (e.g., Government agencies, EM agencies, academia, private agencies, broadcast media, social science) (NWS, n.d.). The Global Weather Enterprise (GWE) is another example of efforts towards increasing the accessibility of weather information (Thorpe & Rogers, 2018). The GWE comprises all the Warning Value Chain components, products, processes, and actors that must come together to provide accurate and reliable weather information (Thorpe & Rogers, 2018). As the GWE is collaborative in nature, partnerships across culturally different sectors are essential to its success (Thorpe & Rogers, 2018).

9.5 Discussion and Integration

The relationship of Partnerships and Collaboration with the two phenomena in this study (IFWs and HIVE Data) is represented in Figure 9.1. Sharing knowledge and data is the interface between these two phenomena, as demonstrated in Figure 9.1, because it fills the knowledge gap identified by meteorologists in practice and in the literature for implementing IFWs (e.g., Potter et al., 2021). Findings in Chapter Six showed the needs of HIVE data throughout the Warning Value Chain for IFWs. Additional findings in Chapter Seven identified existing and potential sources for HIVE data that can support IFWs. However, because the data sources are numerous with many actors involved in collecting and using it, the need for effectively managing, sharing, and accessing the data was identified and further explored in Chapter Eight. Thus, it was found that Partnerships and Collaboration are essential for facilitating effective data sharing practices for IFW implementation.

The findings of the thesis which point to Partnerships and Collaboration as a necessary strategy for implementing IFWs aligns with recommendations in the WMO Guidelines (WMO, 2015) and a more recent guide published by the International Federation of Red Cross and Red Crescent Societies (IFRC) (Harrowsmith et al., 2020). These findings are further exemplified by the UK NHP (Hemingway & Gunawan, 2018). Partnerships for IFW systems allow for partner organisations to understand hazards, identify impacts, and assess user requirements (Harrowsmith et al., 2020). The NHP was lauded for “leading the way in moving from hazard-based to impact-based natural hazard research to better understand and forecast potential impacts” (Hemingway & Gunawan, 2018, p. 508). Such a partnership allows for the inclusion of diverse scientific expertise which promotes efficient, robust, and "practically relevant" forecasting tools (Hemingway & Gunawan, 2018, p. 508). This doctoral research provides further empirical evidence of the need for building and nurturing partnerships and collaboration both for implementing IFWs and for better management of, and access to, HIVE data for IFWs and DRR in general.

Multi-organisational collaboration has many challenges (Sonnenwald, 2007). The process of building partnerships like the NHP requires extensive time, coordination, communication, and interaction between agencies (Hemingway & Gunawan, 2018). Barriers to these factors include resourcing, such as available funding for billable hours, workloads, and establishing facilitations roles, etc. Building trust and increasing the willingness of organisations to participate are additional hurdles (Pennington et al., 2015; Sonnenwald, 2007). Further challenges include mutually identifying goals and objectives and agreeing on timelines, the use of differing terminology and epistemologies, legal issues around intellectual property, and developing workflows and communication standards, and sustaining the collaboration (e.g., maintaining interest, securing funding sources, etc.) (Pennington et al., 2015; Sonnenwald, 2007). Finally, developing partnerships to share data between agencies for an IFW system is based on the initial assumption that agencies that possess the desired data are both willing and able to share this data.

The strategies and approaches portrayed in Figure 9.1 can be enacted to address some of these challenges and for building and nurturing partnerships and collaboration in NZ towards implementing IFWs and collecting, sharing, and using the required HIVE data for IFWs and other DRR efforts. The findings of this thesis build on existing recommendations from the IFRC guide (Harrowsmith et al., 2020) and provide more tangible and direct strategies. For example, networking by attending conferences was identified as a strategy for scoping initial interest and capabilities in building partnerships and collaboration. The results of the networking exercise may then be brought to policymakers and decisionmakers to implement a more top-down approach for mandating formal partnerships which may then open funding opportunities to support these efforts and provide guidance on legal issues with data sharing. Hosting professional development workshops and visits across agencies and cohabitation support building trust between agencies, mutually identifying goals, clarifying terminologies and epistemologies, and sustaining the collaboration.

9.6 Chapter Summary

This chapter presented the core category resulting from the Evolved-Straussian Grounded Theory analysis, accompanied by a chain of evidence, from Chapter Six to Chapter Eight and additional interview and workshop data, supporting the elevation of this category to core category. Partnerships and Collaboration was identified as the core category due to its explanatory power around IFW Systems and accessing and using the required HIVE Data for IFWs. The core category of Partnerships and Collaboration involves using various approaches to establish partnerships across the various agencies and stakeholders that collect, create, and use HIVE to support the implementation of IFWs.

The concepts and relationships comprising this core category were represented in Figure 9.1. The properties and dimensions of this core category were further elaborated. These properties and dimensions are types of partnerships (e.g., formal, and informal), directional approach (e.g., bottom-up, and top-down), and strategies (e.g., Networking, Professional Development, Cohabitation, and Multi-disciplinary collaboration). These properties and respective dimensions represent approaches and strategies to building and nurturing partnerships and collaboration in support of IFW implementation and HIVE data collection, access, and sharing.

Sharing data and knowledge was identified as the interface between the two phenomena in this study (IFW Systems and HIVE Data), as this allows warning agencies to access and use information that they may not otherwise have but require for an IFW system. This activity of sharing data and knowledge is essentially supported by Partnerships and Collaboration in various forms.

The chapter concluded by integrating the properties and dimensions of the core category with the IFW Systems and HIVE data phenomena, and with the IFW and DRR literature. Challenges with building Partnerships and Collaboration were identified from the literature, and the approaches and strategies identified in this chapter were proposed as potential solutions to these challenges. This meets Objectives 5.1 To identify the required partnerships and collaborations required for IFW systems; 5.2 To identify existing partnerships and collaboration in NZ that can support IFW systems; and 5.3 To outline a path forward for nurturing partnerships and collaboration for IFW systems. The next chapter will provide an overall discussion and conclusion of the thesis.

Position of the reader

Part 1	Chapter One Introduction
	Chapter Two Background and Context
Part 2	Chapter Three Research Design
	Chapter Four Methods Results and Overarching Findings
Part 3	Chapter Five Volunteered Geographic Information for people-centred severe weather early warning: A literature review
	Chapter Six Identifying the data uses and gaps for severe weather impact forecasts and warnings
	Chapter Seven Identifying data sources for severe weather impact forecasts and warnings in Aotearoa New Zealand
	Chapter Eight A socio-technical analysis of sharing and governing hydrometeorological impact data in Aotearoa New Zealand
	Chapter Nine Integration of Partnerships and Collaboration to Support IFWs and HIVE Data Collection, Access, and Use
Part 4	Chapter Ten Discussion and Conclusion

Chapter Ten: **Discussion and Conclusion**

This chapter provides a discussion of, and conclusion for, this doctoral thesis. The first section (10.1) revisits the research questions and outlines how these research questions were addressed in the thesis. The second section (10.2) discusses the research implications, followed by limitations and future research directions in the third section (10.3). The final section (10.4) concludes the thesis.

10.1 Research Overview

This thesis contributes to current efforts towards implementing Impact Forecasting and Warning systems for hydrometeorological hazards. This doctoral research study set out to answer the research question:

> Which data are needed to support Impact Forecasting and Warning (IFW) systems for hydrometeorological hazards, and how are they currently collected, stored, and shared in New Zealand?

This question was broken down into five sub-questions. The Evolved-Straussian Grounded Theory research strategy was employed to address these research questions. Each of these research questions and their associated objectives are presented in Table 10.1 and will be addressed in turn. Table 10.1 further summarises the highlights of each chapter in alignment with the research questions and objectives.

Table 10.1. Alignment of chapters with research questions and objectives.

Research Questions	Objectives	Chapter and Paper Highlights
1. What are the current and potential uses of Volunteered Geographic Information (VGI) for severe weather warnings?	1.1 To establish VGI as a potential source of impact data for IFWs.	Chapter Five • Various forms VGI, from geo-located social media, crowdsourcing platforms, participatory mapping/participatory GIS, and local knowledge, have value and a role to play in all components of a severe weather EWS. • Some forms of VGI are more useful for specific EWS components than are others. • VGI processes can bridge the gap between EWSs and audiences of warnings by incorporating local knowledge and personal experiences from stakeholders into the EWS components.
2. What are the data uses and gaps for impact forecasts and warnings?	2.1 Identify the actors involved in an IFW system and their associated roles. 2.2 Determine how HIVE data are used in an IFW system. 2.3 Identify further data gaps/needs for implementing IFWs.	Chapter Six • Supports existing research pointing to the need for creating, gathering, and using impact, vulnerability, and exposure data for IFW systems. • Identifies where each data type (hazard, impact, vulnerability, and exposure) can be used for each Warning Value Chain component. • Offers examples of alternative approaches for impact forecasting and for defining impact thresholds. • Provides new insight into a growing need to identify, model, and warn for social and health impacts.
3. What are the sources of HIVE data?	3.1 Identify the creators, collectors, and users of HIVE data that is relevant to severe weather IFWs. 3.2 Identify the inhibitors and facilitators to collecting and using these data, to support the implementation of an IFW system in New Zealand for severe weather hazards.	Chapter Seven • Identifies various sources for hazard, impact, vulnerability, and exposure data for implementing severe weather IFW systems. • Points to technological advancements for enabling collection and creation of HIVE data, such as GIS-based tools and mobile devices. • Suggests that priorities, motivation, and interest within organisations influence how well data is collected and used. • Identifies a tension between the timeliness and trustworthiness of data needed for emergency response and warnings. • Proposes strategies for addressing challenges and barriers for collecting and using HIVE data.

Research Questions	Objectives	Chapter and Paper Highlights
4. How can HIVE data governance, access, and sharing be improved for hydrometeorological hazards in New Zealand?	4.1 Identify and understand the governance and acquisition process for HIVE data for severe weather hazards in New Zealand. 4.2 To support efforts to fulfil the Sendai Framework priorities around disaster data access. 4.3 To support the implementation of a severe weather IFW system.	Chapter Eight • Identifies a need for data governance of hazard, impact, vulnerability, and exposure data. • Identifies a need for building and nurturing stronger partnerships to continue building trust between stakeholders for sharing data. • Proposes systematic and standardised data collection approaches using GIS-based tools to address data integration challenges.
5. How can partnerships and collaboration facilitate better collection, creation, and access to HIVE data for IFWs?	5.1 To identify the required partnerships and collaborations required for IFW systems. 5.2 To identify existing partnerships and collaboration in NZ that can support IFW systems. 5.3 To outline a path forward for nurturing partnerships and collaboration for IFW systems.	Chapter Nine • Identifies Partnerships and Collaboration as the core category due to its explanatory power around IFW implementation and accessing and using the required HIVE data for IFWs. • Proposes approaches and strategies to building and nurturing partnerships and collaboration in support of IFW implementation and HIVE data collection, access, and sharing (e.g., providing more networking opportunities via conferences, training, workshops; cohabitation; inter-disciplinary collaboration). • Identifies sharing data and knowledge as the interface between the two phenomena in this study (IFW Systems and HIVE Data). • Integrates the properties and dimensions of the core category with the IFW and HIVE data phenomena, and with the IFW and DRR literature.

10.1.1 Research Question 1: What are the current and potential uses of Volunteered Geographic Information (VGI) for severe weather warnings?

Chapter Five answered the first research question *"What are the current and potential uses of Volunteered Geographic Information (VGI) for severe weather warnings?"* in the form of a scoping literature review. This research question was posed for the original topic of this thesis research which aimed to explore the role of social media and crowdsourcing for collecting impact data to support IFWs. Volunteered Geographic Information (VGI) was chosen as the form of social media and crowdsourcing data to explore because of the location information associated with it, which was proven to be an essential data piece for IFWs. Findings from the scoping literature review methodology employed in this manuscript indicated that:

- VGI is useful in all components of a severe weather EWS, but some platforms are more useful for specific components than are others.
    - Participatory mapping/participatory GIS and crowdsourcing support the disaster risk knowledge component of an EWS by validating risk maps/maps, integrating local and spatial knowledge, and populating hazard and impact databases.
    - Geolocated social media and crowdsourcing support detection, monitoring, and warning services by providing near real-time hazard and impact detection, forecasting, and warning verification, and estimates of hazard and impact severity based on incoming reports through these platforms.
    - Geolocated social media supports the communication and dissemination mechanism component by enabling warning services to assess the spread of, and response to, warning messages, and allowing the warning services to update subsequent warning messages based on social media activity.
    - Local knowledge and geolocated social media support preparedness and early response capacity by providing further understanding of knowledge and perceptions of local hazards risks and impacts, and informing local preparedness efforts with real-time hazard and impact information.
- Furthermore, VGI supporting people-centred EWSs by bringing people and their knowledge and experiences into EWSs.

Following the completion of this phase of the research, interviews with participants both in and outside of New Zealand pointed towards more pressing issues around accessing and using vulnerability and exposure data, not just impact data, for IFW systems. Thus, the focus of this doctoral thesis broadened to the topic of accessing and using hazard, impact, vulnerability, and exposure (HIVE) data for IFWs. This led to the development of the next three research questions, discussed next.

10.1.2 Research Question 2: What are the data uses and gaps for impact forecasts and warnings?

Chapter Six answered the research question *"What are the data uses and gaps for impact forecasts and warnings?"* using qualitative data collection and analysis methods employed under the Evolved-Straussian Grounded Theory research strategy. Using the Warning Value Chain (Golding et al., 2019) as a framework, the actors involved in IFW systems were identified, along with various uses of HIVE data from the interview and workshop data for the Value Chain components. Findings from this manuscript included:

- Within the Warning Value Chain:
    - Hazard data is used for Hazard, Observation, Monitoring, and Detection; Weather Forecasting; Hazard Forecasting; Impact Forecasting; and Impact Warnings.
    - Impact data is used for Hazard Forecasting; Impact Forecasting; Impact Warning; and Decision/Action.
    - Vulnerability data and Exposure data are used for Impact Forecasting and Impact Warning.
- Within the Impact Forecasting and Impact Warning value chain components, different approaches for Impact Forecasting and defining impact thresholds were identified that use quantitative models and impact-oriented discussions depending on the data available. For example, model-based approaches use algorithms and quantitative data to identify potential impacts. If quantitative data are not available, impact-oriented discussions using tacit knowledge, map/spatial data, etc. are used. Ideally, both approaches should be used complementarily.
- There is a growing need fill the following data gaps for IFWs:
    - We need to identify, model, and warn for social and health impacts, which have typically taken a back seat to modelling and forecasting physical and infrastructure impacts.
    - Dynamic exposure and dynamic vulnerability are needed to account for antecedent conditions, human response capabilities, and human behaviour, which change over space and time, thus pointing to the need for thresholds to be based on these dynamic factors.

These findings on the data needs and uses within IFW systems will help guide their development, fill data gaps, and provide a pathway for identifying specific relevant data sources.

10.1.3 Research Question 3: What are the sources for HIVE data?

The third research question, *"What are the sources for HIVE data?"* was answered in Chapter Seven using the Evolved-Straussian Grounded Theory data collection and analysis methods of the interview and workshop data. Findings indicated that:

- Many sources of HIVE data are collected for other uses (such as for response efforts for disaster and emergency events, and for research) that have relevant application for IFWs.
    - Examples of sources of HIVE data that are not currently used widely for IFW are social media and crowdsourced data, emergency call centre reports, damage surveys, health and injury data, damage assessments, cultural impacts, census data, and health data.
- Priorities, motivation, and interest within organisations influence how well data is collected. Moreover, agencies tend to prefer official data, but official data has limitations that unofficial data (such as social media and crowdsourcing) may address, such as timeliness.
- To that end, an interesting tension was identified between the timeliness and trustworthiness of data needed for emergency response and warnings.

The findings from this manuscript provide a resource for warning services and other stakeholders, who are looking to implement IFWs or otherwise access hydrometeorological HIVE data, to identify data sets and data sources for their needs.

10.1.4 Research Question 4: What is the governance and acquisition process for HIVE data for severe weather hazards in New Zealand?

The fourth research question, *"How can HIVE data governance, access, and sharing be improved for hydrometeorological hazards in New Zealand?"* was answered in Chapter Eight, again using the Evolved-Straussian Grounded Theory data collection and analysis methods for the qualitative interview and workshop data. Findings are summarised below:

- HIVE data is largely managed by the creators and owners of the datasets. For example, the MetService manages its meteorological observational data and forecasts, NIWA manages the national climatological database, CDEM Groups manager their damage assessment data, LINZ manages national geospatial information, Stats NZ manages census data, and NEMA manages the national loss database for Sendai Framework reporting.
    - A need for establishing data governance principles for HIVE data was identified to improve the accessibility to and sharing of HIVE data.
    - A need for nurturing partnerships was identified for building trust between stakeholders such that data and knowledge can be efficiently shared between agencies for IFWs.
- Furthermore, data integration challenges continue to plague the use of various sources of HIVE data for effective risk and impact assessments for IFWs and beyond. Systematic and standardised data collection approaches using GIS-based tools were identified as strategies for supporting integration.

The findings from this manuscript proposed practical strategies for stakeholders to improve the management of, access to, and sharing of HIVE data for IFWs and other DRR efforts.

10.1.5 Research Question 5: How can partnerships and collaboration facilitate better collection, creation, and access to HIVE data for IFWs?

The fifth and final research question, *"How can partnerships and collaboration facilitate better collection, creation, and access to HIVE data for IFWs?"* was answered in Chapter Nine, which integrates the findings from Chapter Five to Chapter Eight into the core category of Partnerships and Collaboration.

- Partnerships and Collaboration was identified as the core category due to its explanatory power around IFW implementation and accessing and using the required HIVE data for IFWs.
- Sharing data and knowledge was identified as the interface between the two phenomena in this study (IFWs and HIVE Data). The partnerships and collaboration to support this facilitate better collection of, creation of, and access to HIVE data as this allows warning agencies to access and use information that they may not otherwise have but require for an IFW system.
- Challenges with building Partnerships and Collaboration were identified from the literature, and the approaches and strategies identified in this chapter were proposed as potential solutions to these challenges.

Chapter Five to Chapter Eight have answered the research questions and addressed the research objectives, as shown in Table 10.1. Together, these chapters answered the overarching question of "*Which data are needed to support Impact Forecasting and Warning (IFW) systems for hydrometeorological hazards, and how are they currently collected, stored, and shared in New Zealand?"*

10.2 Research Implications and Contributions

Impact Forecasts and Warnings (IFWs) have been proposed by the WMO to address communication gaps and challenges with traditional hydrometeorological Early Warning Systems (EWSs) (Harrowsmith et al., 2020; WMO, 2015). IFWs are commonly described as communicating 'what the weather will do, rather than what the weather will be,' such that the warnings might better align with the position, needs, and capabilities of target audiences. However, a key challenge with implementing IFWs that has been identified both in the literature and in practice is the perceived lack of impact, vulnerability, and exposure data. Yet, impact, vulnerability, and exposure are key elements in assessing and understanding the risk posed by hydrometeorological hazards. This doctoral research thus provides four main contributions to the IFW literature and implementation efforts with regards to the access to, and use of, hazard, impact, vulnerability, and exposure (HIVE) data:

1) This research reiterates the growing need for gathering and using impact, vulnerability, and exposure data for IFWs. Additionally, this research points to an increasingly important need to broaden the apparent focus on understanding impacts to the built environment to social and health impacts arising from hydrometeorological hazards.
2) This research identifies many sources of HIVE data in New Zealand, and points to agencies that possess the data. This provides a pathway for stakeholders to identify data sources and partnerships required for obtaining the required data and knowledge not only for IFWs, but also for general Disaster Risk Reduction (DRR).
3) This research reveals a need for more effective management and governance of impact, vulnerability, and exposure data for hydrometeorological hazards in New Zealand. This would support both IFW implementation and DRR in New Zealand.
4) Finally, this research produced a micro-theory grounded in the qualitative data highlighting the importance of Partnerships and Collaboration for implementing IFWs. This micro-theory (Figure 9.1) also provides strategies for building and nurturing such partnerships to support stakeholders both in and outside of NZ with these efforts.

These implications are further discussed in the following sections.

10.2.1 Data Uses and Gaps for Impact Forecasts and Warnings

Research on implementing IFWs has highlighted the lack of supplemental data as a key barrier to implementing IFWs (Hemingway & Robbins, 2019; Potter et al., 2021; Wei et al., 2018). Meteorologists and forecasters have indicated that they do not possess knowledge of impacts, exposure, or vulnerability to effectively compose IFWs (Potter et al., 2021). While the literature has identified the need for impact, vulnerability, and exposure data for IFWs, it falls short in specifying where or why these data are needed. This doctoral study contributes to the discourse around the data-focused challenges of implementing IFWs, by first providing an evidence base underpinning these needs. This doctoral study then situates each data type (hazard, impact, vulnerability, and exposure) within the Warning Value Chain components, along with actors or users of these data, and provides additional justification around the need for dynamic exposure and dynamic vulnerability data. As shown in Chapter Six, HIVE data is needed throughout the Warning Value Chain. The Warning Value Chain consists of six components (Golding et al., 2019); the first three components (e.g., Observations, Monitoring, and Detection; Weather Forecasting; and Hazard Forecasting) were found to require only the hazard data that is collected and used by hydrometeorological services. These components have been well documented in the literature (Farnell et al., 2017; Kotsuki et al., 2019; Srivastava & Bhardwaj, 2013), thus findings from Chapter Six coincide with this literature and does not explore these components any further.

Findings in Chapter Six regarding the remaining three components of the Warning Value Chain (e.g., Impact Forecasting, Impact Warning, and Decision/Action) contribute to the literature by providing a broader picture of where impact, vulnerability, and exposure data are needed for IFW systems, and for what purpose(s). For example, within the Impact Forecasting component, all four types of data (hazard, impact, vulnerability, and exposure) are required to support either a subjective approach to impact forecasting (i.e., impact-oriented discussions) or an objective approach (i.e., risk or impact modelling)[38]. The actors in this component who possess these data and may be involved in the forecasting process were identified in Chapter Six of this doctoral research as hydrometeorological services, civil defence and emergency management, the lifelines sector, and risk modellers. Within the wider research body of risk and impact modelling (e.g., Deligne et al., 2017; Schmidt et al., 2011), this finding positions the role of risk modelling and impact-oriented discussions and associated actors and datasets within the IFW process. It recognises the value of both subjective and objective approaches and suggests that using these approaches complementarily may be the most effective use.

Within the Impact Warning component of the Warning Value Chain, Chapter Six of this doctoral research outlines the data needs for, actors involved in, and approaches for defining thresholds for impact warnings. Previous research has identified a gap in understanding the decision-making process for issuing IFWs and selecting appropriate thresholds (Harrison et al., 2014; Kox, Kempf, et al., 2018; Potter et al., 2021). This doctoral thesis sheds light on and begins to fill this gap by outlining subjective and objective approaches (like the approaches identified in the Impact Forecasting component) to setting impact thresholds, such as identifying trigger points for damage levels using damage surveys and risk models. Findings from Chapter Five suggest that some of the participatory processes of VGI, such as participatory mapping and participatory GIS may help with setting impact thresholds based on community inputs. Furthermore, crowdsourcing and social media can be used to collect information on damages and other impacts to inform thresholds. This doctoral research further points to the need for dynamic vulnerability and exposure data (Merz et al., 2020); signalling that historic impact data is not enough for defining impact thresholds when population characteristics and movement, land-use practices, and seasons change over space and time.

Within the final component of the Warning Value Chain, Decision/Action, Chapter Six of this doctoral thesis contributes to the literature by offering some contrary findings around the perceived benefits of IFWs to reduce warning fatigue and cry-wolf syndrome (Potter et al., 2021). While most participants indicated the potential for IFWs to reduce the effects of warning fatigue and cry-wolf syndrome, it is important to note that some participants, as reported in Chapter Six, have concerns about crying wolf when warning for impacts that did not eventuate. This finding highlights the compounding uncertainty of forecasting impacts in addition to forecasting hazards and points to the need for more data to verify and/or calibrate models, as well as further behavioural research to understand warning fatigue in the context of IFWs.

[38] It is recognised that risk models, NWP models, etc. can involve assumptions and some subjective determination of parameters (e.g., Flage & Askeland, 2020), and thus have a subjective element in their design. However, when comparing risk modelling approaches to the discussion-oriented approaches identified in this doctoral thesis, these model-based approaches are differentiated as more objective in nature than discussion-oriented approaches.

These findings further highlight the importance, and challenge, of evaluating IFWs (Potter et al., 2021; Robbins & Titley, 2018).

Findings of Chapter Six further contribute to the discussion around providing prescribed actions along with IFWs (Weyrich et al., 2018). While many participants from the EM sector reiterated the need to include prescribed actions in the warnings, one participant remained sceptical around the responsibility of providing prescribed actions to the communities within their jurisdiction, which are perceived as large and self-sufficient. This finding raises two important questions around designing and implementing IFWs: (1) what are the needs of warning recipients? and, (2) who is responsible for formulating and providing the prescribed actions? The first question echoes the need to work with communities to determine their specific warning systems needs to ensure the warnings are useful (Tarchiani et al., 2020; Thomalla et al., 2006). Findings from the literature review presented in Chapter Five suggest that Volunteered Geographic Information (VGI) is one option that may facilitate community engagement to identify warning needs for people-centred EWSs. The second question highlights the importance of clearly establishing roles and responsibilities within an IFWs. This work thus requires partnerships and collaboration such that the roles and responsibilities can be defined and allocated accordingly (Becker et al., 2017; Wein et al., 2016).

Finally, the findings from Chapter Six of this thesis highlight the need for understanding and warning for different types of impacts. Findings are consistent with previous research identifying cultural and social limitations in disaster preparedness, particularly warning response, and the need to understand the cultural contexts influencing preparedness (Ayeb-Karlsson et al., 2019). In addition to identifying gaps in modelling and warning for social and cultural impacts, this research identified a gap in NZ of warning for health impacts of certain hydrometeorological hazards, particularly severe thunderstorm-induced asthma. A previously overlooked impact of severe thunderstorms, that of asthma attacks, have caused outbreaks in both Australia and NZ, where hospitals were responding to abnormally high numbers of asthma attacks in a short period of time (Sabih et al., 2020; Thien et al., 2018). Findings from this research echo calls for capturing severe weather health impacts such as asthma attacks (Hew et al., 2017), wildfire smoke inhalation and smog (Chen et al., 2017; Cisneros & Schweizer, 2018), exposure to extreme temperatures and conditions (Astrom et al., 2014; Burgstall et al., 2019; Chen et al., 2015; Zhang et al., 2021), and mental health impacts, to build a wider view and understanding of health impacts beyond injuries and deaths. This should then be integrated into an IFW system to meet the goals of the Sendai Framework (Aitsi-Selmi & Murray, 2016). Understanding these health impacts can be met through increased partnerships with health agencies.

Research has identified confusion around who IFWs are designed for and whether they are designed for individuals or society (Potter et al., 2021). This doctoral research echoes this question, identifying differences in vulnerability and exposure to hydrometeorological hazards between urban and rural settings. This is a critical question that the global community must address.

10.2.2 Sources of hazard, impact, vulnerability, and exposure (HIVE) data in New Zealand

The literature has identified a key challenge for implementing IFWs around identifying and accessing the required data sources for IFWs (Hemingway & Robbins, 2019). While Chapter Six identified the specific needs and uses for hazard, impact, vulnerability, and exposure data in an IFW system and provide the above-mentioned contributions to the literature, Chapter Seven continued addressing this challenge by identifying sources for the required HIVE datasets both for IFWs and for general Disaster Risk Reduction (DRR). A key contribution of this doctoral research lies in identifying specific existing and potential data sources for hazards, impacts, vulnerability, and exposure. In addition to identifying these data sources, this doctoral research also identified both IFW and non-IFW uses for these datasets to allow researchers and practitioners to identify which datasets might be suitable for their needs.

In conjunction with existing literature, this doctoral research further highlights the importance and value of tacit knowledge and experience in defining impact thresholds and informing warning decisions. Tacit knowledge and experience for decision-making in EWS is not a new concept. For example, previous studies have demonstrated the use of tacit knowledge and experience for decision-making in EWSs and IFWs (Doyle, 2011; Fearnley, 2013; Potter, 2014). EM services and councils provide feedback to warning services to adjust warning thresholds according (Chapter Six; Chapter Seven; Frugis & Wasula, 2011; Kox, Lüder, et al., 2018). Forecasters and scientists also rely on experience for critical decisions involving much uncertainty around setting Volcanic Alert Levels (Fearnley, 2013; Potter, 2014), issuing flash flood and other hydrometeorological warnings (Morss et al., 2015), and developing and issuing weather forecasts (Doswell III, 2004). Much of this transferable knowledge and experience is developed through education, training, and experiencing hazardous events (Doswell III, 2004; Doyle, 2011; Fearnley, 2013; Roebber & Bosart, 1996). The findings of this doctoral research in Chapters Six and Seven add to this body of research with the NZ context of hydrometeorological hazards for IFWs, and explicitly recognise tacit knowledge and experience as an important data source for IFWs and DRR. More importantly, this doctoral research highlights the risk of losing undocumented tacit knowledge and experience due to staff turnover, etc. Thus, it is recommended that efforts are made to document this valuable resource, ideally in a format that can be used for data-driven decision-making, such as in the form of spatial layers. Regular exercises can also help to boost experience, facilitate knowledge transfer, and build capacity between team members, departments, and across agencies (Bhagavathula et al., 2021; Doyle, 2011; Molka-Danielsen et al., 2018; NEMA, 2009), and may help with defining and reviewing warning thresholds.

In terms of using these data sources, this doctoral research identified a critical tension between timely and trustworthy data, as officials (e.g., warning agencies, emergency managers, responders) need both timely and trustworthy data, but often have to compromise on either factor. This finding echoes the argument made by Mehta et al. (2017) and Potter et al. (2020) on the need to verify data from social media, crowdsourcing, and other publicly generated data. Furthermore, this doctoral research links the importance of being able to trust data with the need for warning services to be perceived as trustworthy (Covello & Sandman, 2001; Terti et al., 2019).

Findings from this doctoral research around strategies for developing innovative ways to collect HIVE data align with the Policy Capacity Framework (Wu et al., 2018) which outlines three levels of capacity development and implementation: individual, organisation, and systemic; and three dimensions: analytical, managerial, and political. This doctoral research found that individuals credited with driving innovative approaches possess analytical, technical, communication, and leadership skills to drive technological innovation within their sector (see Chapter Seven). Additionally, some agencies were found to possess technical and administrative capacity at the organisational level by providing and coordinating the resources needed to allow the individuals to implement their innovative solutions (see Chapter Seven). More investigation is needed to understand the policy capacities at the systemic level and political dimension within the NZ EM and severe weather warning space.

10.2.3 Management and Governance of HIVE Data

This doctoral study built further understanding around the management, acquisition, and sharing of HIVE data for severe weather hazards in New Zealand, towards supporting Sendai Framework priorities and implementing IFWs. The literature has indicated that the Emergency Management sector may possess much of the impact, vulnerability, and exposure data needed for IFWs (e.g., Kox, Lüder, et al., 2018; Potter et al., 2021). Findings from this doctoral research presented in Chapter Seven provided the evidence to support this suggestion and additional issues have been identified pertaining to the management of and access to these data, further explored in Chapter Eight. These findings corroborate those of Crawford et al. (2018), who found that CDEM Groups and Councils in NZ were not clear on who was responsible for collecting and managing risk data. Land Information New Zealand (LINZ) identified data custodians for many fundamental geospatial datasets (LINZ, 2014a), yet findings from this doctoral research show that many risk-related datasets have been overlooked in the LINZ assessment classification of fundamental geospatial datasets. To that end, this doctoral research identified a need for data governance of impact, vulnerability, and exposure data for hydrometeorological hazards. This involves identifying and appointing stewards and custodians of the relevant datasets such that the datasets can be maintained and available for further use beyond their initial purpose.

Accessing and sharing datasets for IFWs and other DRR uses is another challenge that has been identified in the literature (De Groeve, 2015; Fakhruddin, Chu, et al., 2019; Kaltenberger et al., 2020). In Chapter Eight of this doctoral research, socio-technical intervening conditions were found to inhibit these efforts, such as trust/distrust, privacy and security, and integration challenges. Some action/interaction strategies were identified to address these intervening conditions: building partnerships and ensuring privacy and security to increase trust, and implementing systematic and standardised data collection practices. These findings highlight the importance of inter-agency knowledge and data sharing both for IFWs and for general DRR efforts (Doyle & Paton, 2017; Fakhruddin, Chu, et al., 2019; Hemingway & Gunawan, 2018). The consequences of restrictive data access and lack of information sharing for DRR can lead to disastrous consequences, as was seen in the USA following the landfall of Hurricane Katrina in 2005 where agencies made duplicative evacuation plans resulting in a 24-hour delay to the evacuation, and where agencies sent survivors to overcrowded hospitals (Peled, 2011). It is possible to establish open data access and sharing for DRR. Local, provincial, and national agencies, and regional and national academic and research institutions in Argentina collaboratively established an open data platform for flood impact reduction, "with a view to socializing knowledge for early alerts" (De Giusti et al., 2016, p. 86). The findings from this doctoral research point to the need to establish similar efforts for hydrometeorological data in NZ.

10.2.4 The importance of Partnerships and Collaboration for implementing IFWs

Partnerships and Collaboration was identified as the central theme (i.e., core category) to implementing IFWs and collecting, accessing, and using the required data. The relationship of Partnerships and Collaboration with the two phenomena in this study (IFWs and HIVE Data) is represented in Figure 9.1. Sharing knowledge and data is the interface between these two phenomena because it fills the data gap identified by meteorologists in practice and in the literature for implementing IFWs (e.g., Potter et al., 2021). The idea of Partnerships and Collaboration is not new, as it has been identified by the WMO and other agencies as a necessary strategy for implementing IFWs (Harrowsmith et al., 2020; WMO, 2015). Furthermore, the UK NHP has been exemplified for its role in implementing IFWs in the UK (Hemingway & Gunawan, 2018). This study provides further empirical evidence from the NZ context of the need for building and nurturing partnerships and collaboration both for implementing IFWs and for better management of, and access to, HIVE data for IFWs and DRR in general.

Multi-organisational collaboration has many challenges that have been identified in the literature (Pennington et al., 2015; Sonnenwald, 2007). The strategies and approaches proposed in Chapter Nine can be enacted for addressing some of these challenges and for building and nurturing partnerships and collaboration in NZ towards implementing IFWs and collecting, sharing, and using the required HIVE data for IFWs and other DRR efforts. The findings of this thesis build on existing recommendations from the IFRC guide on implementing IFWs (Harrowsmith et al., 2020) and provide more tangible and direct strategies.

This doctoral thesis contributes to the global understanding of how hydrometeorological and emergency management services can implement IFWs, by advancing the discussion around implementing IFWs as per the WMO's guidelines, and around building up disaster risk data in accordance with the Sendai Framework Priorities. An important outcome of this research is the provision of a pathway for stakeholders to identify data sources and partnerships required for implementing a severe weather IFW system.

10.3 Limitations and Future Research Directions

Several limitations of this doctoral study must be acknowledged. While the qualitative nature of data collection and analysis herein limits the generalisability of results beyond the participants, this approach offers in-depth understanding of a problem not readily available from quantitative approaches, appropriate for an exploratory study such as this (Blumer, 1969; Miles & Huberman, 1994; Patton, 2002). Furthermore, the purpose of theory-building in Grounded Theory is not to generalise, but to generate a theory with the most explanatory power for a particular set of data (Strauss & Corbin, 1998). The results of this doctoral thesis are grounded in the experience and knowledge of the participants of this study in a specific time and place (Alammar, 2018). Thus, this may be considered a local, micro-theory (Figure 9.1), rather than a formal theory (Alammar, 2018). To increase the generalisability of these results beyond the participants and beyond the NZ context, future research can be conducted to test the concepts developed in this research to a study in another area and/or amongst a different set of participants (Chametzky, 2013).

The events of and response to the COVID-19 pandemic interfered with the data collection efforts for this PhD study. As such, several key informants were unable to be recruited and participate in this study due to their involvement in the COVID-19 response, such as EM practitioners well-versed in the collection and management of Wellbeing and Welfare data. Furthermore, interview and workshop methods had to be flexible and adaptable to the uncertain and ever-changing conditions posed by the COVID-19 risks and response. While in-person interviews and workshops were preferred to facilitate high quality data collection, this was not always feasible. The first workshop coincided with COVID-19 alert level changes and associated 'lockdowns' in parts of NZ, and as such had to be made virtual. For consistency, the remaining two workshops were also held virtually. This created an opportunity to experiment with novel workshop data collection methods, such as the online whiteboard platform Mural[39]. The results of these workshops revealed both strengths and weaknesses of running virtual workshops and provides opportunities for learning from and planning future virtual data collection methods.

[39] https://www.mural.co/

The coding process in Grounded Theory research can be described as interpretive and hence subjective in nature (Alammar, 2018). The role of the researcher is to construct concepts and categories that are both grounded in the data and 'feel right' to the researcher (Alammar, 2018). In this process, the researcher relies on their experience and knowledge of the literature and of the field to interpret the data, construct concepts, and identify relationships between the concepts (Glaser & Strauss, 1967). As a geographer with several years of experience working in the GIS field, it can be argued that the interpretation of the data was rather data-heavy featuring elements of GIS. If the data collected for this study were given to a different coder, different codes and categories, and thus, different results, would likely be produced. Broadening the topic of this PhD research when the data and participants were pointing away from the original topic of VGI for collecting impact data towards the new topic of accessing impact, vulnerability, and exposure data exemplifies my ability as a researcher to discover the story that the participants and the data want to tell. Furthermore, I ensured transparency of my methodology and results chapters (Chapters Chapter Three to Chapter Nine) by providing direct quotes from my participants; member checking the interview references, quotes, and interpretations with my participants; and practicing sensitivity towards my participants.

The findings presented in this research are focused on the core category of Partnerships and Collaboration. However, a core category of Governance was also identified (Chapter Four) and is an equally interesting and important component to this research. However, it was deemed beyond the scope of this doctoral research and identified as a research question worthy of its own future research project. For example, future research could explore how governance can support these partnerships and collaboration, and how the governance structure of NZ or other countries influence how IFWs and other EWSs are designed and implemented.

Theoretical sensitivity is a required skill employed by the Grounded Theory researcher (Glaser & Strauss, 1967), and pertains to the researcher's ability to develop meaning from the data and assign relevant concepts (Corbin & Strauss, 2008). The researcher must be able to decide which categories are important and provide explanations on the categories' relationships (Corbin & Strauss, 2008). As a novice researcher in Grounded Theory, my level of theoretical sensitivity might have limited some of the results of this research.

This study focuses on one family of hazards out of many that are present in New Zealand. Throughout the course of this research, participants and colleagues pointed to the need for multi-hazard research and multi-hazard EWSs. The choice to focus on hydrometeorological hazards for this research is justified by my own background and experience in conducting research on hydrometeorological hazards, and because IFWs have predominantly emerged from hydrometeorological hazard research. The funding for this research through the Resilience to Nature's Challenges Weather & Wildfire theme also required a hydrometeorological focus. The PhD topic/scholarship was also developed to be in alignment with the WMO WWRP HIWeather research project, which has a hydrometeorological focus. There is opportunity for exploring how the findings from this research and the IFW research body can be transferred to other hazards and to multi-hazard approaches.

There is further opportunity to address the issues identified in this research, such as the question of roles and responsibilities and strengthening partnerships for IFWs and HIVE data collection and sharing, through the current review of the CDEM sector in NZ (i.e., the Regulatory Framework Review ('Trifecta') Programme) (NEMA, 2021b). This review involves projects for developing a new Emergency Management Act; reviewing the National CDEM Plan Order 2015 and the accompanying Guide to the National CDEM Plan 2015; and developing the National Disaster Resilience Strategy Roadmap (NEMA, 2021b).

10.4 Conclusion

Three research gaps were identified at the beginning of this doctoral research study. First, the initial gap that this research aimed to fill was that of the role of Volunteered Geographic Information (VGI) within people-centred Early Warning Systems (EWS), intending to support Impact Forecasts and Warnings (IFWs). After conducting a scoping literature review and preliminary interviews with stakeholders of hydrometeorological warning systems both outside of and in New Zealand, the second research gap was identified as a need to understand and characterise the *uses* for hazard, impact, vulnerability, and exposure (HIVE) data within an IFW system. Finally, upon developing this understanding, there was a need to identify the *sources* of HIVE data and understanding how they are *governed, accessed,* and *shared* to support IFWs. This exploratory study employed an Evolved-Straussian Grounded Theory (ES-GT) research strategy to address these gaps.

The overarching findings and results of the ES-GT research strategy were first presented in Chapter Four. Thirty-nine individuals involved in hydrometeorological warning systems and DRR within and outside of NZ were interviewed, with an additional twenty individuals that participated in three virtual workshops. Results of the ES-GT analysis identified two research phenomena underpinning this doctoral research: (1) IFW implementation, and (2) HIVE Data. Following an exploration of the first research question regarding VGI for EWSs, the results of this thesis were organised by phenomenon. Finally, the core category resulting from the ES-GT analysis was identified as Partnerships and Collaboration. The resulting micro-theory of this doctoral thesis thus integrated the core category with the two research phenomena.

The first research gap regarding understanding the role of VGI within people-centred EWSs was explored through a scoping literature review (Chapter Five) and preliminary interviews. The scoping literature review identified VGI as a tool for both capturing the necessary data in an EWS and for facilitating engagement to support people-centred EWSs. Interviews following this scoping literature review indicated that there was a perceived greater need to identify the sources of not just impact data, but also vulnerability and exposure data for IFWs. The second research gap was identified.

The second research gap concerning understanding and characterising the role of HIVE data within an IFW system was answered by situating the role of HIVE data within the Warning Value Chain (Chapter Six) based on interviewing and conducting workshops with experts, practitioners, and researchers in the hydrometeorological warnings and disaster management space. Chapter Six identified the various actors and users of the data within the Warning Value Chain and explored how HIVE data is used across the value chain. Key findings were that two approaches exist for forecasting impacts (e.g., an objective model-based approach, and a subjective discussion-based approach) and that there is a need to further integrate social impacts of hydrometeorological hazards into IFWs.

Following this, the sources of HIVE data were identified based on interviews and workshops with its creators and users to begin addressing the second research gap (Chapter Seven). Following the ES-GT research strategy, intervening conditions were identified that may interfere with data collection efforts, such as priorities, motivation, interest within organisations, and mistrust in the data. Action/interaction strategies were proposed based on the qualitative data to address these intervening conditions. Examples of these action/interaction strategies include garnering support and buy-in from decision-makers, leadership within the field of practice to drive priorities and establishing measures for quality control and data standardisation.

Upon identifying the HIVE data sources and learning from a participant that "although we all complain about a lack of data, a lot of the time, there is quite a bit of data out there that could be used and isn't being used very well" (Risk Modelling NZ. A) subsequent research explored why these data are not being used very well (Chapter Eight). Data governance and data access and sharing were identified as important themes influencing the use of HIVE data in New Zealand. Intervening conditions that inhibit or facilitate data governance, access, and sharing were identified, along with action/interaction strategies. Intervening conditions include unclear roles and responsibilities for managing and governing the data, distrust between agencies, and data integration challenges. Action/interaction strategies to address these intervening conditions include building partnerships and establishing standards and processes for systematic data collection.

One key action/interaction strategy was found to thread throughout most themes of this doctoral research, tying the research gaps together: Partnerships and Collaboration. This category was explored in Chapter Nine, where it was integrated into the broader results of the thesis and the literature and a micro-theory was created. Sharing data and knowledge was identified as the interface between the two phenomena in this study (IFW implementation and HIVE Data), as it allows warning agencies to access and use information that they may not otherwise have but require for an IFW system. Sharing data and knowledge requires strong partnerships and collaboration. Approaches and strategies for building and nurturing partnerships were proposed to support IFW implementation and HIVE data collection, access, and sharing.

The chapters presented in this thesis have limitations and point towards areas for future research. This doctoral thesis contributes to the academic discussion around the steps required to implement IFW systems and provides practical guidance to warning services and researchers around opening access to and sharing HIVE data for both IFW implementation and DRR efforts. This doctoral research thus supports current and essential efforts to reduce impacts on people and communities from hydrometeorological hazards and to help report this reduction through Sendai Framework initiatives.

Appendix A: Statements of Contribution

DRC 16

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UNIVERSITY OF NEW ZEALAND

GRADUATE RESEARCH SCHOOL

STATEMENT OF CONTRIBUTION
DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the candidate and the candidate's Primary Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated below in the *Statement of Originality*.

Name of candidate:	Sara Harrison
Name/title of Primary Supervisor:	Raj Prasanna
In which chapter is the manuscript /published work:	Five

Please select one of the following three options:

(●) The manuscript/published work is published or in press

- Please provide the full reference of the Research Output:

Harrison, S., Potter, S., Prasanna, R., Doyle, E. E. H., & Johnston, D. (2020). Volunteered Geographic Information for people-centred severe weather early warning: A literature review. Australasian Journal of Disaster and Trauma Studies, 24(1).

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

The candidate conducted the data collection and analysis, drafted the manuscript, and made subsequent revisions based on supervisors' and reviewers' feedback.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Digitally signed by Sara Harrison Date: 2021.09.23 10:30:45 +12'00'
Date:	23-Sep-2021
Primary Supervisor's Signature:	Raj Prasanna Digitally signed by Raj Prasanna Date: 2021.09.24 11:15:21 +12'00'
Date:	24-Sep-2021

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In which chapter is the manuscript /published work:	Six

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- Please provide the full reference of the Research Output:

Harrison, S. E., Potter, S. H., Prasanna, R., Doyle, E. E. H., & Johnston, D. M. (2022). Identifying the data uses and gaps for severe weather impact forecasts and warnings. Weather, Climate, and Society. https://doi.org/10.1175/WCAS-D-21-0093.1

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- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate:

- Describe the contribution that the candidate has made to the manuscript/published work:

The candidate conducted the data collection and analysis, drafted the manuscript, and made subsequent revisions based on supervisors' and reviewers' feedback.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Sara Harrison Digitally signed by Sara Harrison Date: 2022.02.15 07:59:43 +13'00'
Date:	15-Feb-2022
Primary Supervisor's Signature:	Raj Prasanna Digitally signed by Raj Prasanna Date: 2022.02.15 08:21:34 +13'00'
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In which chapter is the manuscript /published work:	Seven

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- Please provide the full reference of the Research Output:

Harrison, S. E., Potter, S. H., Prasanna, R., Doyle, E. E. H., & Johnston, D. (In Press). 'Where oh where is the data?': Identifying data sources for hydrometeorological impact forecasts and warnings in Aotearoa New Zealand. International Journal of Disaster Risk Reduction.

( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

- The percentage of the manuscript/published work that was contributed by the candidate: 80.00

- Describe the contribution that the candidate has made to the manuscript/published work:

The candidate conducted the data collection and analysis, drafted the manuscript, and made subsequent revisions based on supervisors' and reviewers' feedback.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Sara Harrison Digitally signed by Sara Harrison Date: 2021.09.23 10:30:45 +12'00'
Date:	23-Sep-2021
Primary Supervisor's Signature:	Raj Prasanna Digitally signed by Raj Prasanna Date: 2021.09.24 09:02:29 +12'00'
Date:	24-Sep-2021

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( ) The manuscript is currently under review for publication – please indicate:

- The name of the journal:

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- Describe the contribution that the candidate has made to the manuscript/published work:

The candidate conducted the data collection and analysis, drafted the manuscript, and made subsequent revisions based on supervisors' and reviewers' feedback.

( ) It is intended that the manuscript will be published, but it has not yet been submitted to a journal

Candidate's Signature:	Sara Harrison Digitally signed by Sara Harrison Date: 2022.02.15 08:01:43 +13'00'
Date:	15-Feb-2022
Primary Supervisor's Signature:	Raj Prasanna Digitally signed by Raj Prasanna Date: 2022.02.15 08:22:39 +13'00'
Date:	15-Feb-2022

This form should appear at the end of each thesis chapter/section/appendix submitted as a manuscript/ publication or collected as an appendix at the end of the thesis.

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Appendix B: Information Systems Research Paradigms

Positivism/Post-positivism

The Positivist/Post-positivist paradigm is associated with a realist ontological approach, meaning that 'reality is real' and independent of the 'knower' or the 'social actor' (Lee, 2004; Scotland, 2012). The Positivism/Post-positivism research paradigm is typically guided by an objectivist epistemology (Scotland, 2012). The early positivist paradigm was guided by the assumption that the researcher and the research subject were independent, however this was modified by the post-positivism paradigm where it is recognised that the researcher's background knowledge of theories and hypotheses can influence what is observed (Mertens, 2015). Thus, in the post-positivist paradigm, researchers must approach the research subject objectively and prevent their biases from influencing the outcomes (Guba & Lincoln, 1994; Mackenzie & Knipe, 2006; Mertens, 2015).

The approach of Positivist/Post-positivist research is described as "experimental and manipulative" (Guba & Lincoln, 1994, p. 110), suggesting that the research typically follows a quantitative approach, however, a qualitative approach can also be used (Mertens, 2015). The research is guided by hypotheses that are empirically tested and verified (Guba & Lincoln, 1994). James Scotland described the Positivist/Post-positivist methodology as consisting of "verifiable evidence sought via direct experience and observation; this often involves empirical testing, random samples, controlled variables (independent, dependent and moderator) and control groups" (Scotland, 2012, p. 10). This kind of research tends to investigate, determine, and predict the causal relationships (i.e. the 'how' and 'why') and theories developed from the data deductively (Creswell, 2014; Scotland, 2012). Examples of data collection methods include experiments, quasi-experiments, tests, surveys, and scales (Mackenzie & Knipe, 2006).

Interpretivism

Seemingly opposite to the Positivism/Post-positivism paradigm, the ontological position of the Interpretivist paradigm is a relativist one, meaning that reality is formed by the social actors and their social structure and culture, and that the world is 'meaningless' without consciousness (Lee, 2004; Lincoln & Guba, 2005; Scotland, 2012). Interpretivism is guided by a transactional and subjectivist epistemology (Guba & Lincoln, 1994; Mertens, 2015). Knowledge of a subject or object is gained through the researcher's transactional interactions with it and findings are created as the research is conducted (Guba & Lincoln, 1994; Mertens, 2015; Scotland, 2012). In this sense, knowledge is subjective. It is based on personal experience and is built through participation (Scotland, 2012).

The Interpretivist approach is described as "hermeneutical and dialectical" (i.e., the research is built on discussions and interpretation) (Guba & Lincoln, 1994, p. 111). The research approach is typically qualitative (Mertens, 2015). The researcher employs methods that require interaction with the participant(s) to understand their perspective and build context (Scotland, 2012). Theories are drawn from the data through induction, rather than deduction (Morgan, 2007). Example research strategies include Case Study, Phenomenology, Hermeneutics, and Ethnography (Scotland, 2012). Data collection methods include interviews, observations, document reviews, and visual data analysis (Mackenzie & Knipe, 2006; Mertens, 2015).

Critical Theory

The Critical Theory paradigm holds a historical realism ontological approach (Guba & Lincoln, 1994). This means that human experiences and cultures shape reality over time and there are multiple versions of reality based on social positioning (Guba & Lincoln, 1994; Mackenzie & Knipe, 2006; Mertens, 2015). The epistemological approach under this paradigm is similar to that of the Interpretivist, with the added dimension of applying a cultural lens and maintaining awareness of power issues (Mertens, 2015). This means that the researcher is aware of the cultural complexities and power dynamics present in the interaction (Mertens, 2015).

The Critical Theory paradigm is described as "dialogic and dialectical" (Guba & Lincoln, 1994, p. 110). The researcher and subject must develop a transactional dialogue to exchange and develop ideas, and to "transform ignorance and misapprehensions" (Guba & Lincoln, 1994, p. 110). The researchers are described as "pluralistic and evolving in their methodologies" (Mertens, 2015, p. 33). The methodology is typically designed to include diverse, marginalised groups and allow them to participate in the research (Mackenzie & Knipe, 2006; Mertens, 2015).

Pragmatism

The Pragmatic paradigm is a dissident research paradigm as it places less emphasis on ontology and epistemology, and more emphasis on the nature of human experience (Morgan, 2014). As a paradigm, Pragmatism recognises the value of the former paradigms, namely Positivism/Post-positivism and Interpretivism, in conducting social research (Morgan, 2014). Pragmatists see "no problem with asserting both that there is a single 'real world' and that all individuals have their own unique interpretations of that world" (Morgan, 2007, p. 72). Epistemologically, Pragmatists gain knowledge from inquiries and actions (Goldkuhl, 2004; Morgan, 2014). In Göran Goldkuhl's words, "Pragmatism means the recognition of the complete dialectic between knowledge and action: proper action is an action with knowledge; the right knowledge is active knowledge" (Goldkuhl, 2004, p. 24). Within the field of IS, "a Pragmatist is interested in chance and action… the research endeavour is towards knowledge, which makes a positive difference, i.e., knowledge which contributes to improvement of IS practices" (Goldkuhl, 2004, p. 20).

Given that Pragmatists place less emphasis on the ontological and epistemological approaches to research and more on action and experience, Morgan

(2007) argues that methodology is the focus as it connects "issues at the abstract level of epistemology and the mechanical level of actual methods" (p. 68).

Pragmatic research is most commonly associated with a 'mixed-methods' approach to use both quantitative and qualitative research to develop and test theories through abductive reasoning (Johnson & Onwuegbuzie, 2004; Morgan, 2007). The methodology is guided by the research question(s) and the methods are selected based on their potential to provide "useful answers" (Johnson & Onwuegbuzie, 2004, p. 18). Thus, a Pragmatic researcher must recognise that "our values and our politics are always a part of who we are and how we act", and choose what research would have the most impact, and how (Morgan, 2007, p. 70).

Participatory Inquiry

Participatory Inquiry is a fifth research paradigm with application in IS research (Breu & Peppard, 2001). The Participatory Inquiry paradigm was first proposed in 1997 by John Heron and Peter Reason who argued that the dominant paradigms described by Guba and Lincoln (Guba & Lincoln, 1994) did not account for 'experiential knowing'. The ontological approach to the Participatory Inquiry paradigm is that reality is subjective-objective and participative (Heron & Reason, 1997; Lincoln & Guba, 2005). This means that a world exists outside of the observer (it is 'objectively given'), but the observer perceives and understands the world based on their own experiences and interactions with the world (it is 'subjectively represented' in the human mind) (Breu & Peppard, 2001; Heron & Reason, 1997).

Epistemologically, the Participatory Inquiry paradigm involves four forms of 'knowing': experiential, presentational, propositional, and practical (Heron & Reason, 1997). Experiential knowledge refers to knowing through experience; knowing through direct, participative encounters (Heron & Reason, 1997). Presentational knowledge is grounded from experiential knowing which is then represented in concepts, metaphors, and stories (Breu & Peppard, 2001; Heron & Reason, 1997). Propositional knowledge is knowing "that something is the case" (Heron & Reason, 1997), and is expressed in statements and theories that arise from the research conclusions (ibid). Practical knowledge is "knowing how to do something" (Heron & Reason, 1997, p. 281), shown through skills and competencies (ibid). The researcher or 'knower' practices critical subjectivity to maintain an awareness of the four ways of knowing and of how they are interacting (Heron & Reason, 1997). Critical subjectivity ensures the quality of Participatory Inquiry research as the knowers must continue to critically examine their beliefs, assumptions, and theories in the process (Breu & Peppard, 2001).

The methodology is similar to that of the Pragmatic and Critical Theory paradigms; the methodology is designed for action and intervention, with a focus on participation and collaboration between the researcher and participants (Breu & Peppard, 2001; Heron & Reason, 1997; Lincoln & Guba, 2005). This requires that "all involved engage together in democratic dialogue as co-researchers and co-subjects" (Heron & Reason, 1997, p. 283). The central principle to this type of research is that it is done with the people, rather than on them (Heron & Reason, 1997).

Appendix C: Research Strategies

Action Research

Action Research (AR) has been widely discussed in IS literature (e.g., Baskerville & Myers, 2004; Iivari & Venable, 2009). It can be described as research that is "grounded in practical action, aimed at solving an immediate problem situation while carefully informing theory" (Baskerville, 1999, p. 3). The goal of AR is to simultaneously inform practice and research to create change (Baskerville & Myers, 2004; Iivari & Venable, 2009). Three key characteristics of AR are:

1. The researcher is actively involved, with expected benefits for both researcher and organization.
2. The knowledge obtained can be immediately applied. There is not the sense of the detached observer, but that of an active participant wishing to utilize any new knowledge based on an explicit, clear conceptual framework.
3. The research is a cyclical process linking theory and practice (Baskerville & Wood-Harper, 1998) (Baskerville & Wood-Harper, 1998, p. 239).

Iivari and Venable (2009) describe AR as "highly context dependent" (p. 2) because of the heavy involvement of a "client" to identify and address their needs. AR is an iterative process that involves collaboration between the researcher and subjects through five phases: diagnosing, action planning, action taking, evaluating, and specifying learning (Susman & Evered, 1978). However, Goldkuhl (2008) argued that the evaluation and learning phases happen throughout the process and so should be integrated into the first three phases.

For a comprehensive AR study, each phase should be completed (Susman & Evered, 1978). However, varying degrees of intervention and collaboration has led to the classification of different types of AR (Chein et al., 1948; Susman & Evered, 1978). Different data collection methods can be used, such as questionnaires, interviews, observation, etc. (Susman & Evered, 1978). This makes it a suitable research strategy under the Pragmatic paradigm.

Practical Inquiry

Practical Inquiry is rooted in the Pragmatic paradigm, and is focused on generating knowledge for general practice (Goldkuhl, 2007). Practical Inquiry has many similarities to AR, and was proposed by Goldkuhl (2008) due to criticisms around AR and its practical relevance. Thus, the primary difference between AR and practical inquiry is the contribution towards local practice versus general practice. AR, as stated earlier, is highly contextual and thus contributes knowledge for local practice whilst also contributing to the greater research community (Goldkuhl, 2008). Alternatively, practical inquiry is concerned with creating knowledge for general, practical use outside of the local practice, which also contributes to the scientific body of knowledge (Goldkuhl, 2008). AR and practical inquiry are considered the same research only when the resulting knowledge contributes to both local and general practice (Goldkuhl, 2008).

Design Science Research

Design Science Research (DSR) is an established research strategy in IS (Hevner et al., 2004). DSR "creates and evaluates [information technology] artefacts intended to solve identified organizational problems" (Hevner et al., 2004, p. 77). The leading principle of DSR is to produce an artefact to address a problem (Hevner et al., 2004). Artifacts include constructs, models, methods, instantiation, social innovations, or new resource properties (Aken, 2004; Hevner et al., 2004; Järvinen, 2007). The artefact is built by drawing from existing theories and knowledge (Peffers et al., 2007). DSR is different from AR because there is no specific client or collaboration between the researcher and client (Iivari & Venable, 2009). However, it can also be argued that the artefact is developed and designed for a generalised class of clients (people or organisations) that would or could use the artefact (Iivari & Venable, 2009).

Case Study

Case Study is the last strategy that may be applicable to this research. It is the most widely used research strategy in IS research as it enables understanding of the interactions between information technology innovations and organisational contexts (Darke et al., 1998). Case Study research is most commonly associated with qualitative research (Harrison et al., 2017), however it can be argued that it is not tied to one fixed research paradigm, but is flexible in ontology, epistemology, and methodology (Luck et al., 2006). The flexibility of Case Study research makes it a suitable strategy under the Pragmatic paradigm, especially for evaluating the consequences of choices and actions (Jacobs, 2010).

Case Study research has no specific requirements guiding it, which allows for the research design to be tailored to the research questions (Meyer, 2001). However, this flexibility also opens the research up to criticism around the methodological choices (Meyer, 2001). Thus, the researcher must be clear and open about their methodological choices (Meyer, 2001). Case studies can be single- or multi-case, with benefits and limitations for each (Darke et al., 1998). A single Case Study allows researchers to conduct in-depth investigations of a phenomena to provide "rich description and understanding" (Darke et al., 1998, p. 277). Multiple cases allow for cross-case analysis and comparison, and for investigating a phenomenon in various settings (Darke et al., 1998). Multi-case studies can strengthen research findings (Darke et al., 1998).

Appendix D: Interview Guides

Note: The interview guides were meant to be a guideline for how interviews were conducted. Due to the iterative nature of the GT research strategy, and the semi-structured nature of the interview guides, the follow-up questions were asked during the interviews that were not provided on the script. Time constraints also limited how many questions could be asked, as such questions of higher priority were highlighted in yellow to ensure they were not missed. Furthermore, due to the diverse backgrounds, expertise, and experiences of the participants involved in this study, the interview guides were frequently adjusted to be more applicable to the participant in question, and to explore emergent themes that were identified during the coding process.

General Prompts:

1. Thank you for meeting me
2. Ethics & information sheet
3. Introduce myself and my project
4. Start audio recording

PHASE 1 INTERVIEWS

Preliminary Interview Guide

1. What is your organisation's role during a severe weather event?
2. What is your role within your organisation?
    a. How long have you been in this role?
3. What do you know about impact-based forecasting and warnings?
    a. Does your organisation issue them?
    b. If not, why not?
    c. If so,
        i. Did or does your organisation face any challenges with implementing an IBFW system? If so, what were/are they?
        ii. What are the data needs for building impact-based forecasts and warnings (IBFW)?
            1. How has your organisation met these needs?
            2. What data do you need to inform your IBFW system?
            3. What are the challenges with obtaining the required data?
    d. What benefits do you see from impact-based forecasts and warnings?
    e. What do you think the future of impact-based forecasting and warnings is?
4. What data does your organisation collect about severe weather events?
    a. What are the sources of these data?
    b. What is the data used for?
    c. Does your organisation collect and store impact-related data?
        i. If yes,
            1. How do you collect impact data?
            2. What is the impact data used for?
            3. What are the challenges in collecting and storing?

4. How could alternative data sources and processes help to address these challenges? Which ones?
ii. If no,
1. Why not?
iii. What alternative sources of data has your organisation used or would be interested in using more of?
1. Why or why not?
d. What data do you need to populate such a database?
i. What are you missing?
5. How can alternative data support the implementation, development, or formulation of impact-based forecasts and warnings?
   a. If so, why and how?
   b. If not, why not?
6. What research would you like to see in this area?
7. Do you have any other comments or past experiences which you think might be relevant to tell me?

PHASE 2 INTERVIEWS

National Loss Database Interview Guide

General Information:
1. What is your role within your organisation?
2. Can you (talk to me very briefly about impact databases) explain the purpose of the national losses/impacts databases in general?
3. What is your involvement in building the national losses/impacts database?
4. Can you tell me more details about the impacts/losses database that you're developing?
   a. Timeline for completion?
   b. Designated name of the database?

Purpose and Uses of the database:

5. Why is MCDEM building this database?
   a. Intended uses? Goals & objectives?

Involvement and access:

6. Can you please tell me about who will be contributing to, and using this database, and how they will do that?
   a. Users – who and how?
   b. Contributors – who and how?
   c. Any others you would like to engage with, but haven't yet?

Database and data characteristics:

7. Can you please **describe** the characteristics of the data that you will be using?
   a. What data will be in the database?
      i. Losses? Impacts? Hazards? Other?
      ii. Fields and attributes?
      iii. Evaluation/assessment?
   b. Format?
      i. Spatial or non-spatial? Why?
   c. Scale?

i. Spatial scale – why?
ii. Temporal scale – why?
d. Any other aspects of the data that you think are worth highlighting?

8. Can you describe the reasons for using the data that you're using, versus other possible sources?
9. Are there any other loss databases in NZ that this one will relate to?
10. Do you know how key contributors get their data? (sources of impact data)
    a. Is that enough data? Is there a gap there that needs to be filled?
    b. Would more data be useful?
    c. Is the right type of data being used?
    d. What do you see as potential data sources to fill gaps that currently exist?
    e. Is crowdsourcing going to be an effective gap-filler? And if not, why not?

Challenges & Opportunities:

11. How do you think people will use this database?
    a. I'm aware of the global movement of impact-based warnings.
        i. Briefly, what do you understand an impact-based warning to be?
        ii. Has MCDEM thought much about them and who would be responsible for issuing them?
12. What have been some challenges you've faced in building the database so far?
13. What are some of the challenges you see going forward?
14. What would help you to overcome some of these challenges?
15. If you could wave a magic wand, and have a complete database, what would be the value/influence of having it?

Wrap up:

16. What would help you make progress on developing, building, designing this database for its intended uses and additional uses?
17. Is there anything you would like to add or discuss?

Risk Modelling Interview Guide

General Information:

1. What is your role within your organisation?
2. Can you briefly share your thoughts on the purpose of the national losses/impacts databases in general?
3. What is your involvement in using and collecting impact data?
4. Can you tell me about the impacts/losses data that you use and collect?

Purpose and Uses of the impact data and risk/impact modelling:

5. Why does your organisation collect and use impact data?
    a. Intended uses? Goals & objectives?
6. Can you please tell me about the risk/impact modelling that you conduct?
    a. What type of data do you need?
    b. How do you get that data?
        i. Why do you get the data this way?
    c. What kind of reformatting of the data do you have to do, if at all?
    d. How do you manage situations when the data isn't available?

Database and data characteristics:

7. Can you please **describe** the characteristics of the data that you use?
    i. Losses? Impacts? Hazards? Other?
    ii. Fields and attributes?
    iii. Evaluation/assessment?
  e. Format?
    i. Spatial or non-spatial? Why?
    ii. Other?
  f. Scale?
    i. Spatial scale – why?
    ii. Temporal scale – why?
  g. Any other aspects of the data that you think are worth highlighting?
8. Can you describe the reasons for using the data that you're using, versus other possible sources?
9. Is there any other impact or loss data in NZ that would help in your work?
  a. Is it enough data? Is there a gap there that needs to be filled?
  b. Would more data be useful?
  c. Is the right type of data being used?
  d. What do you see as potential data sources to fill gaps that currently exist?
  e. Is crowdsourcing going to be an effective gap-filler? And if not, why not?

Challenges & Opportunities:

10. I'm aware of the global movement of impact-based warnings.
  a. Briefly, what do you understand an impact-based warning to be?
  b. How do you think your work, such as risk/impact modelling, can contribute to impact-based warnings?
11. What have been some challenges in collecting and using the impact data so far for your purposes (e.g., risk modelling)?
12. What are some of the challenges you see going forward?
13. What would help you to overcome some of these challenges?
14. If you could wave a magic wand, and have a complete database, what would be the value/influence of having this database?

Wrap up:

15. What would help you make progress on developing, building, designing risk models and relevant data for its intended uses and additional uses?
16. Is there anything you would like to add or discuss?

Spatial Data Interview Guide 1

1. How has this project progressed?
  a. Who is involved?
  b. What are the roles?
2. Impact data – where, why, what, how, and when is it collected?
  a. How is it used?
  b. How is it stored?
  c. What are the sources of impact data?
  d. Why is it needed?

3. Mentioned in presentation the importance of data custodianship, what has been your experience with assigning or managing data custodianship in [region]? Who is the custodian? Why?
    a. What have been some challenges in this regard?
    b. "Where existing solutions may exist, attempts should be made to leverage of existing national schemas and datasets that may be hosted by another agency, e.g., Land Information New Zealand's Property Data Management Framework (PDMF) and Address Information Management System (AIMS)." (p. 192)
4. What have been the biggest challenges and lessons learned?
5. Can it be scaled nationally? Why or why not? How?
6. How do you see this helping warning systems, particularly impact-based forecasts and warnings?
7. How could or does this relate to the national loss database at [agency]?
8. What can help progress this project?
9. What is your vision or hope for this project?

NZ Severe Weather Catalogue Guide

General Information:

1. What is your role within your organisation?
2. What is your involvement in using and collecting impact data?
    a. Why does your organisation collect impact data?
3. Can you tell me about your organisation's severe weather database?
4. Can you tell me about the standardised collection form for capturing weather impacts?
5. Can you describe the reasons for using the data that you're using, versus other possible sources?
6. Is there any other impact or loss data in NZ that would help in your work?
    a. Is it enough data? Is there a gap there that needs to be filled?
    b. Would more data be useful?
    c. Is the right type of data being used?
    d. What do you see as potential data sources to fill gaps that currently exist?
7. Briefly, what do you understand an impact-based warning to be?
    a. How do you think your collection of impact data via the storms database or the standardised collection form can contribute to impact-based warnings?
8. What have been some challenges in collecting and using the impact data so far for your purposes?
9. What are some of the challenges you see going forward?
10. What would help you to overcome some of these challenges?
11. If you could wave a magic wand, and have a complete database, what would be the value/influence of having this database?
12. Is there anything you would like to add or discuss?

Spatial Data Interview Guide 2

1. Can you tell me a little bit about your organisation?
2. What is your role within your organisation?
3. What do you know about a national loss or impact database for New Zealand?
4. What is [organisation's] involvement in building a national losses/impacts database?
5. Can you tell me what it means to be a data custodian? Data custodianship? What is involved?
6. How does [organisation] gain access and provide access to their datasets?
7. Could you tell me about [organisation's] key data sets for resilience project?
    a. What is the purpose or objective of this project? What are the data sets?
    b. What are the data sources?
        i. Do you know how key contributors get their data?
    c. How does impact data or the national loss database fit in here, if at all?
8. How do you think people will use this database?
    a. I'm aware of the global movement of impact-based warnings.
        i. Briefly, what do you understand an impact-based warning to be?
        ii. How do you see the [organisaton's] project fitting into IBWs?
9. What have been some challenges you've faced in this project so far?
10. What are some of the challenges you see going forward?
11. What would help you to overcome some of these challenges?
12. If you could wave a magic wand, and have a complete database, what would be the value/influence of having it?

Loss Modelling Interview Guide

1. Can you briefly provide an overview of the work that you do with regards to risk, impact, and/or loss modelling?
2. Can you briefly share your thoughts on the purpose of the national losses/impacts databases in general?
3. What does risk, impact, and loss modelling mean to you?
4. What kind of data do you need or use for your work?
    a. What are the various sources of your data? And resulting products?
5. What do you think is the difference between loss and impact data?
6. Can you tell me about the impacts/losses data that you use?
7. Can you please **describe** the characteristics of the data that you use?
        i. Losses? Impacts? Hazards? Other?
        ii. Fields and attributes?
        iii. Evaluation/assessment?
    h. Format?
        i. Spatial or non-spatial? Why?
        ii. Other?
    i. Scale?
        i. Spatial scale – why?
        ii. Temporal scale – why?
    j. Any other aspects of the data that you think are worth highlighting?

8. Can you describe the reasons for using the data that you're using, versus other possible sources?
9. Is there any other impact or loss data in NZ that would help in your work?
    a. Is it enough data? Is there a gap there that needs to be filled?
    b. Would more data be useful?
    c. Is the right type of data being used?
    d. What do you see as potential data sources to fill gaps that currently exist?
    e. Is crowdsourcing going to be an effective gap-filler? And if not, why not?
10. I'm aware of the global movement of impact-based warnings.
    a. Briefly, what do you understand an impact-based warning to be?
    b. How do you think your work, such as risk/impact modelling, can contribute to impact-based warnings?
11. What have been some challenges in collecting and using the impact data so far for your purposes (e.g. risk modelling)?
12. What are some of the challenges you see going forward?
13. What would help you to overcome some of these challenges?
14. If you could wave a magic wand, and have a complete database, what would be the influence of having this database?
15. Is there anything you would like to add or discuss?

Response Agency Interview Guide

Hazard information:

1. Does FENZ use any hazard forecasts or information, such as severe weather forecasts, felt reports or shake maps for earthquakes, or ashfall prediction maps?
    a. If yes, what is it used for?

Impact information:

2. What kind of impact information do you collect?
3. Where do you collect the information from (e.g., 111 calls, social media, CDEM (follow up question if needed: do you look at impact data collected by other agencies))
    a. Aside from 111 calls, do you collect any impact information from the public through crowdsourcing and social media? Why/why not?
4. What is the impact information used for?
    a. What are other uses of this impact information (thinking of heat mapping done of 111 calls to map tornado damage)?
5. Does the resulting impact data get stored, or shared with any other agencies? Who, and what for?
    a. Prompt about national loss database if not brought up
6. What are some challenges in collecting, managing, storing, and/or sharing impact information/data?
    a. What would help you overcome some of these challenges?
    b. Do you think FENZ would benefit from accessing more impact data, such as from crowdsourcing using apps, or through impact models? How so?

c. What are some of the challenges for FENZ if real-time impact information was collected from the public and made openly available on a web tool?

Lifelines Sector Interview Guide

Current warnings and warning needs:

1. Can you tell me about the severe weather warnings that you receive from the MetService?
    a. Do they currently meet the lifelines groups' needs? Why or why not?
    b. What kind of decisions do lifelines try to make with severe weather warnings?
    c. Are these warnings meeting your needs?
2. How might impact-based warnings be useful or not useful for the lifelines group sector? Why or why not?
    a. Impact-based forecasting and warning systems require knowledge of exposure and vulnerability of assets to begin designing new trigger points for warnings that are based on impacts – Do you think lifelines groups could help MetService or CDEM set thresholds, such as for wind speeds, at which impacts occur?
        i. How so? Why not?
        ii. What are the potential opportunities and challenges?
    b. Are lifelines in touch with CDEM?

Impact Data:

3. What kind of impact information do lifelines utilities use and collect?
    a. Staff have historical knowledge
4. What is the information used for?
5. What are some challenges in collecting, managing, storing, and/or sharing impact information/data?
    a. What would help you overcome some of these challenges?
    b. Do you think lifelines utilities would benefit from accessing more impact data, such as from crowdsourcing using apps, or through impact models? How so?
6. Is there any potential for using this information to support the development of an impact-based forecasting and warning system? Why or why not?

Agriculture Sector Interview Guide

Introduction:

1. Could you please tell me about [organisation] and your role with them?

    Impact Data:

2. What kind of impact information do [organisation] use and collect?
    a. Staff have historical knowledge
3. What is the information used for?
4. What are some challenges in collecting, managing, storing, and/or sharing impact information/data?
    b. What would help you overcome some of these challenges?

c. Do you think [organisation] would benefit from accessing more impact data, such as from crowdsourcing using apps, or through impact models? How so?

5. Is there any potential for using this information to support the development of an impact-based forecasting and warning system? Why or why not?
   - share what we have done to connect directly with our farmers during severe weather
   - how we use geospatial technology right through our intel space,
   - barriers with connecting this information to the right agencies and how we are overcoming those

Current warnings and warning needs:

1. Can you tell me about the severe weather warnings that you receive from the MetService?
2. How might impact-based warnings be useful or not useful for the agricultural sector? Why or why not?
3. Impact-based forecasting and warning systems require knowledge of exposure and vulnerability of assets to begin designing new trigger points for warnings that are based on impacts – Do you think [organisation] could help MetService or CDEM set thresholds, such as for wind speeds, at which impacts occur?
   i. How so? Why not?
   ii. What are the potential opportunities and challenges?

Data Integration and Sharing Interview Guide

1. Provide brief overview of reason for interviewing
   a. There are a lot of different groups/organisations collecting different types of impact data in different ways
   b. Some of the key challenges with using the impact data
2. I'm curious about any efforts in New Zealand to develop standard practices data sharing and integration in NZ, do you know of any?
3. What has your experience been in NZ with data sharing, integration, and interoperability? Perhaps in the context of government (policy & planning), and maybe even more specifically for disaster management.
4. The future of spatial data infrastructure/data sharing in New Zealand?

Weather Warnings Interview Guide

1. Can you please tell me about the MetServices' new warning system?
   a. What are the thresholds for the new warning system?
2. For the Southland event in February this year, what was the decision-making process behind issuing the Red Warning for the Southland event?
3. How accurate was the warning in comparison to what occurred on the ground?
   a. How was the warning verified? (e.g., did any observed impacts help to verify the warning? How so or why not?)
4. What kind of feedback (if any) did you receive from Southland with regards to warning for this event?
5. What are the key learnings from this event?

6. How does the MetService's new warning system compare to impact-based warnings?

PHASE 3 INTERVIEWS

Flood Warning Interview Guide 1

1. Can you please tell me about the [region's] flood warning programme?
2. What do you think about impact-based warnings?
    a. Will the new warning system include impacts? Why or why not?
    b. What do you think are the challenges, limitations, or barriers with impact-based warnings?
3. What are your current warning needs?
4. How does your team or organisation collect impact data?
5. What is the impact data used for?
6. How is it collected and stored?
7. Who can access and use the data?
8. What are your challenges with impact data?
9. What kind of information or data do you have on flood exposure and vulnerability?
10. Are you missing any of this data? If so, what are you missing?
11. What are your big plans for the [region's] flood warning programme and what do you need to get there?

Warnings & impact-based warnings:

12. Decision-making for issuing warnings and what kind of content to include in the warning, any inclusion of impact information
13. Perspectives on impact-based warnings – data needs, challenges, opportunities
14. Current warning needs

Impact data:

15. How impact data is collected, used, stored, and accessed
16. General impact data management practices, impact data sources, sharing, etc.
17. Impact assessments

Exposure and vulnerability:

18. Any information, knowledge, or data on exposure and vulnerability (both physical and social) that may support impact-based warnings (e.g., floodplains and flood banks, socio-economic status, etc.).

Public Health Response Interview Guide

1. Can you please describe your role at [Hospital]?
2. What is your experience with severe weather warnings in your role?
3. How does [Hospital] receive and respond to severe weather warnings?
4. Are there any improvements you'd like to see in the severe weather warnings from a public health perspective?
5. Can you please tell me about severe thunderstorm induced asthma and the [event] in 2017?
    a. Was the hospital well-prepared for this event?
6. Is this the first observance of severe thunderstorm asthma in New Zealand?
    a. Why do you think this hasn't this been observed before or after?
7. How was the diagnosis of thunderstorm asthma determined?

8. Was CDEM notified?
9. What would you like to see improved in terms of severe weather communication from the public health perspective?

Risk Modelling Interview Guide 2

Collecting, using, storing, and sharing impact data for risk and impact modelling and other uses

1. What have been some challenges in collecting and using the impact data so far for your purposes?

Vulnerability and exposure

2. How does vulnerability and exposure fit into risk and impact modelling?
3. What are potential data sources of vulnerability and exposure?
4. Can you please tell me about **dynamic exposure**?
5. What are the challenges with capturing exposure and vulnerability?
6. What do you think might help to overcome these challenges?

Defining thresholds for impact-based warnings, and the potential role of vulnerability curves for this.

7. Do you have any thoughts on using vulnerability curves for setting thresholds for impact-based warnings?
8. What are some of the challenges you see going forward?
9. What would help you to overcome some of these challenges?

NZ Historic Weather Events Catalogue

10. How useful is this catalogue for risk modelling?
    - If not useful, why not?
11. If you could wave a magic wand, and have a complete database, what would be the value/influence of having this database?

Data Science Interview Guided

1. Can you please tell me about [organisation]?
2. What is your role at [organisation]?
3. What role do you think [organisation] has in Disaster Risk Reduction in New Zealand?
    a. For example, what has been [organisation's] role during COVID-19?
    b. Can the data from your organisation data be used for risk and impact modelling? How so?
4. How do you think the work at [organisation] can support early warning systems, for example, severe weather warnings?
5. How can agencies (e.g., Civil Defence Groups, councils, etc.) access your services and/or products?
6. What do you think the future is for big data in disaster risk reduction?
    a. What are some perceived challenges and opportunities?

Risk Modelling and Flood Warning Interview Guide

1. Can you please tell me about the project?
2. Is impact information included in the warnings?
3. Can you please tell me about the impact forecasting component?

4. What have been challenges with the impact forecasting? How have you overcome them?
5. How were the warning thresholds defined?
    - What data/information were these based off of?
6. From the challenges that you listed in your email, could you please expand on the user needs/requirements challenge and how you addressed that?
    - Likewise for:
        - Assets data
        - Exposure, damage/fragility or loss functions?
7. Ongoing investment in maintenance/improvements to data quality?
8. What are your thoughts on real-time IBFWs? What do you think the future is for IBFWs, and real-time IBFWs in the Pacific Islands context and the NZ context?
9. Where does crowdsourcing fit in?

Weather Service Interview Guide

1. Can you please tell me about your organisation?
2. Where do you get your data from?
3. Do you have any issues with getting data?
4. Do you have any challenges with verification?
5. The World Meteorological Organisation is pushing for member nations to issue impact-based warnings, which aim to communicate not only what the weather will be, but also what it will do to give extra meaning to the warning audiences. Do you know much about IBWs?
    a. Do you give advice about impacts?
    b. Do you gather any information or data on impacts?
        i. If so, what do you do with that data or information?
6. For impact-based warnings, we need to know more about exposure and vulnerability of people and assets. Do you have any data or knowledge on vulnerability and exposure?
    a. If so, what do you do with it?
7. Whose responsibility do you think it is to warn about severe weather in New Zealand and give advice about impacts?
8. There's a global movement towards building stronger public, private, and academic partnerships for weather forecasting and warning, what are your thoughts on public, private, and academic partnerships?
9. Do you have any other comments or questions?

National Governance Interview Guide

1. Do you know anything about Impact-based warnings?
2. The WMO is pushing for member nations to implement impact-based warnings for severe weather hazards; and the MetService is aware that they need to integrate impact-oriented or impact-based messaging, and potentially thresholds, into their warnings. But the challenge is that impact-based forecasts and warnings require an understanding of the underlying vulnerability and exposure of people and assets. I've spoken with the MetService and a variety of civil defence groups and council hydrologists and found that the MetService don't have the knowledge or data on exposure and vulnerability, and thus don't

think it's their responsibility to build up that knowledge base and integrate it into their warnings. Meanwhile, CDEM Groups and councils may possess this knowledge and data but have indicated that they're not responsible for issuing severe weather warnings; rather they usually just pass the warnings on from the MetService.

    a. Whose responsibility do you think it would be in NZ to meld vulnerability and exposure together for severe weather impact-based forecasts and warnings?

3. As said earlier, I've seen that it's the MetService's responsibility to issue warnings, but I've noticed other agencies doing that as well. What are your thoughts on that?
    a. What are some potential implications for that?
4. A key theme for implementing severe weather impact-based forecasts and warnings is that of building strong working relationships and partnerships with agencies that possess the various knowledge and data needed for the warning system. For example, the Natural Hazards Partnership was established in the UK consisting of 17 public sector organizations and government departments involved in monitoring, forecasting and warning for their special areas of interest (I can pass on a paper about this partnership to you if you haven't seen it yet). This partnership provides a structured forum for exchanging knowledge, information, data, expertise, etc. for improving the delivery of warning services.
    a. How do you think we can strengthen partnerships and collaboration in NZ towards a similar aim? What is [organisation's] role in that?
5. Science advice groups seem to be popping up for various hazards like volcanos, tsunami, and I heard one might be forming for landslips… Do you have any thoughts on a weather and floods one?
6. Building onto this idea of partnerships and collaboration, in some countries, like the UK and China, these partnerships have facilitated the cohabitation of agencies, where, for example, meteorologists and hydrologists sit together in the same room, enabling more direct and efficient communication. Do you think that's a possibility in NZ? Why or why not?

   If we have time:

7. I chatted with someone from [organisation] in late 2018 about the national loss database for Sendai Reporting and the technical ins and outs of the database and the status of it. But I wanted to ask you about the governance perspective of this database, particularly whose responsibility is it to provide data to the database?
8. Could you please clarify who is responsible for issuing urban and coastal flood warnings in NZ?

Flood Warning Interview Guide 2

1. I've had a look at the National Civil Defence and Emergency Management Plan and what it says about floods, and it doesn't appear to define the different type of floods nor does it specify warning responsibilities. The Ministry for the Environment website says that "Regional councils issue flood warnings and work with district and city councils to let people know that floods are on the way. If a

flood is severe and widespread your regional council may declare an emergency for all or part of the region and coordinate a response with your district/city council." (Ministry for the Environment, 2016, para. 16). The [organisation's] Group Plan aligns with this by outlining the [Council] as the agency responsible for issuing flood warnings, but neither of these sources specify the type of flood.

   a. Could you please walk me through who is responsible for issuing urban floods and coastal floods? Are they treated differently from river floods?

2. What constitutes an urban flood?
   a. What are the thresholds and where is the boundary of urban flood?
3. Could you please tell me about the Significant Wave Hazards:
   a. how has that project been going?
   b. What have been some challenges with it?
   c. What challenges still need to be addressed for it?
   d. How has this new warning system performed over the last year?

Appendix E: Workshop Agenda and Activities

Auckland and Southland Workshops

1. Introduction
    a. Purpose of workshop, ethics, and recording
    b. Ice breaker and introduction to Mural
    c. Introduction to the project
2. Present the impact framework
3. Activity 1: Initial Impressions
    a. What are your general thoughts on the framework?
    b. What do you like?
    c. What do you dislike?
4. Activity 2: Data Requirements and Sources
    a. What data do we need for Impact-based Forecasts and Warnings?
    b. What do we have already?
    c. What's missing from the list in the blue box in the framework?
    d. What are some impediments and facilitators to accessing these data?

	We Need	We have	The list is missing	Access impediments	Access facilitators
Hazards	-put sticky notes here-				
Exposure					
Vulnerability					
Impacts					

5. Activity 3: System and Data Life
    a. Please pick 2-3 diverse datasets/datasources that are important and identify the life track of these data

	Name of the dataset	How is it collected / created?	Where does the data go?	What is the data used for?	What happens to the data after its initial use?
Data 1					
Data 2					

    b. How do you understand what impacts are occurring or could occur?

I/we understand impacts that **are** occurring by…	I/we understand impacts that **could** occur by…

6. Activity 4: Outcomes
    a. Are there any examples of how you use the data identified previously?

7. Activity 5: Application
    a. How would you use or apply this framework?
    b. Are there any aspects that you would adapt or change for your use?

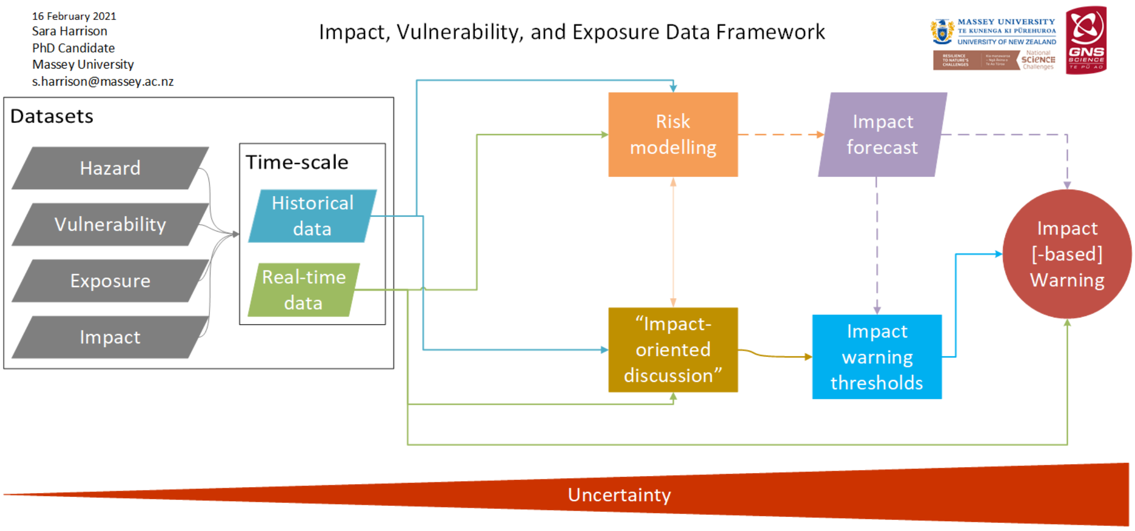
Aspects that I would change…	How I would change it and why…

    c. Do you have any thoughts on whether you would use impact-based forecasts and warnings?
        i. Why or why not?

Why?	Why not?

GNS Workshop

1. Present the impact framework



2. Please help me strengthen the links along the dotted lines in the framework:
    a. How do we see risk modelling supporting or informing impact[-based] forecasts and warnings?
    b. How can risk modelling and impact forecasts be used to help define impact[-based] thresholds for impact[-based] warnings?
    c. What are the challenges or limitations to using risk modelling for impact[-based] forecasts and warnings?
        - What is needed to overcome or address these challenges/limitations?
3. Share your thoughts on sticky notes directly on the framework in the Mural

Appendix F: Human Ethics Notifications, Information Sheets, and Consent Forms

Human Ethics Notification - 4000019769

humanethics@massey.ac.nz <humanethics@massey.ac.nz> Tue, Jul 3, 2018 at 10:36 AM
To: Sara.Harrison.[redacted]R.Prasanna[redacted] R.A.Flett[redacted]
Cc: humanethics@massey.ac.nz

HoU Review Group
A/Pro Ross Flett

Ethics Notification Number: 4000019769
Title: Contextual Interviews with emergency management practitioners and meteorologists

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research.
If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Professor Craig Johnson, Director (Research Ethics), email humanethics@massey.ac.nz. "

Please note that if a sponsoring organisation, funding authority or a journal in which you wish to publish require evidence of committee approval (with an approval number), you will have to complete the application form again answering yes to the publication question to provide more information to go before one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

You are reminded that staff researchers and supervisors are fully responsible for ensuring that the information in the low risk notification has met the requirements and guidelines for submission of a low risk notification.

If you wish to print an official copy of this letter, please login to the RIMS system, and under the Reporting section, View Reports you will find a link to run the LR Report.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

Human Ethics Notification - 4000021843

humanethics@massey.ac.nz <humanethics@massey.ac.nz> Fri, Oct 11, 2019 at 2:28 PM
To: Sara.Harrison[redacted] R.Prasanna[redacted] R.A.Flett[redacted]
Cc: humanethics@massey.ac.nz

HoU Review Group
A/Pro Ross Flett

Ethics Notification Number: 4000021843
Title: Data Needs for Impact-based forecasting and warning systems in New Zealand: Exploring the production, sharing and management of impact data from severe weather events

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Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and
Director (Research Ethics)

Human Ethics Notification - 4000022328

humanethics@massey.ac.nz <humanethics@massey.ac.nz> Wed, Jul 22, 2020 at 5:55 PM
To: Sara.Harrison[redacted]R.Prasanna[redacted]R.A.Flett[redacted]
Cc: humanethics@massey.ac.nz

HoU Review Group
A/Pro Ross Flett

Ethics Notification Number: 4000022328
Title: Impact data for severe weather hazards and events in New Zealand

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

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MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GNS SCIENCE

Joint Centre of Disaster Research
School of Psychology
Wellington Campus

Data Needs for Impact-based forecasting and warning systems in New Zealand: Exploring the production, sharing and management of impact data from severe weather events

INFORMATION SHEET

Research Information
This research contributes to Sara Harrison's PhD through Massey University. There is a growing need for the standardised collection and storage of impact data post-disaster. The importance of systematically recording, sharing, and publicly accounting for disaster losses and impacts is threaded throughout the Sendai Framework for Disaster Risk Reduction 2015-2030. Moreover, the World Meteorological Organization (WMO) has pushed for the implementation of impact-based forecasting and warning systems, furthering the need to systematically collect, store, and share impact data. Yet, methods for collecting the required impact data differ by country and region, making standardised collection and sharing difficult.

This exploratory PhD research, supported by the HIWeather Project within the WMO's World Weather Research Programme and funded by the Resilience to Nature's Challenges Phase 2 Weather & Wildfire Theme, aims to map out existing and potential impact data sources from severe weather events in New Zealand. The expected outcome of this research is a framework outlining the process of getting impact data from the source (e.g. the public) to the end-users (e.g. Civil Defence groups, the MetService, impact/risk modellers, etc.) for impact-based forecasts and warnings.

Results may be published in scientific journals and other publications. This research will contribute to the implementation of impact-based forecasts and warnings in New Zealand while also supporting efforts towards meeting the requirements of the Sendai Framework to build a national impacts and losses database.

Invitation to Participate
You are cordially invited to participate in this study through a qualitative interview in which Sara will ask a number of questions around the collection, storage, and use of impact data, as well as the process of implementing impact-based forecasting and warning systems in New Zealand. The purpose of these interviews is to help build an understanding of the current and potential uses and sources of impact data from severe weather events in New Zealand. It is envisaged that the interview will take one hour (depending on your availability).

Participant Identification and Recruitment

- Participants will be selected and recruited based on their position and role in risk communication and warning systems for severe weather hazards and in handling impact data including, but not limited to, officials from national hydrometeorological services, national and local civil defence both within and outside of New Zealand.
- Participant names and contact information will be obtained from publicly available information such as organization web pages, as well as key contacts within Sara's research network.
- There are no known or anticipated risks to you as a participant in this study.

Research Procedure
With your permission, the interview will be audio recorded to facilitate collection of information, and later transcribed for analysis. All information you provide is considered completely confidential. Your name will not appear in any thesis or report resulting from this study, however, with your permission, anonymous quotations may be used. Interview transcripts will be anonymised to protect your confidentiality.

Data Management
At the conclusion of the research, the data will be stored in a secure location at the Joint Centre for Disaster Research, which is part of the School of Psychology at Massey University, Wellington, New Zealand. All data collected will be held in this secure location for five years post research completion. The only persons with access to this data will be the current research team.

Participant's Rights
Whilst your contribution would be most appreciated, **you are under no obligation to participate in this research.** Following the Massey University Code of Ethical Conduct, if you choose to participate you have the right to:

- decline to answer any particular question;
- withdraw from the study at any time;
- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded;
- ask for the recorder to be turned off at any time during the interview.

Information about the Researchers
Please feel free to contact one or all of the following people if you have questions about the research being undertaken.

Sara Harrison, PhD Candidate, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

Supervisors:
Dr. Sally Potter, Hazard and Risk Management Researcher, GNS Science, Lower Hutt, New Zealand.
Email: [redacted] phone: [redacted]

Dr. Raj Prasanna, Senior Lecturer, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

Dr. Emma Hudson-Doyle, Lecturer, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

Prof. David Johnston, Director/Professor of Disaster Management, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

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MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

GNS SCIENCE TE PŪ AO

Joint Centre of Disaster Research
School of Psychology
Wellington Campus

Data Needs for Impact-based forecasting and warning systems in New Zealand: Exploring the production, sharing and management of impact data from severe weather events

PARTICIPANT CONSENT FORM

I have read, or have had read to me in my first language, and I understand the Information Sheet attached. I have had the details of the study explained to me, any questions I had have been answered to my satisfaction, and I understand that I may ask further questions at any time. I have been given sufficient time to consider whether to participate in this study and I understand participation is voluntary and that I may withdraw from the study at any time.

Declaration by Participant:

1. I **agree / do not agree (circle)** to the interview being audio recorded.
2. I **wish / do not wish (circle)** to have my recordings returned to me.
3. I **agree / do not agree (circle)** to the use of anonymous quotations in any thesis or publication that comes of this research.
4. I **agree / do not agree (circle)** to participate in this study under the conditions set out in the Information Sheet.

I ____ hereby consent to take part in this study.

Signature: ___________________________ Date: ___________________

Findings:

I wish to be sent a copy of the findings from this research - **Yes / No (Circle)**

If yes, please include your email here:____

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School of Psychology
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- ask any questions about the study at any time during participation;
- provide information on the understanding that your name will not be used unless you give permission to the researcher;
- be given access to a summary of the project findings when it is concluded;
- ask for the recorder to be turned off at any time during the interview.

Information about the Researchers
Please feel free to contact one or all of the following people if you have questions about the research being undertaken.

Sara Harrison, PhD Candidate, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

Supervisors:
Dr. Sally Potter, Hazard and Risk Management Researcher, GNS Science, Lower Hutt, New Zealand.
Email: [redacted] phone: [redacted]

Dr. Raj Prasanna, Senior Lecturer, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

Dr. Emma Hudson-Doyle, Lecturer, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted], phone: [redacted]

Prof. David Johnston, Director/Professor of Disaster Management, Joint Centre for Disaster Research, Massey University, Wellington, New Zealand.
Email: [redacted] phone: [redacted]

This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named above are responsible for the ethical conduct of this research.

If you have any concerns about the conduct of this research that you wish to raise with someone other than the researcher(s), please contact Prof Craig Johnson, Director, Research Ethics, telephone 06 356 9099 x 85271, email humanethics@massey.ac.nz.

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

Joint Centre of Disaster Research
School of Psychology
Wellington Campus

Data Needs for Impact-based forecasting and warning systems in New Zealand: Exploring the production, sharing and management of impact data from severe weather events

PARTICIPANT CONSENT FORM

I have read, or have had read to me in my first language, and I understand the Information Sheet attached. I have had the details of the study explained to me, any questions I had have been answered to my satisfaction, and I understand that I may ask further questions at any time. I have been given sufficient time to consider whether to participate in this study and I understand participation is voluntary and that I may withdraw from the study at any time.

Declaration by Participant:

1. I **agree / do not agree (circle)** to the workshop being recorded.
2. I **wish / do not wish (circle)** to have my recordings returned to me.
3. I **agree / do not agree (circle)** to the use of anonymous quotations in any thesis or publication that comes of this research.
4. I **agree / do not agree (circle)** to participate in this study under the conditions set out in the Information Sheet.

I ____ hereby consent to take part in this study.

Signature: ____________________________ Date: ____________________

Findings:

I wish to be sent a copy of the findings from this research - **Yes / No (Circle)**

If yes, please include your email here:____

Appendix G: Auckland and Southland Hazard Profiles

Auckland Profile

Auckland Region was selected because of notable historic severe weather events such as the 2017 New Lynn storms and consequent flood, and the 2018 windstorm (Golubiewski, 2019; Smol, 2018). Auckland is a large metropolitan city in the North Island of NZ; thus, it offers an urban context for the case analysis.

In 2018, the population of Auckland was 1.57 million and growing, making up 32% of New Zealand's population (Stats NZ, 2018). Thirty percent of the region is considered urban, with the remaining 70% rural (Auckland Emergency Management, 2016); however, 90% of Auckland's population lives in urban areas (Auckland Emergency Management, 2016). Auckland is the largest urban centre in New Zealand, located on the northern coast of the North Island, and makes up 2% of New Zealand's landmass (Auckland Emergency Management, 2016). Auckland Region is made up of harbours, mountain ranges, islands, lakes, and streams (Auckland Emergency Management, 2016). In addition to Auckland's central urban centre, the region also has isolated communities, such as on islands (Auckland Emergency Management, 2016). Auckland is exposed to several hazards, namely volcanic and meteorological hazards. Auckland lies on an active volcanic field containing at least 50 volcanoes (Auckland Civil Defence, 2016).

Meteorological Hazards

The weather in and around Auckland can change quickly, with weather systems originating from the Tasman Sea during summer and autumn, including subtropical storms and ex-tropical cyclones (Auckland Emergency Management, 2016). Floods are the most common weather hazard in Auckland, followed by damaging winds and rough seas (Auckland Emergency Management, 2016). A 'superstorm' (i.e., a storm system that incorporates numerous hazards) poses a significant risk to Auckland, as a combination of severe winds, heavy rain, and land instability; and flood has the potential to produce power outages, storm surge, and coastal erosion (Auckland Emergency Management, 2016). A regional risk assessment for Auckland identified four meteorological hazards as the highest priority for risk management, out of five: 1) coastal inundation (storm surge due to severe weather), 2) flooding (river and catchment due to heavy rainfall), 3) infectious human disease pandemics, 4) severe winds, and 5) severe storms (i.e., "super storm" (Auckland Emergency Management, 2016, p. 58)).

Warnings

The warning setup in Auckland is like that of the rest of New Zealand, relying on NEMA for national warnings, and the MetService for weather monitoring and issuing subsequent watches, warnings, and alerts (Auckland Emergency Management, 2016).The Auckland Council is the primary source of flood information, and is responsible for monitoring and issuing flood warnings in Auckland Region (Auckland Emergency Management, 2016).The Auckland Council uses a network of remote stations to monitor rainfall, river flows, and lake levels, which is used for forecasting flood (Auckland Emergency Management, 2016). When the respective levels reach a predetermined threshold (or warning level), notifications are sent to stakeholders (Auckland Emergency Management, 2016).

The MetService is the primary agency responsible for issuing severe weather watches, warnings, and alerts, and the Auckland Civil Defence Group offers support for disseminating the Auckland-oriented alerts, and adds additional information to the warning, such as recommended protective actions (which includes advice that reflects guidelines developed by NEMA) (EM. NZ. Reg. D, E). In a recent interview, officials from the Auckland EM Group indicated that they are moving towards using impact-oriented language in their messages (EM. NZ. Reg. D, E).

Southland Profile

Southland Region was selected for the second regional workshop. In February 2020, Southland experienced heavy rainfall, floods, and landslides. During this event, the MetService issued the first Red Warning since the implementation of its new national severe weather warning system (See Chapter Two Section 2.4). Southland is the southernmost region of NZ, located on the southwestern portion of NZ's South Island. Southland is considered a remote region, as such it provides a rural context.

Southland Region encapsulates 13% of NZ's land area, making it the country's second largest region by area (Emergency Management Southland, 2017). Southland has a "unique and rugged" landscape comprised of mountain ranges, forested wilderness, fiords, and rivers (Emergency Management Southland, 2017). Despite taking up such a large land area, the population of Southland makes up only 2% of NZ's population; having just over 97,400 residents. Unlike Auckland, Southland does not have any significant urban centres, rather it has several smaller cities and numerous rural communities. Invercargill City has over half of Southland Region's population, with 51,696 residents (Emergency Management Southland, 2017). The second largest urban area is Gore, with 7,356 residents (Emergency Management Southland, 2017). The sparse spread of Southland Region's population, along with the remoteness of the settlements and communities in the Region's rugged landscape increase the potential for people to become quickly isolated in emergencies (Emergency Management Southland, 2017). As such, it is of high importance for these communities to be self-reliant and prepared (Emergency Management Southland, 2017). Southland's landscape and geographical location presents many hazards and associated risks; the most "extreme" risk being tsunami (specifically landslide induced tsunami) and earthquake (Emergency Management Southland, 2017, p. 23). Severe weather also presents "very high" risk to the region, and with climate change, it is expected that risks from these hazards will increase (Emergency Management Southland, 2017, p. 23).

Meteorological Hazards

Southland is exposed to weather systems moving into the region from the west and from the south (Emergency Management Southland, 2017). Gale force winds occur frequently, but rarely cause damage (Emergency Management Southland, 2017). Fiordland, an area of Southland with few permanent residents but is a large tourist attraction, receives over 8,000mm of rain per year (Emergency Management Southland, 2017). Alternatively, Southland's lowlands and hills receive 800 to 1,200mm of rain per year (Emergency Management Southland, 2017). Most of Southland's population lives on floodplains, putting these communities at significant risk to flood impacts, despite extensive flood mitigation work (Emergency Management Southland, 2017). This risk became a reality in February 2020, when residents of the low-lying areas of Gore, Wyndham, and Mataura were evacuated during a flood emergency (Quinlivan et al., 2020). This event led to the MetService issuing its first Red Warning since the implementation of the new warning system in May 2019 (MetService, 2019a).

Warnings

The warning system in Southland Region is similar to that of Auckland, whereby NEMA is the authoritative agency for issuing national warning messages (Emergency Management Southland, 2017). Emergency Management Southland (EMS) is the point of contact for receiving and disseminating all warnings to the appropriate stakeholders (Emergency Management Southland, 2017). The Southland Emergency Management Group Plan identifies the MetService as the agency responsible for surveillance, monitoring, assessment, and issuing of alerts for severe weather hazards (Emergency Management Southland, 2017). Environment Southland Regional Council is the agency responsible for issuing flood warnings and operates a Flood Warning Operations Centre (Environment Southland Regional Council, 2021).

Appendix H: Codebook

Name	Files	References
Although we all complain about a lack of data, a lot of the time, there is quite a bit of data out there that could be used and isn't being used very well.	1	1
Community Risk Awareness	1	1
Consuming data vs. holding information	2	2
Cultural Conditions	0	0
Cultural Conditions\New Zealand Practice	5	5
Cultural Conditions\New Zealand Practice\Canterbury Governance Structure	1	1
Cultural Conditions\New Zealand Practice\CIMS Structure	1	3
Cultural Conditions\Reactive vs. Proactive CDEM practices	6	9
Cultural Conditions\Reactive vs. Proactive CDEM practices\Lack of motivation to improve, think things are good as they are	1	2
Cultural Conditions\Reactive vs. Proactive CDEM practices\Lack of motivation to improve, think things are good as they are\Economic viability	1	3
Cultural Conditions\Reactive vs. Proactive CDEM practices\Lack of motivation to improve, think things are good as they are\She'll be alright	1	1
Data for IBFWs and General DRR	0	0
Data for IBFWs and General DRR\Data and Information Sharing	1	2
Data for IBFWs and General DRR\Data and Information Sharing\Attitude shift for better data sharing and access	2	4
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data	13	37
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Anti-competitive behaviour	1	2
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Commercial or proprietary licensing	2	4
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Comparing New Zealand to China and Russia	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Data collected by different agencies is managed and stored differently which makes it difficult for integration	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Different countries have different standards and cultures	1	3
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Fear of publishing impacts	2	2
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Fear of publishing impacts\Catastrophising it	1	1

Appendix H: Codebook

Name	Files	References
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Fear of publishing impacts\Property Values	2	5
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Liability	1	2
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Near real-time data	2	2
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Open Data	4	10
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Open Data\Open Data for private use	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Open Data\Open Data for private use\America-Canada model	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Outdated model of sharing data	2	2
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Outdated model of sharing data\Financial motive vs. for the good of New Zealand	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Ownership	2	2
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Political	3	5
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Political\Impact data is political data	1	4
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Political\Impact data is political data\Impact data has a lot to do with the organisation of the government	2	6
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Poor data collection and management practices	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Poor data collection and management practices\Pessimism or frustration	3	3
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Privacy	8	27
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Trust	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Trust\Reliability	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Challenges and barriers to sharing data\Trust\Suspicion between institutions in New Zealand inhibits progress in risk maangement	2	2
Data for IBFWs and General DRR\Data and Information Sharing\Data Integration	9	22
Data for IBFWs and General DRR\Data and Information Sharing\Data Integration\Common Operating Picture	8	21
Data for IBFWs and General DRR\Data and Information Sharing\Data Integration\Spatial data infrastructure	1	5

Name	Files	References
Data for IBFWs and General DRR\Data and Information Sharing\Data Integration\Spatial data infrastructure\Transition from SDI to unstructured or hybrid data sharing and access	1	3
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data	2	3
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\More data is available or exists than we think	3	6
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Realisation that data has value and use beyond its initial intended purpose	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data	3	7
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Different ways of communicating the information or data	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Ethical data collection	3	4
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Need for a common framework for aggregating all sources of data	6	9
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Need for a common framework for aggregating all sources of data\Need to get time critical data before it is lost	6	7
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Need for a common framework for aggregating all sources of data\Need to get time critical data before it is lost\Sometimes a time delay in collecting the data can help	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Drivers for sharing data\Various stakeholders that create, manage, share, access, use data\Need for better collaboration and coordination	5	5
Data for IBFWs and General DRR\Data and Information Sharing\Outcomes of sharing data	0	0
Data for IBFWs and General DRR\Data and Information Sharing\Outcomes of sharing data\Using data from other agencies to learn from past events and predict future events	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data	0	0
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Cooperation and collaboration	18	38
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Custodianship	5	10
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data directories	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data integration	5	15

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Name	Files	References
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data integration\Common alerting protocol	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data portal	2	12
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data portal\Central repository	1	6
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data standards	4	15
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data standards\Challenges	1	2
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data standards\Meta-data	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data standards\Nation-specific	1	4
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Data standards\Spatial GIS Data	10	20
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Interconnected systems	1	1
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Networking and relationships	5	11
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Online Web Maps	3	12
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Training	2	2
Data for IBFWs and General DRR\Data and Information Sharing\Requirements and practices of sharing data\Two-way flow of information from public-authorities	1	2
Data for IBFWs and General DRR\Data Collection and creation	0	0
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation	8	28
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Data challenges	9	24
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Data ownership	1	2
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Privacy	1	4
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Resource Limitations	7	7
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Resource Limitations\Finance or funding limitations	5	6

Name	Files	References
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Resource Limitations\Human-Power and Time Limitations	4	6
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Roles and Responsibility	2	4
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Sharing	7	7
Data for IBFWs and General DRR\Data Collection and creation\Challenges or Barriers to Data Use, Access, Creation\Transparency	3	5
Data for IBFWs and General DRR\Data Collection and creation\Data Sources	11	62
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources	0	0
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Citizen science	4	8
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Citizen science\Do the challenges with citizen science outweigh the benefits of it	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Citizen science\Engagement and contributions	3	6
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Citizen science\Training	1	2
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Community reports (is it a form of citizen science)	2	5
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing	12	52
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\Digital divide and urban bias	1	2
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\NZ Flood Pics	1	19
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\NZ Flood Pics\Citizen science for quality control	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\NZ Flood Pics\Desire to keep the project independent from institutions	1	4
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\NZ Flood Pics\Desire to keep the project independent from institutions\Public trust in the platform	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\NZ Flood Pics\Desire to keep the project independent from institutions\What insitutionalising it could mean	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Crowdsourcing\Trusted crowdsourcing and crowdsourcers	2	3

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Name	Files	References
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Media Reports	3	5
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media	18	66
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Drivers for adoption of social media platforms and data	0	0
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Drivers for adoption of social media platforms and data\Age	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Facebook	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\For evaluation	2	3
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Instagram	1	3
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\One-way social media communication	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\People interfering in the response and putting themselves and others at risk	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Public image, transparency, and trust	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Public perceptions vs. official perceptions of impacts	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Quality control	3	3
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Skewed data	3	3
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\SnapChat	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Tourism	1	2
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Triangulating across different platforms	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Alternative or unofficial data sources\Social media\Twitter	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources	0	0
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\111 calls	2	2
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\Drones	1	1
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\QuickCapture	2	7

Name	Files	References
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\Satellite Imagery	2	4
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\Survey123	2	2
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\Tacit knowledge and prior experience	10	23
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\Tacit knowledge and prior experience\Experience to inform decisions and to learn from previous impacts is a double edged sword	2	2
Data for IBFWs and General DRR\Data Collection and creation\Data Sources\Official and Trusted Data Sources\Tacit knowledge and prior experience\Risk of losing undocumented tacit knowledge and experience	1	2
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events	0	0
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes	2	5
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Post-event Technical Advisory Group Review and Recommendations	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Rapid Impact Assessment needs	1	2
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Rapid Impact Assessment needs\Data Standards	2	7
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Rapid Impact Assessment needs\Efficiency	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Rapid Impact Assessment needs\Post-earthquake damage assessments	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Rapid Impact Assessment needs\Pre-earthquake data	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Canterbury earthquakes\Rapid Impact Assessment needs\Time constraints	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\COVID-19 Response	1	4
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Cyclone Pam	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Edgecumbe Floods	2	2
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Kaikoura earthquakes	3	7

Name	Files	References
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Melbourne Thunderstorm-induced asthma	1	3
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Pigeon Valley Fire	1	3
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Port Hills fires	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Southland Floods	2	5
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Southland Floods\Red Warning	1	5
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Southland Floods\Red Warning\Difficult decision to evacuate	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Southland Floods\Red Warning\Unexpected public perceptions of the red warning	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Waikato Thunderstorm-induced asthma	1	10
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Waikato Thunderstorm-induced asthma\Over-burdened health system	1	3
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\West Coast events	1	2
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Events\Whakaari White Island Volcanic Eruption	1	3
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Modelling Calibration	1	6
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Organisational culture can drive innovation	2	3
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Organisational culture can drive innovation\An individual with the required skills and knowledge to drive change and innovation	1	2
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Recognising the value of information	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Research	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Technological Advancements	2	4
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Top level government investment and prioritisation	4	5
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data	3	8

Name	Files	References
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Different ways of communicating the information or data	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Ethical data collection	3	4
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Need for a common framework for aggregating all sources of data	6	9
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Need for a common framework for aggregating all sources of data\Need to get time critical data before it is lost	5	6
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Need for a common framework for aggregating all sources of data\Need to get time critical data before it is lost\Sometimes a time delay in collecting the data can help	1	1
Data for IBFWs and General DRR\Data Collection and creation\Drivers for IVE Data Collection\Various stakeholders that create, manage, share, access, use data\Need for better collaboration and coordination to establish data collection needs and standards	4	4
Data for IBFWs and General DRR\Data Collection and creation\Systematic Impact Data Collection	6	11
Data for IBFWs and General DRR\Data Collection and creation\Systematic Impact Data Collection\Best practice guidelines	1	1
Data for IBFWs and General DRR\Data Collection and creation\Systematic Impact Data Collection\Best practice guidelines\Ethical practice	3	4
Data for IBFWs and General DRR\Data Collection and creation\Systematic Impact Data Collection\Standardisation	3	11
Data for IBFWs and General DRR\Data Storage and Management	9	23
Data for IBFWs and General DRR\Data Storage and Management\Archiving	1	1
Data for IBFWs and General DRR\Data Storage and Management\Business as usual vs. new tools only for emergency use	1	1
Data for IBFWs and General DRR\Data Storage and Management\Different ways of storing and managing data	1	1
Data for IBFWs and General DRR\Data Storage and Management\Need to know what to do with the data	1	1
Data for IBFWs and General DRR\Data Storage and Management\Trust or distrust in how the data is stored and managed	3	3
Data for IBFWs and General DRR\Data Uses and Usability	0	0
Data for IBFWs and General DRR\Data Uses and Usability\Data Usability	1	1
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs	12	35
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Quality control	4	9

Name	Files	References
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Trust in the data	7	20
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Trust in the data\Confidence in data and subsequent analyses	1	1
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Trust in the data\Importance of official data	1	3
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Up-to-date information	4	5
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Up-to-date information\Real-time impact data for impact-based warnings	4	6
Data for IBFWs and General DRR\Data Uses and Usability\IBFW Data Usability Needs\Up-to-date information\Time-value of data	1	2
Data for IBFWs and General DRR\Data Uses and Usability\Stakeholders and Users of Impact Data	0	0
Data for IBFWs and General DRR\Data Uses and Usability\Stakeholders and Users of Impact Data\NZGIS4EM	4	7
Data for IBFWs and General DRR\Data Uses and Usability\Stakeholders and Users of Impact Data\Pacific Pilot Case Studies	1	2
Data for IBFWs and General DRR\Data Uses and Usability\Stakeholders and Users of Impact Data\Stakeholders	2	2
Data for IBFWs and General DRR\Data Uses and Usability\Stakeholders and Users of Impact Data\Stakeholders\Different needs for different stakeholders	10	31
Generation Change	1	1
Government and data access	1	7
Government-Private System	1	3
IBFW Implementation	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Agency remit or responsibility	16	47
IBFW Implementation\Challenges or Barriers to IBFW implementation\Agency remit or responsibility\Data custodianship	2	5
IBFW Implementation\Challenges or Barriers to IBFW implementation\Agency remit or responsibility\Legislation	2	2
IBFW Implementation\Challenges or Barriers to IBFW implementation\Agency remit or responsibility\Need national cohesion	2	6
IBFW Implementation\Challenges or Barriers to IBFW implementation\Agency remit or responsibility\Shifting roles or adding onto existing roles	4	5
IBFW Implementation\Challenges or Barriers to IBFW implementation\Communicating to different audiences	6	11
IBFW Implementation\Challenges or Barriers to IBFW implementation\Conflicting messages	1	2
IBFW Implementation\Challenges or Barriers to IBFW implementation\Liability	1	2
IBFW Implementation\Challenges or Barriers to IBFW implementation\Scaling problems	1	1
IBFW Implementation\Challenges or Barriers to IBFW implementation\Scaling problems\Spatial Scale	5	10

Name	Files	References
IBFW Implementation\Challenges or Barriers to IBFW implementation\Scaling problems\Temporal Scale	1	1
IBFW Implementation\Challenges or Barriers to IBFW implementation\Scaling problems\Warning spatial scale doesn't match spatial scale of impacts	1	1
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Communicating Uncertainty	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Compounding Uncertainty	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Consequences of Uncertainty	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Consequences of Uncertainty\Hesitancy to include impact messaging and to implement IBFWs	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Consequences of Uncertainty\Misunderstanding of the models, forecasts, and warnings	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Sources of Uncertainty	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Sources of Uncertainty\Lack of data	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Sources of Uncertainty\Lack of knowledge and expertise	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Sources of Uncertainty\Uncertainty in forecasting the hazard	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Sources of Uncertainty\Uncertainty of roles and responsibilities	0	0
IBFW Implementation\Challenges or Barriers to IBFW implementation\Uncertainty\Sources of Uncertainty\Uncertainty of the impacts	0	0
IBFW Implementation\Drivers for IBFWs	0	0
IBFW Implementation\Drivers for IBFWs\Better communication with the public	5	9
IBFW Implementation\Drivers for IBFWs\Better communication with the public\Boundary warnings vs. free-hand drawn warnings	1	1
IBFW Implementation\Drivers for IBFWs\Better communication with the public\CDEM offer value-add to MetService messages by adding on impact information	1	2
IBFW Implementation\Drivers for IBFWs\Better communication with the public\Giving meaning to the meteorological information	4	5
IBFW Implementation\Drivers for IBFWs\Better communication with the public\Shift from hazard focus to human and impacts focus	1	1
IBFW Implementation\Drivers for IBFWs\Better communication with the public\Shift from text-based to images in warning messages	1	1
IBFW Implementation\Drivers for IBFWs\International trend of IBFWs	2	2
IBFW Implementation\Drivers for IBFWs\International trend of IBFWs\National Review and Recommendations	1	3

Name	Files	References
IBFW Implementation\Drivers for IBFWs\International trend of IBFWs\Need to evaluate and communicate current efforts towards IBFWs for other countries to learn from and prepare for challenges	4	8
IBFW Implementation\Drivers for IBFWs\International trend of IBFWs\Sendai Framework requirements	1	1
IBFW Implementation\Drivers for IBFWs\International trend of IBFWs\WMO Guidelines	2	4
IBFW Implementation\Drivers for IBFWs\New MetService Warning System	1	5
IBFW Implementation\Drivers for IBFWs\New MetService Warning System\Still Threshold-based	1	1
IBFW Implementation\Drivers for IBFWs\New MetService Warning System\Stronger media presence and engagement	1	1
IBFW Implementation\Drivers for IBFWs\Vision for impact-based warnings	5	9
IBFW Implementation\Drivers for IBFWs\Vision for impact-based warnings\Using impact data to classify hazards	1	2
IBFW Implementation\IBFW Data and Information Needs	0	0
IBFW Implementation\IBFW Data and Information Needs\Exposure	19	60
IBFW Implementation\IBFW Data and Information Needs\Exposure\Demographics	3	8
IBFW Implementation\IBFW Data and Information Needs\Exposure\Dynamic Exposure	6	11
IBFW Implementation\IBFW Data and Information Needs\Exposure\Dynamic Exposure\Agent-based modelling	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources	2	2
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\FENZ	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\Flood models	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\KiwiRail	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\LINZ	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\NZTA	2	2
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\Ongoing question of data sources	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Exposure data sources\StatsNz DataVentures	1	1
IBFW Implementation\IBFW Data and Information Needs\Exposure\Movement and location of people	3	3
IBFW Implementation\IBFW Data and Information Needs\Hazard	6	13
IBFW Implementation\IBFW Data and Information Needs\Hazard\Flood Models	1	1
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Needs	3	5
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Sources	0	0
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Sources\Climate Records	1	1

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Uses	2	4
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Uses\Hazard Risk Communication	1	3
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Uses\Land use zoning disputes	1	1
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Uses\Learning from experience	2	2
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Uses\Model Calibration	2	2
IBFW Implementation\IBFW Data and Information Needs\Hazard\Hazard Data Uses\Model Calibration\Damage Surveys to correct models and reduce uncertainty	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact	4	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Geographic and Location information	5	12
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data as input vs. output	3	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data as input vs. output\Input	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data as input vs. output\Output	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management	1	5
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Balance between too much and enough data	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Challenge with capturing less tangible or physical impacts and indirect impacts	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Costs and Resources	3	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Council documenting impacts on internal assets vs. privately owned assets	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Data availability	2	14
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Level of detail	2	7
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Maintenance	2	7
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Maintenance\Lack of motivation or interest in data creation and maintenance	6	11
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Maintenance\Lack of motivation or interest in data creation and maintenance\Alternatively, interest and skills as driver for better data creation and management practices	2	3

Appendix H: Codebook

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Maintenance\Lack of motivation or interest in data creation and maintenance\Amount of work required	1	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Maintenance\Who is the most suitable for managing data in terms of skills and expertise	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Needs-based datasets & database development	3	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Priorities	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Priorities\Influence of management on science directions	4	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Priorities\Waiting for someone else to take the lead	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Resources	2	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Struggles	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Whose responsibility	6	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Whose responsibility\Government role vs. sector roles	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Creation and Management\Whose responsibility\NEMA as a broker	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources	8	24
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\ACC	2	5
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\CDEM response records and situational reports	2	8
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\GNS Science	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Insurance	5	13
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Media reports	2	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\National Archives	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Ongoing question of data sources	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment	7	22

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Access to sites	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Capture Tool	1	21
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Capture Tool\Flexibility and customisation	1	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\CDEM Impact Assessments	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\CDEM Impact Assessments\Phase 1 Wide area impact assessment	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\CDEM Impact Assessments\Phase 2 Rapid Damage Assessment	2	5
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\CDEM Impact Assessments\Phase 3 Detailed Impact Assessment	2	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Collect only the data that will be used	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Contractors	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Standardisation	3	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Standardisation\Government endorsed template	2	5
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Standardisation\National damage assessment dictionary	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\Training	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Post-event damage assessment\When is a good time to collect the data	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Public scan	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Risk Modelling Inputs	2	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Social media and crowdsourcing	2	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Stats NZ	2	3

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Sources\Tacit knowledge	3	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses	15	67
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Business case	2	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Decision-making and planning	4	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Decision-making and planning\Research vs. practice	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Decision-making and planning\Science-based practice and policy	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Emergency Management Planning, Response and Recovery	5	8
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Emergency Management Planning, Response and Recovery\Messaging for planning and preparedness	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Impact data for different uses and purposes	5	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Intelligence	3	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Intelligence\Human Intelligence	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Intelligence\Open Source Intelligence	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Intelligence\Operational Intelligence	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Landuse planning and development policies	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Landuse planning and development policies\Planning	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Population Exposure Model	2	5
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Rapid Impact Assessments	4	12
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Research Analysis	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Communication	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Management	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling	4	11
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Asset information	1	12

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Asset information\Attributes	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Asset information\Building data	1	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Computational Fluid Dynamics Model	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Computational Fluid Dynamics Model\Variability in wind gusts and damage surveys	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Sense-checking	2	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Tunnel vision limiting risk and impact modelling	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Uncertainty	8	17
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Uncertainty\Damage Surveys to correct models and reduce uncertainty	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Uncertainty\How to communicate the uncertainty	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions	6	30
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Types of vulnerability functions	0	0
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Types of vulnerability functions\Analytical vulnerability function	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Types of vulnerability functions\Empirical vulnerability function	2	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Types of vulnerability functions\Expert opinion vulnerability function	2	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Types of vulnerability functions\Judgement-based	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Verification	7	11
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Verification\Bringing reality to the forecasters and modellers	1	1

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Risk Modelling\Vulnerability functions\Verification\Bringing reality to the forecasters and modellers\An expert's surprise at the value of damage assessments to drive home the reality of the event	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Sendai Framework	2	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Sendai Framework\DesInventar Sendai	1	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Warnings	3	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Warnings\Impact-based warnings	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Warnings\Impact-based warnings\Historic Impacts	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Warnings\Impact-based warnings\Identifying triggers or Indicators	1	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Data Uses\Warnings\Impact-based warnings\Question of IBW efficacy	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\European Severe Weather Database	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database	7	11
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Event driven vs. not event driven	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\How to convey the meaning of the data	2	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Inclusion criteria	1	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Inclusion criteria\Judgement call for including impact data into national loss database	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Maturing the system, the future of the system	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Software	1	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\The value of it	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Users	1	4

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Uses	1	10
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Vision	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\National dataset or database\Why NEMA is doing it	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\NIWA Historic events catalog	3	7
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Databases\Storm Data	1	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Models	0	0
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Models\Different methodologies depending on the hazard and the kinds of impacts you want to model	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Models\Different methodologies depending on the hazard and the kinds of impacts you want to model\Emergency Service Vehicle Damage Models	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Models\Different methodologies depending on the hazard and the kinds of impacts you want to model\Not wanting to rely only on models	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Models\Different methodologies depending on the hazard and the kinds of impacts you want to model\UK Surface Water Flooding Model	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Impact Models\Different methodologies depending on the hazard and the kinds of impacts you want to model\UK Vehicle Overturn Model	1	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Lag or delay in incoming impact information and issuing warnings	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts	0	0
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Community Impacts	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Direct vs. indirect impacts	3	7
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Focus on physical impacts	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts	5	11
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Health Impacts	2	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Mortality	1	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Post-event surveys	1	2

Name	Files	References
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts	5	19
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Cultural Heritage and Impacts	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Cultural Heritage and Impacts\How to measure significance	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Physical impacts lead to social impacts	3	4
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Physical impacts lead to social impacts\How to capture that properly in the data	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Social impact post-event assessment	2	6
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Welfare information	4	9
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Human and social Impacts\Social and Cultural Impacts\Welfare information\Need a process to capture it properly	1	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Physical Damage and Impacts	7	27
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Physical Damage and Impacts\Utility outages	1	3
IBFW Implementation\IBFW Data and Information Needs\Impact\Types of Impacts\Urban vs. rural impacts	2	2
IBFW Implementation\IBFW Data and Information Needs\Impact\Why we need more than just historical impact data	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Why we need more than just historical impact data\Change in landscape (dynamic exposure)	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Why we need more than just historical impact data\Climate Change	1	1
IBFW Implementation\IBFW Data and Information Needs\Impact\Why we need more than just historical impact data\Future events can be more extreme than past events	1	1
IBFW Implementation\IBFW Data and Information Needs\Vulnerability	14	26
IBFW Implementation\IBFW Data and Information Needs\Vulnerability\Dynamic Vulnerability	5	12
IBFW Implementation\IBFW Data and Information Needs\Vulnerability\Underlying health conditions	2	2
IBFW Implementation\IBFW Data and Information Needs\Vulnerability\Vulnerability Data Sources	1	1
IBFW Implementation\IBFW Data and Information Needs\Vulnerability\Vulnerability Data Sources\Flood models	1	1

Name	Files	References
IBFW Implementation\Impact Thresholds	3	5
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds	11	26
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge	15	46
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge\Difference across stakeholders	3	7
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge\Feedback or Circular Process	2	2
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge\Joint decisions	2	2
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge\Joint or consistent messaging across agencies	8	14
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Partnering with agencies for impact knowledge\Sharing Data	3	5
IBFW Implementation\Impact Thresholds\Defining Impact Thresholds\Subscription system	1	2
IBFW Implementation\Impact Thresholds\Many factors to consider when deciding on the warning level	1	1
IBFW Implementation\Impact Thresholds\Thresholds that are too sensitive or too widescale	2	2
IBFW Implementation\Needs of the data to be useful and usable for IBFWs	12	35
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Trust in the data	7	20
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Trust in the data\Confidence in data and subsequent analyses	1	1
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Trust in the data\Credibility	2	2
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Trust in the data\Importance of official data	1	3
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Trust in the data\Quality control	4	9
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Trust in the data\Validation	4	7
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Up-to-date information	4	5
IBFW Implementation\Needs of the data to be useful and usable for IBFWs\Up-to-date information\Real-time impact data for impact-based warnings	4	6
IBFW Implementation\Warning audience decision-making	6	7
IBFW Implementation\Warning audience decision-making\In favour of more general warnings as opposed to impact-based or action-based warnings	1	2
IBFW Implementation\Warning audience decision-making\In favour of more general warnings as opposed to impact-based or action-based warnings\Community-based plans and actions	2	5

Name	Files	References
IBFW Implementation\Warning audience decision-making\In favour of more general warnings as opposed to impact-based or action-based warnings\Need to have enough 'bubbles of control'	1	1
IBFW Implementation\Warning audience decision-making\Lifelines Utilities	1	3
IBFW Implementation\Warning audience decision-making\Methods of Communicating Impact Information	2	2
IBFW Implementation\Warning audience decision-making\Methods of Communicating Impact Information\Different platforms and agencies for communicating information	1	2
IBFW Implementation\Warning audience decision-making\Methods of Communicating Impact Information\Including prescribed actions	5	7
IBFW Implementation\Warning audience decision-making\Methods of Communicating Impact Information\Role of the media	4	8
IBFW Implementation\Warning audience decision-making\Methods of Communicating Impact Information\Stakeholders working in silos and not referring to each other's information	1	2
IBFW Implementation\Warning audience decision-making\Warning Impacts and Outcomes	0	0
IBFW Implementation\Warning audience decision-making\Warning Impacts and Outcomes\Awareness	4	6
IBFW Implementation\Warning audience decision-making\Warning Impacts and Outcomes\Cry Wolf	5	6
IBFW Implementation\Warning audience decision-making\Warning Impacts and Outcomes\Not associating impacts with the hazards	1	2
IBFW Implementation\Warning audience decision-making\Warning Impacts and Outcomes\Not taking the warnings seriously based on past experiences	2	3
IBFW Implementation\Warning audience decision-making\Warning Impacts and Outcomes\Warning Fatigue	2	4
LIMS and PIMS	1	1
Machine learning and artificial intelligence	4	5
Need for government leadership	1	3
Need for government leadership\Political Direction	1	1
Need for government leadership\Political Direction\Political direction vs. bottom-up	1	1
Needs-based research and development	2	2
Needs-based research and development\User Needs Drive the Design of the System	6	10
Partnerships, Collaboration, and Relationships	0	0
Partnerships, Collaboration, and Relationships\Agencies running professional development workshops to build relationships	1	1
Partnerships, Collaboration, and Relationships\Cohabitation	1	1
Partnerships, Collaboration, and Relationships\Cohabitation\Need for cohabitation	1	1
Partnerships, Collaboration, and Relationships\Cohabitation\NZ example of cohabitationa	1	1
Partnerships, Collaboration, and Relationships\Community of knowledge	1	3
Partnerships, Collaboration, and Relationships\Informal Partnership	3	4
Partnerships, Collaboration, and Relationships\MetService-NIWA	1	7
Partnerships, Collaboration, and Relationships\MetService-NIWA\Government cannibalising itself	1	3

Name	Files	References
Partnerships, Collaboration, and Relationships\Regional flood group	1	1
Partnerships, Collaboration, and Relationships\Science advice groups	1	1
Private Weather forecasting and warning services	1	2
Red Cross Hazards App	3	6
Red Cross Hazards App\Chained Crowdsourcing	1	1
Red Cross Hazards App\Impact alerts	1	1
Resilience	4	4
Resilience\LINZ Resilience Challenge	1	2
Samoa Flood Early Warning Project	1	2
Systems Needs	0	0
Systems Needs\Adaptability and flexibility	1	2
Tax-funded publicly owned data	1	1
Unclear definitions and terminology	10	37
Unclear definitions and terminology\Base data vs. operational data	2	2
Unclear definitions and terminology\Examples of impact-based services	4	6
Unclear definitions and terminology\Impact assessment vs. situational awareness	2	2
Unclear definitions and terminology\Impact-based warnings definitions	2	3
Unclear definitions and terminology\Impact-oriented warnings	1	1
Unclear definitions and terminology\Information vs. intelligence	1	1
Unclear definitions and terminology\Loss	1	3
Unclear definitions and terminology\Loss\Monetary Loss	2	3
Unclear definitions and terminology\Multi-disciplinary	3	4
Unclear definitions and terminology\Vulnerability and Exposure	16	30
Unclear definitions and terminology\Vulnerability and Exposure\Always changing over time	4	9
Unclear definitions and terminology\Vulnerability and Exposure\Exposure	11	32
Unclear definitions and terminology\Vulnerability and Exposure\Vulnerability	12	22
Warning Chain in New Zealand	7	25
Warning Chain in New Zealand\Greater Wellington Region Flood Early Warning Program	2	4
Warning Chain in New Zealand\Greater Wellington Region Flood Early Warning Program\Integration	1	1
Warning Chain in New Zealand\Greater Wellington Region Flood Early Warning Program\Lead Times	2	3
Warning Chain in New Zealand\MetService Convective Storm Warnings	1	1
Warning Evaluation	1	7
Who is governing who	2	2

Appendix I: Axial Coding Results

Contextual Conditions	
Cultural Conditions	Economic Viability
	Nation-specific cultural conditions; NZ Culture and Practice ("She'll be right"; think things are good as they are; Lack of motivation to improve
	LIMS and PIMS
	Drivers for adoption of social media platforms and data
Governance Structure	Roles and responsibilities
	Financial motive vs. for the good of NZ; Top level government investment priorities
	Influence of management on science
	Sendai Framework requirements; Why NEMA is doing it (building the national loss database)
	LINZ Resilience Challenge
	Canterbury Governance Structure
	CIMS Structure
	WMO Guidelines
NZ Warnings	MetService convective storm warnings
	Warning chain in New Zealand
	Greater Wellington Region Flood Early Warning Program
	Integration
	Lead times

Causal Conditions	
Events	Melbourne Thunderstorm-induced asthma; Waikato Thunderstorm-induced asthma
	Cyclone Pam
	West Coast events
	Whakaari White Island Volcanic Eruption
	COVID-19 response
	Edgecumbe Floods; Southland Floods
	Pigeon Valley Fire; Port Hills Fire
	Kaikoura earthquakes; Canterbury earthquakes
	Event driven vs. not event driven
Research & Technological Advancements	ArcGIS Online; Survey123; Social media; Crowdsourcing
	Risk modelling; risk assessments
	Developing a historical database for research
Need to Improve warnings	International trend of IBFWs; National Review and recommendations (Australia); Need to evaluate and communicate current efforts towards IBFWs for other countries to learn from and prepare for challenges
	Drivers for IBFWs; Shift from hazard focus to human and impacts focus; Not associating impacts with the hazards
	Better communication with the public; Not taking the warnings seriously based on past experiences; Warning fatigue
	Boundary warnings vs. free-hand drawn warnings (Is this NZ or UK or USA or multiple?)
	Warnings; Impact-based warnings; Question of IBW efficacy

Phenomena	
Data Collection	Data Availability; More data exists than we think
	Various stakeholders that create, manage, share, access, use data; Stakeholders and users of impact data; Stakeholders
	Different ways of communication the information or data
Data Sharing	Drivers for sharing data; Realisation that data has value and use beyond its initial intended purpose; "Although we all complain about a lack of data, a lot of the time, there is quite a bit of data out there that could be used and isn't being used very well."
	Requirements and practices of sharing data
Data Management	Custodianship
	Different ways of storing and managing data
IBFW Implementation	Vision for IBFWs
	Defining Impact Thresholds; Impacts to identify hazards
	Impact-based warnings definitions
	Impact-oriented warnings
	Multi-disciplinary
IBFW Data Needs	Hazard; Hazard data needs
	Impact; Historic Impacts; Why we need more than just historical impact data
	Physical damage and impacts; Utility outages
	Types of impacts; Physical impacts lead to social impacts; Focus on physical impacts; Direct vs. indirect impacts; Urban vs. rural impacts
	Social and cultural impacts; Cultural Heritage and impacts; Human and social impacts; Health Impacts; Mortality; Community Impacts
	Loss; Monetary loss
	How to measure significance; How to capture that properly in the data; How to convey the meaning of the data
	Impact data as input vs. output; Input; Output
	Exposure; Dynamic Exposure; Change in landscape (Dynamic exposure); Movement and location of people
	Vulnerability and Exposure; Always changing over time
	Vulnerability; Dynamic Vulnerability; Underlying health conditions
	Climate change; Future events can be more extreme than past events
	Geographic and location information

Intervening Conditions	
Data Collection Challenges and Considerations	Balance between too much and enough data; Need to know what to do with the data
	Level of detail
	Government role vs. sector roles
	Challenge with capturing less tangible or physical impacts and indirect impacts
	Council documenting impacts on internal assets vs. privately owned assets
	Priorities; Lack of motivation or interest in data creation and maintenance; Waiting for someone else to take the lead
	Amount of work required
	Resources
	Scaling problems; Spatial Scale; Temporal Scale
	Struggles; Access to sites
	Different countries have different standards and cultures
	Ongoing question of data sources
	When is a good time to collect the data?
	Information vs. intelligence
Data Management Challenges	Maintenance
	Whose Responsibility; NEMA as a broker; Who is the most suitable for managing data in terms of skills and expertise
	Costs
	Consuming data vs. holding information
	Business as usual vs. new tools only for emergency use
Social challenges to sharing data	Trust; Suspicion between institutions in NZ inhibits progress in risk management; Trust or distrust in how the data is stored and managed
	Pessimism or frustration
	Ownership (of the data)
	Political; Impact data is political data; Impact data has a lot to do with the organisation of the government
	Resource limitations; Finance or funding limitations; Human-power and time limitations
Ethical Considerations	Privacy
	Fear of publishing impacts; Catastrophising it (the event by publishing the impacts)
	Commercial or proprietary licensing;
Technical challenges to sharing data	Outdated model of sharing data; Need for better collaboration and coordination
	Reliability of the people producing and maintaining the data
	Trust in the data; Confidence in the data and subsequent analysis
	Welfare information (need a process to capture it properly)
	Need a common framework for aggregating all sources of data; Data collected by different agencies is managed and stored differently which makes it difficult for integration

	Need to get time critical data before it is lost; Sometimes a delay in collecting the data can help
	Poor data collection and management practices
Uncertainty	Communicating uncertainty
	Compounding Uncertainty
	Sources of Uncertainty
	Uncertainty of the impacts; Uncertainty in forecasting the hazard
	Lack of knowledge and expertise; Lack of data
	Uncertainty of roles and responsibilities
	Unclear definitions and terminology (Base data vs. operational data; impact assessment vs. situational awareness; Information vs. intelligence; impact-based warnings definitions; impact-oriented warnings; vulnerability and exposure)
Governance challenges	Agency remit or responsibility; Shifting roles or adding onto existing roles
	Data custodianship
	Need national cohesion
	Legislation
	Liability
	Different platforms and agencies for communicating information
IBFW Data Usability Needs	Trust in the data; Confidence in the data and subsequent analysis; Importance of official data
	Different needs for different stakeholders
	Up-to-date information; Near real-time data; Real-time impact data for IBFWs; Lag or delay in incoming impact information and issuing warnings
Alternative or unofficial data challenges	Skewed data; Digital divide and urban bias; Age
	Credibility
	Do the challenges with citizen science outweigh the benefits of it?
Challenges with applying the knowledge, data, and information	Defining thresholds; Difference across stakeholders; Many factors to consider when deciding on the warning level; Thresholds that are too sensitive or too widescale; Not wanting to rely only on models
	Warning spatial Scale doesn't match spatial scale of impacts
	Tunnel vision limiting risk and impact modelling
	Evaluation
	Experience to inform decisions and to learn from previous impacts is a double edged sword
	Communication to different audiences

Action/Interaction Strategies	
Data Collection Strategies	Quality Control; Inclusion criteria; Judgement call for including impact data into national loss database
	Needs-based datasets and database development; Collect only the data that will be used
	Post-event surveys
	Training
	Recognising the value of information
Building Partnerships for better data sharing practices	Networking and relationships; Attending conferences (e.g., MetService attending NEMA Conference; building the idea of a national severe weather and flood advisory group to fellow conference attendees); Facilitating workshops (e.g., MetService hosted workshops for CDEM people);
	Cooperation and collaboration; Need for better collaboration and coordination
	Attitude shift for better data sharing and access
	Information partnership
Data Management and Integration Strategies	Spatial Data infrastructure
	Archiving
	Transition from SDI to unstructured or hybrid data sharing and access
	Interconnected systems
	Data integration
	Data directories
	Spatial GIS Data
	Machine Learning and Artificial Intelligence
Standardisation Strategies	Systematic Impact Data Collection; Training
	Data standards; Best practice guidelines; Government endorsed template; National damage assessment dictionary
	Meta-data
Hazard Data Collection and Sharing Strategies	Flood models
	Hazard data sources
	Climate Records
Impact Data Collection and Sharing Strategies	Impact Data sources
	ACC
	CDEM response records and situational reports; CDEM Impact Assessments (Phase 1 Wide Area Assessment, Phase 2 Rapid Damage Assessment, Phase 3 Detailed Impact Assessment)
	Public scan
	GNS Science
	Insurance
	Media Reports
	National Archives

	Social media and crowdsourcing
	Stats NZ
	Tacit knowledge; Tacit knowledge and prior experience
	Impact data assessments; Social impact post-event assessment; Rapid impact assessments; CDEM Impact Assessments; Post-event damage assessment; Contractors
Exposure Data Collection and Sharing Strategies	Exposure Data Sources
	FENZ
	Demographics
	Ongoing question of data sources
	Stats NZ Data Ventures
	Flood models
	KiwiRail; NZTA
Vulnerability Data Collection and Sharing Strategies	Vulnerability Data Sources
	Flood models
Alternative or unofficial data sources	Crowdsourcing; Red Cross Hazards app Chained Crowdsourcing; NZ Flood Pics
	Citizen science
	Social media; Instagram; Twitter; Facebook; SnapChat;
	Community Reports
Official or Traditional Data sources	111 calls
	Drones
	Media reports
	QuickCapture; RiACT/Capture tool; Flexibility and customisation
	Satellite Imagery
	Survey123
Alternative or unofficial data strategies	Trusted crowdsourcing and crowdsourcers; Citizen science for quality control; Triangulating across different platforms; Training
Defining and Setting Thresholds	Partnering with agencies for impact knowledge; Sharing data
	Joint decisions; Joint or consistent messaging across agencies
	Different methodologies depending on the hazard and the kinds of impacts you want to model
	Identifying triggers or indicators
Strategies to improving warnings	CDEM offer value-add to MetService messages by adding on impact information
	Shift from text-based to images in warning messages
	Stronger media presence and engagement
"Push and pull" system design strategies	Needs-Based research and development; User needs drive the design of the system; System needs; Adaptability and flexibility

	Users (of the national loss/impact database); Uses (of the national loss/impact database)
	Innovation
Strategies for addressing uncertainty	Damage Surveys to correct models and reduce uncertainty
Strategies for driving innovation and change	An individual with the required skills and knowledge can drive change and innovation; Alternatively, Interest and skills as driver for better data creation and management practices; generation change
	Political direction
	Bottom-up organisation
	Organisational culture can drive innovation

Consequences/Outcomes/Impacts (+/-)	
Social Data Sharing Outcomes	Property Values; Liability
	Transparency
	NZGIS4EM
	Ethical Data collection
	Community of knowledge
Technical Data Sharing Outcomes	Common alerting protocol
	Common Operating Picture
	Open data
	Online web maps
	Standardisation
	Risk of losing undocumented tacit knowledge and experience
	Desinventar Sendai
Consequences of Uncertainty	Hesitancy to include impact messaging and to implement IBFWs
	Misunderstanding of the models, forecasts, and warnings
(IBF)Warning Outcomes	Giving meaning to the meteorological information
	Feedback or circular process
	Warning audience decision-making; Lifelines Utilities
	Awareness; Cry wolf; Community risk awareness
	In favour of more general warnings as opposed to impact-based or action-based warnings
	Community-based plans and actions
	Need to have enough 'bubbles of control'
	Role of the media
Alternative or Unofficial Data Risks and Benefits	Two-way flow of information from public authorities; one-way social media communication; Engagement and contributions
	Public trust in the platform; Public impact, transparency, and trust

	What institutionalising it (NZ Flood pics) could mean; Desire to keep the project independent from institutions (NZ Flood pics)
	People interfering in the response and putting themselves and others at risk
	Public perceptions vs. official perceptions of impacts
IBFW Products	Pacific Pilot Case Studies
	Emergency Services Vehicle Damage Models
	UK Surface Water Flooding Model
	UK Vehicle Overturn Model
	Flood Early Warning Project
	New MetService Warning System
	Subscription system
	Methods of Communicating impact information
	Including prescribed actions
	Examples of impact-based services
Impact Databases	Storm Data (US)
	European Severe Weather Database
	NZ National Loss Database; Maturing the system, the future of the system; Software; The value of it; Vision
	NIWA Historic Events catalogue
Policy, Decision-Making, Practice	Reactive vs. proactive CDEM practice)
	Tourism
	Business Case
	Decision-making and planning; Planning; Land use planning and development policies
	Research analysis
	Risk Management; Hazard Risk Communication; Risk Communication; Emergency Management Planning, Response, And Recovery; Messaging for planning and preparedness
	Land use zoning disputes
	Learning from experience
	Science-based practice and policy
	Impact data for different uses and purposes
	Intelligence; Human Intelligence; Open Source Intelligence; Operational Intelligence
Data uses	For evaluation
	Impact data uses
	Hazard data uses
	Model calibration; Validation
	Population exposure model
	Risk modelling; Risk Modelling inputs; Asset information; Building data; Attributes; Vulnerability functions (empirical vulnerability function, expert opinion vulnerability function, judgement-based vulnerability function)
	Computational fluid dynamics (hazard modelling)

	Vulnerability functions; Types of vulnerability functions; Analytical vulnerability function
	Verification
	Bringing reality to the forecasters and modellers; An expert's surprise at the value of damage assessments to drive home the reality of the event

Appendix J: Chapter Five Publication

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Volunteered Geographic Information for people-centred severe weather early warning: A literature review

Sara Harrison[1],
Sally Potter[2],
Raj Prasanna[1],
Emma E. H. Doyle[1],
David Johnston[1]

[1] Joint Centre for Disaster Research, Massey University, New Zealand.
[2] GNS Science, New Zealand.

Author correspondence:
Sara Harrison,
Joint Centre for Disaster Research,
Private Box 756,
Wellington 6140
New Zealand.
Email: S.Harrison@massey.ac.nz

URL: http://trauma.massey.ac.nz/issues/2020-1/AJDTS_24_1_Harrison.pdf

Abstract

Early warning systems (EWSs) can prevent loss of life and reduce the impacts of hazards. Yet, recent severe weather events indicate that many EWSs continue to fail at adequately communicating the risk of the hazard, resulting in significant life and property loss. Given these shortcomings, there has been a shift towards people-centred EWSs to engage with audiences of warnings to understand their needs and capabilities. One example of engaging with warning audiences is through the collection and co-creation of volunteered geographic information (VGI). Much of the research in the past has primarily focused on using VGI in disaster response, with less exploration of the role of VGI for EWSs.

This review uses a scoping methodology to identify and analyse 29 research papers on EWSs for severe weather hazards. Results show that VGI is useful in all components of an EWS, but some platforms are more useful for specific components than are others. Furthermore, the different types of VGI have implications for supporting people-centred EWSs. Future research should explore the characteristics of the VGI produced for these EWS components and determine how VGI can support a new EWS model for which the World Meteorological Organization is advocating: that of impact-based forecasting and warning systems.

Keywords: *early warning system, people-centred early warning system, volunteered geographic information, disaster risk reduction, severe weather*

Early warning systems (EWSs) can prevent loss of life and reduce the impacts of hazards by providing members of the stakeholders and the public with information about likely, imminent risks on which they can act to prepare themselves and their property. As such, they have been a focus of disaster risk reduction since the Hyogo Framework for Action 2005-2015 through to the current Sendai Framework for Disaster Risk Reduction 2015-2030 (UNISDR, 2005, 2015). EWSs are described as having four key operational components: Disaster Risk Knowledge; Detection, Monitoring, and Warning Services; Communication and Dissemination Mechanisms; and Preparedness and Response Capacity (see Figure 1; Basher, 2006; Golnaraghi, 2012).

The first component, Disaster Risk Knowledge, involves systematically collecting and analysing data related to risk, such as the exposure and vulnerability of people and infrastructure to nearby hazards (Ahmed et al., 2012; Basher, 2006; Sai, Cumiskey, Weerts, & Bhattacharya, 2018). This involves assessing risk and vulnerability, building evacuation plans, and tailoring warning systems. Detection, Monitoring, and Warning Services make up the second component and are central to EWSs. This component requires reliable technology and involves continuous, automated detection and hazard monitoring (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Furthermore, data, forecasts, and warnings should be archived for post-event analysis and

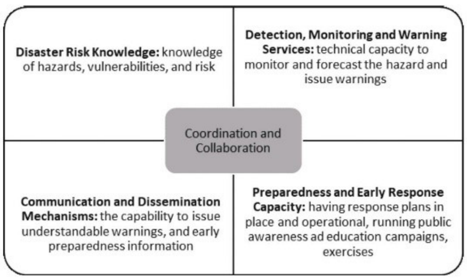

Figure 1. Four operational components of an early warning system. Adapted from Basher (2006), Golnaraghi (2012), and WMO (2018).

for continual system improvements (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Impact data collected during and after a severe weather event would support both of these first two components (Harrison, Silver, & Doberstein, 2015).

The third component of an EWS is Communication and Dissemination, which is needed to reach those at risk. This involves using clear, concise, and understandable messages to enable proper preparedness (Ahmed et al., 2012; Basher, 2006; Sai et al., 2018). Multiple communications channels are necessary to reach as many people as possible (Ahmed et al., 2012; Basher, 2006). The fourth component of an EWS is Preparedness and Early Response Capacity. This involves running education and preparedness programmes to help people "understand their risks, respect the national warning services, and know how to react to warning messages" (WMO, 2018, p. 6). All four components of an EWS play a key role in crisis and risk communication.

EWSs share common characteristics with crisis and emergency risk communication theory. Like EWSs, the goal of crisis and risk communication theory is to provide sufficient and appropriate information to stakeholders that would allow them to "make the best possible decisions about their well-being" in a short period of time under uncertainty (Reynolds & Quinn, 2008, p. 14S). This involves understanding stakeholder (including the public) perceptions of risk and of the effectiveness of response, understanding the needs, capabilities, experiences, and predispositions of the stakeholders, and formulating messages based on these understandings for different audiences throughout the stages of crisis (Morgan, Fischhoff, Bostrom, Lave, & Atman, 1992; Reynolds & Seeger, 2005; Veil, Reynolds, Sellnow, & Seeger, 2008). Crisis and emergency risk communication theory is applied in risk messaging, crisis messaging, and warnings for health and emergency situations including, but not limited to, disease outbreaks, bioterrorism, hurricanes, and tornadoes (Reynolds & Seeger, 2005). The EWS framework presented in Figure 1 is thus supported by objectives of crisis and emergency risk communication theory, although the EWS framework does not include an apparent consideration for two-way communication: a key component in crisis and emergency risk communication theory for evaluating the effectiveness of communication (Garcia & Fearnley, 2012; Veil et al., 2008).

Recent severe weather events indicate that many EWSs continue to fail at adequately communicating the risk (and associated impacts) of the hazard, resulting in significant life and property loss due to limited understanding of, and response to, warnings (Ching, Carr de los Reyes, Sucaldito, & Tayag, 2015; Fleming et al., 2015; Wagenmaker et al., 2011). As such, there has been a push for "people-centred" EWSs to bring the "human factor" into consideration when designing and implementing EWSs and issuing warnings.

People-Centred Early Warning Systems

The broader EWS literature has recognised a communication gap between warning services and warning recipients, resulting in target audiences taking inadequate protective action despite receiving warnings (Anderson-Berry et al., 2018; Basher, 2006; Weyrich, Scolobig, Bresch, & Patt, 2018). In 2006, Basher introduced the concept of people-centred EWSs to address the "human factor" in EWSs, as he stated "failures in Early Warning Systems typically occur in the communication and preparedness elements" (Basher, 2006, p. 2168). Since then, there has been a shift towards people-centred EWSs which are developed for, and with, the target audiences to identify their needs and capacities and to transfer responsibility back to the audience to take protective actions (Basher, 2006; Scolobig, Prior, Schröter, Jörin, & Patt, 2015).

The United Nations Office for Disaster Risk Reduction (UNDRR; formerly known as the UNISDR) listed "investing in, developing, maintaining and strengthening people-centred multi-hazard, multi-sectoral forecasting, and Early Warning Systems" as an objective towards meeting the fourth priority of the Sendai Framework (UNISDR, 2015, p. 21). This "people-centred" aspect involves incorporating local and indigenous knowledge about hazards, promoting and applying low-cost EWSs that are appropriate to the audience based on their needs and capabilities, and broadening information channels (UNISDR, 2015; WMO, 2018). According to the Sendai Framework, people-centred EWSs can be developed through engagement with the audiences of warnings (e.g., individuals, communities, sectors: UNISDR, 2015; WMO, 2018).

One such example of engaging with warning audiences and understanding their needs and capabilities is through volunteered geographic information (VGI; WMO, 2017). VGI is information produced by or gathered from the public with associated locational attributes. The location-based information from VGI allows officials to identify high-risk areas, populations, and infrastructure

(Goodchild & Glennon, 2010; Granell & Ostermann, 2016; Haworth, 2018; Roche, Propeck-Zimmermann, & Mericskay, 2011).

Volunteered Geographic Information

VGI is valuable to disaster management because disasters are inherently location- and time-dependent and the location information from VGI allows officials to understand where the high-risk areas and populations are (Goodchild, 2007; Goodchild & Glennon, 2010; Granell & Ostermann, 2016; Haworth, 2018; Roche et al., 2011). The broader literature body around VGI, crowdsourcing, citizen science, and social media discusses and debates the relationship of these terms to each other and their associated characteristics and differences. It is argued that VGI overlaps both with citizen science and crowdsourcing (Cooper, Coetzee, & Kourie, 2018; Haklay, 2013, 2017). In Haklay's (2013) typology, crowdsourcing is classified as the lowest level of participation in citizen science. Citizen science (including crowdsourcing) is considered VGI when the information produced through the differing levels of participation includes geographic information (Haklay, 2017).

VGI can be collected in various ways, producing different types and formats of data. From reviewing the VGI and disaster risk reduction literature, we identified four types of VGI that are generally produced and/or collected for disaster risk reduction; these are summarised in Table 1. Geo-located social media refers to VGI that is posted online by social media users that has associated geographical location information. The term social media recognises online blogs, micro-blogs, online social networking, and forums, which enable sharing of text, audio, photographs, and videos (Alexander, 2014). Facebook, Twitter, Sina Weibo, WeChat, Instagram, and SnapChat are some examples of popular social media platforms. During a severe weather event, authorities can use social media to disseminate alerts and warnings and collect information from members of the public about the event and its impacts (Alexander, 2014; de Albuquerque et al., 2017; Goodchild, 2007; Harrison & Johnson, 2016; Roche et al., 2011; Simon, Goldberg, & Adini, 2015; Slavkovikj, Verstockt, Van Hoecke, & Van de Walle, 2014).

For this review, crowdsourcing refers to gathering information from active public participation, namely reports submitted via online forms or mobile applications (Harrison & Johnson, 2016). Crowdsourcing has historically been used in the response to a disaster for building situational awareness, coordinating resources, and aiding response efforts (Harrison & Johnson, 2016; Haworth & Bruce, 2015; Poblet, Garcia-Cuesta, Casanovas, 2014). Within the severe weather context,

Table 1
Summary of Volunteered Geographic Information types.

VGI Process	Spatial Data Format	Data Type	Data Sources	Disaster Risk Reduction Phase	Analysis/Outcomes
Geo-located social media harvesting	Point data	Impact data, exposure data, vulnerability data, hazard data Photos, videos, text	Facebook, Instagram, Twitter, Snapchat, Flickr, Sina Weibo, etc.	All	Cluster analysis, early detection, situational awareness, post-event damage/ impact assessment, response coordination
Crowdsourcing	Point data	Impact data, exposure data, vulnerability data, hazard data Photos, videos, text	Online reporting forms, mobile application	Readiness, Risk Reduction, During, Response	Cluster analysis, early detection, situational awareness, damage/impact assessment, response coordination
Participatory mapping/ Participatory GIS	Point, line, polygon	Impact data, exposure data, vulnerability data, hazard data, expert local knowledge Shapefiles	Community members, community leaders, stakeholders	Readiness, Risk Reduction, Recovery	Hazard and risk assessments/modelling, impact forecasting, customise/personalise warnings systems for the community, identify impact thresholds, inform/improve readiness and reduction efforts based on local knowledge
Local Knowledge	Point, line, polygon, written, audio	Impact data, exposure data, vulnerability data, hazard data, expert local knowledge Shapefiles	Community members, community leaders, stakeholders, experts	Readiness, Risk Reduction, Recovery	Hazard and risk assessments/modelling, impact forecasting, customise/personalise warnings systems for the community, identify impact thresholds, inform/improve readiness and reduction efforts based on local knowledge

crowdsourcing was used in the aftermath of Hurricane Katrina to locate missing people and allocate response efforts (Roche et al., 2011). In other examples, crowdsourcing is used for people on the ground to submit reports on flood levels and weather phenomena observations (Harrison & Johnson, 2016; Horita et al., 2018).

Participatory mapping and participatory Geographic Information Systems (participatory GIS) use local spatial knowledge to create spatial data or to verify and update existing data (Peters-Guarin, Mccall, & van Westen, 2012). Participatory mapping generally evolves into participatory GIS when hand-drawn maps or features are digitised and integrated into a GIS for further analysis (Brown & Kyttä, 2014; Forrester & Cinderby, 2011). Participatory mapping is often used to map exposure and vulnerability to hazards in communities to support disaster risk planning (Gaillard & Pangilinan, 2010; Haklay, Antoniou, & Basiouka, 2014). For weather-related hazards, Haworth, Whittaker, and Bruce (2016) found that participatory mapping enabled local knowledge exchange for community preparedness to bushfire risks.

Local knowledge refers to knowledge possessed by locals about their communities, neighbourhoods, traditions, history, environment, and hazards, among others. Local knowledge has not been clearly defined in the literature. For the purposes of this paper, we consider local knowledge as information gathered in similar participatory mapping and participatory GIS processes but not translated into a map or GIS. Recently, the access to and integration of local knowledge has been recognised for its importance to disaster risk reduction (Anderson-Berry et al., 2018; Gall & Cutter, 2016; Sebastian et al., 2017; UNISDR, 2015).

Past research has focused heavily on the role of VGI in disaster response, with less exploration in understanding how VGI can inform warnings before or during a severe weather event (Harrison & Johnson, 2016; Haworth & Bruce, 2015; Horita, Degrossi, Assis, Zipf, & de Albuquerque, 2013; Klonner et al., 2016). In Klonner and colleagues' (2016) systematic literature review, the authors focused on documenting research on VGI for preparedness and mitigation but did not provide clear findings in the context of warnings for severe weather. Assumpção, Popescu, Jonoski, and Solomatine (2018) identified the role of citizen observations in providing data for flood modelling and forecasting to solve issues of data scarcity, but again with no mention of warnings.

The original conception of VGI began with identifying its value for early detection and warning of hazards, using "citizens as sensors" (Goodchild, 2007). Since then, some work has emerged exploring VGI for early warnings of various hazards, such as earthquakes, landslides, and tsunami (Carley, Malik, Landwehr, Pfeffer, & Kowalchuck, 2016; Elwood, Goodchild, & Sui, 2012; Goodchild, 2007; Granell & Ostermann, 2016; Harrison & Johnson, 2016). Horita, de Albuquerque, Marchezini, and Mendiondo (2016) argued that VGI may help address challenges of assigning proper warning thresholds by incorporating local knowledge of response capabilities. Meissen and Fuchs-Kittowski (2014) developed a conceptual framework which demonstrated how crowdsourced data can be fully integrated into an existing EWS as another dataset to augment or enhance the warnings by providing context. However, no further evidence to date indicates the adoption into practice of this framework for any type of EWS. Finally, Marchezini and colleagues (2018) conducted a literature review of research on citizen science and EWSs and found that more research is needed to identify how citizen science can be "mainstreamed" into EWSs.

Some agencies have started collecting VGI to detect, monitor, and track events and their impacts. In the United Kingdom (UK), the British Geological Survey collects landslide impact data from Twitter including text descriptions, photos, and video footage of the resulting impacts (Pennington, Freeborough, Dashwood, Dijkstra, & Lawrie, 2015). These data are integrated into the National Landslide Database, which is used to create a Hazard Impact Model (Pennington et al., 2015). In Canada, the National Meteorological Service uses hazard information posted by the public on Twitter to detect weather events such as tornadoes and to verify and update current weather watches and warnings (Harrison & Johnson, 2016). However, there is a gap in the literature for fully characterising the role of VGI for severe weather warnings. It is important to fill this gap because information and knowledge possessed by citizens have the potential to uncover "areas of importance or concern" that have yet to be identified in an official capacity (Haworth, Bruce, & Middleton, 2012, p. 40). VGI offers a way to capture local knowledge about previous severe weather events and their extent, severity, and resulting impacts, as well as information on the local exposure and vulnerability that warning services may not necessarily possess (Fleming et al., 2015; GFDRR, 2016; Krennert, Pistotnik, Kaltenberger, & Csekits, 2018; Sai et al., 2018; WMO, 2017). This paper uses a scoping review method to identify previous research into the use of VGI for severe weather EWSs, to attempt to answer the research question: *What are the current and potential uses of VGI for severe weather warnings?* The objective of this review is to determine how VGI has been, or could be, used within EWSs for severe weather hazards.

Method

This literature review uses a scoping method to explore areas of existing research and identify research gaps in VGI for severe weather early warning systems (Arksey & O'Malley, 2005; Paré, Trudel, Jaana, & Kitsiou, 2015). Scoping reviews provide a "rigorous and transparent method for mapping areas of research" in a short time (Arksey & O'Malley, 2005, p. 30). The aim is to describe the nature of the current literature on VGI for severe weather EWSs by describing the quality and quantity of the research (Grant & Booth, 2009; Paré et al., 2015). Scoping reviews are recognised for their strength in providing a broad picture of the state of research in a given topic area and are well-cited in the information systems field (Grant & Booth, 2009; Paré et al., 2015; Tan et al., 2017). This scoping review follows the five-step process defined by Arksey and O'Malley (2005): 1) identify the research question, 2) identify relevant studies, 3) select studies, 4) chart the data, and 5) report the results.

Table 2
Search string employed in EBSCO Discovery and Scopus databases.

Topics covered	Search string statement
Warnings and Disaster Risk Knowledge	("risk communication" OR "warning*" OR "impact model*" OR "risk model*" OR "impact warning*" OR "impact*based warning*" OR "impact forecast*" OR "impact*based forecast*" OR "risk*based warning*" OR "risk*based communication")
	AND
A broad definition of VGI to include social media, participatory mapping, local knowledge based on location	("participatory" OR "participatory mapping" OR "VGI" OR "volunteered geographic information" OR "participatory GIS" OR "PGIS" OR "geographic crowdsourc*" OR "citizen science" OR "crowdsourc*" OR "social media")
	AND
Severe weather hazards as defined under the WWRP HIWeather Implementation Plan (Jones & Golding, 2014)	("weather" OR "storm*" OR "snow*" OR "wind*" OR "tornado*" OR "hurricane*" OR "cyclone*" OR "typhoon*" OR "monsoon*" OR "flood*" OR "mudslide" OR "flash flood*" OR "rain*" OR "wildfire")

The initial literature search involved developing a search string to capture the broad topic area of VGI and social media for warning of severe weather hazards. The search string comprised three joined statements, shown in Table 2, to cover warnings and Disaster Risk Knowledge (as per the first component of the EWS framework: Basher, 2006; Golnaraghi, 2012), VGI, and severe weather, which were entered into two academic-focused databases, Scopus and EBSCO Discovery Service, in August 2018. Literature review papers have been published on similar topics in this space that have searched no more than two databases (e.g., Klonner et al., 2016; Tan et al., 2017). Furthermore, Scopus is recognised for indexing a larger number of journals than other databases and is the largest searchable citation and abstract source for various scientific fields (Falagas, Pitsouni, Malietzis, & Pappas, 2008; Guz & Rushchitsky, 2009). Moreover, when searching the two databases many duplicate results were found between the two databases, ensuring confidence in the coverage.

"Participatory GIS" and "participatory mapping" are different types of VGI, and thus were identified as separate search terms. During the process of developing the search string, it was found that additional VGI research was left out of the search due to the specificity of "participatory mapping" and "participatory GIS", thus the search was widened with the term "participatory" to capture more VGI studies. Similarly, "flash flood" and "flood" are likely redundant, however, they were both included to ensure full coverage. The asterisk in the search string acts as a *wildcard* to search for variations of the root term. The search covered all years from the earliest available until mid-2018 and included only peer-reviewed journals and conference proceedings in English. The search resulted in 1,015 hits from Scopus and 122 from EBSCO. After removing duplicates, 1,027 unique publications were captured.

The following inclusion-exclusion criteria were used to select publications most relevant to this study:

1) Publications that specifically focused on severe weather hazards as defined under the World Weather Research Programme's (WWRP) High Impact Weather Implementation Plan (Jones & Golding, 2014; *n* = 254);
2) Studies that explicitly discussed warnings, preparedness, mitigation, impact modeling and

forecasting, or risk mapping (reducing to n = 141); and,

3) Studies that focused on VGI, crowdsourcing, citizen science, participatory mapping, local knowledge gathering, or social media data (reducing to n = 42).
4) Finally, publications had to be original, complete research papers (n = 29).

After applying the inclusion-exlcusion criteria, information from the resulting papers was extracted according to different categories (see Table 3). Initially, the severe weather hazard(s) considered in the study were identified, after which the EWS framework was used to classify the papers and determine how VGI is or could be used within the EWS framework (these results are presented later in Figure 3). This classification involved identifying for which EWS component the VGI was used (see Figure 1), followed by the element within the EWS component (i.e., the specific task, tool, or process that the VGI was used for within the EWS component, such as risk mapping, detection, monitoring, forecasting, or warning dissemination). The VGI platform was identified (e.g., participatory mapping, participatory GIS, social media, crowdsourcing, citizen science, local knowledge), as well as the type of data that was collected (Haklay, 2017; Harrison & Johnson, 2016). These categories were chosen to determine the representation of VGI in severe weather EWSs.

Results

The search of the two databases led to 1,027 unique publications. After applying the inclusion-exclusion criteria, the final number of papers selected for this study was 29. The categories listed in Table 3 were used as a structure for analysis and discussion, and were chosen based upon the dominance of those themes in the papers.

Table 3
Categories for literature review.

Category	Description
Hazard	The type of severe weather hazard(s) considered in the study.
Early Warning System Component	The component from the EWS framework that each study applies to.
VGI Platform	The source of the VGI data, such as from social media, or from crowdsourcing (i.e., citizen observation), citizen science (i.e., a higher level of engagement than crowdsourcing; Haklay, 2013), participatory mapping, participatory GIS, or local knowledge.
Data Type	The type of data that was collected through the VGI process, such as local knowledge captured through interviews and/or participatory mapping, hazard data from social media or crowdsourcing, etc.

Hazard Type

The selected articles covered a range of severe weather hazards as defined in the World Weather Research Programme (WWRP) High Impact Weather (HIWeather) implementation plan (Jones & Golding, 2014). Some hazards are represented more than others; of the 29 articles, 16 focused on flood hazards, followed by seven studies that covered general severe weather hazards, two studies that examined rain-induced landslides, two for cyclones, and one each for air quality and urban heat wave.

The 16 flood studies covered a range of elements within the EWS components. These elements were identified by reviewing the selected studies and aligning them with the EWS components. Table 4 provides a summary of the selected studies which examined floods. Most studies covered flood detection, monitoring, and forecasting using VGI collected from social media and crowdsourcing. The next most common elements that were covered in the flood studies were vulnerability

Table 4
Summary of selected studies covering flood hazards.

EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
Disaster Risk Knowledge	Modelling	To integrate local knowledge into GIS outputs for flood risk management using participatory GIS in order to understand how people cope and adapt	Participatory GIS	Interviews with households in Barangay, Philippines	Peters-Guarin et al., 2012
	Modelling	Validating flood models using quantitative and qualitative VGI	Participatory Mapping	Local knowledge from workshop participants and interviewees	Rollason et al., 2018
	Risk mapping	To provide an example of how to engage and collaborate with local stakeholders for flood management	Participatory Mapping	Land feature layers, input from locals	Lavers et al., 2018

Table 4 *(continued)*

	Vulnerability assessment	To present a risk management framework that is based on local knowledge of the vulnerability to water hazards	Local knowledge	Meetings, workshops, interviews with people, media, and public sectors related to risk management	Arias et al., 2016
	Vulnerability assessment	To present a new methodology for incorporating stakeholder's participation, local knowledge, and locally spatial characteristics for vulnerability assessments of flood risk	Participatory GIS	Demographic data, infrastructure, hazard data (e.g., average annual rainfall), questionnaire interviews with experts and community members	Hung & Chen, 2013
	Vulnerability assessment	To present a new database for collection and assessment of flood damage using a bottom-up approach to gather and identify damage data	Social media	Personal blogs, on-site observations, public administration, social media, online media, local authorities, corporate websites	Saint-Martin et al., 2018
Detection, Monitoring, Warning Services	Detection	To develop a service-oriented architecture for flood management to capture real-time information about floods	Crowdsourcing	Rainfall, river, news, OpenStreetMap	Sharma et al., 2016
	Detection	To develop a methodology for interpreting image tags on social media for early detection of a flood and recording the impacts	Social media	Flickr posts - timestamps and location metadata	Tkachenko et al., 2017
	Detection, Forecasting	SWOT analysis of web-based access to data and model simulations, and insight on pEWMS, and conceptual framework for a Nordic pEWMS	Crowdsourcing, Social Media	Denmark: groundwater level observations Iceland: flood photos Finland: mobile phone observations	Henriksen et al., 2018
	Detection, Monitoring	To assess social media feasibility for flood detection, monitoring, and forecasting and develop a novel methodology for doing so	Social media	Twitter data	Rossi et al., 2018
	Forecasting	To develop a methodology using social media for estimating rainfall runoff estimations and flood forecasting	Social media	Twitter data	Restrepo-Estrada et al., 2018
	Forecasting	To present a real-time modelling framework to identify likely flooded areas using social media	Social Media	Twitter data, LiDAR	Smith et al., 2017
	Monitoring	To estimate flood severity in an urban coastal setting using crowdsourced data	Crowdsourcing	Crowdsourced street flooding reports	Sadler et al., 2018
	Monitoring	To present a conceptual framework for collecting and integrating heterogeneous data from sensor networks and VGI	Crowdsourcing	Flood data from in-situ sensors and volunteers	Horita et al., 2015
	Monitoring	To present a new methodology for monitoring flood hazards using remote sensing and VGI	Crowdsourcing, Social Media	Volunteered data (photos, videos, news), Landsat, DEM, meteorological data, river data	Schnebele & Cervone, 2013
Detection, Monitoring, Warning Services; Communication and Dissemination Mechanism; Preparedness and Early Response Capacity	Warning messaging, preparedness	To test if evidence exists for social media reducing flood losses by informing mitigation decisions before the flood	Social media	Surveys, in-depth interviews with households who experienced flooding in Bangkok, 2011	Allaire, 2016

assessments and risk mapping and modelling, using VGI from participatory GIS, participatory mapping, local knowledge, and social media. Just one study looked at using social media for detection, warning messaging, and for informing preparedness decisions (Allaire, 2016).

The remaining 13 studies covered other hazards, such as general severe weather, cyclones, landslides, air quality, and urban heatwaves. Table 5 provides a summary of the selected studies covering these various hazards. The general category refers to studies that did not identify a specific severe weather hazard, but referred only to "severe weather", usually in the context of severe weather warnings (Fdez-Arroyabe, Lecha Estela, & Schimt, 2018; Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017; He, Ju, Xu, Li, & Zhao, 2018; Krennert et al., 2018; Longmore et al., 2015; Lu et al., 2018).

In the general category, most of the selected studies looked at detection and forecasting using social media and crowdsourcing, followed by tracking warning dissemination across social media, and one study that used crowdsourcing for both risk and vulnerability assessment and providing warnings. The two cyclone studies each used social media and local knowledge to detect and forecast cyclone damage and to understand local responses to warnings, respectively. The two landslide studies both used VGI for landslide hazard and impact modelling, using crowdsourcing and social media. Finally, both the air quality and urban heatwave studies explored VGI from social media to forecast air quality and detect heatwaves based on individual exposure.

These studies indicate that VGI is used in the mapping, modelling, detection, monitoring, and warning of a number of severe weather hazards but that floods are the most heavily studied, with the widest range of VGI application across all of the elements. How these studies fit within the EWS framework is analysed in the following section.

Early Warning System Components

The papers were categorised by EWS component, as per Basher's (2006) framework (see Figure 1): 1) Disaster Risk Knowledge (*n* = 8); 2) Detection, Monitoring, and Warning Services (*n* = 16); 3) Communication and Dissemination Mechanisms (*n* = 2); and 4) Preparedness and Early Response Capacity (*n* =1). Two studies were found to fall into more than one EWS component. The studies were then classified by the specific elements within each component (e.g., hazard mapping, risk mapping, vulnerability assessment, modelling, hazard monitoring, detection, monitoring, warning, messaging, dissemination).

Disaster Risk Knowledge. Eight studies fall into the Disaster Risk Knowledge component of the EWS framework. Four of these studies looked at the use of VGI for hazard, risk, or impact modelling for landslides and floods (Choi, Cui, & Zhou, 2018; Pennington et al., 2015; Peters-Guarin et al., 2012; Rollason, Bracken, Hardy, & Large, 2018). Choi and colleagues (2018) presented a crowdsourcing-based smartphone application to aggregate landslide reports, which populates a landslide database for further hazard analysis. Similarly, Pennington and colleagues (2015) presented a landslide database for the UK that is partially populated by reports from Twitter to capture their impacts for further modelling. In the floods space, Peters-Guarin and colleagues (2012) utilised participatory GIS to integrate local knowledge of coping and adaptation practices into GIS-based flood risk analysis. Alternatively, Rollason and colleagues (2018) used participatory mapping to validate existing flood models.

The other four studies in the Disaster Risk Knowledge component involved risk mapping and vulnerability assessments, also for floods (Arias et al., 2016; Hung & Chen, 2013; Lavers & Charlesworth, 2018; Saint-Martin et al., 2018). Lavers and Charlesworth (2018) engaged with landowners to capture their knowledge of flood risk to inform flood management. Arias and colleagues (2016) presented a risk management framework for floods based on local knowledge of the vulnerability to water hazards. Hung and Chen (2013) incorporated stakeholders' participation and local knowledge through participatory GIS for vulnerability assessments of flood risk. Saint-Martin and colleagues (2018) developed a flood damage database (DamaGIS) to collect and assess flood damage, sourced from corporate websites, personal blogs, local authorities, on-site observations, social media, and online media. Furthermore, Saint-Martin and colleagues argued that social media can extend coverage to areas lacking regular media coverage and reveal damage that might have otherwise gone undetected.

Detection, Monitoring, and Warning. Within the Detection, Monitoring, and Warning component, 16 studies were identified. Four studies used VGI for hazard detection. Tkachenko, Jarvis, and Procter (2017) and Sharma and colleagues (2016) looked at VGI for

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Harrison et al.

Table 5
Summary of selected studies covering other severe weather hazards.

Hazard	EWS Component	Element	Purpose of the study	VGI Platform	Data Type	Reference
General	Disaster Risk Knowledge; Detection, Monitoring, Warning Services	Risk mapping	To present a data infrastructure that can be used to delineate individual vulnerability to meteorological changes	Crowdsourcing	User profiles on a mobile app	Fdez-Arroyable et al., 2018
	Detection, Monitoring, Warning Services	Detection	To present an Android-based application for geohazard reduction using crowdsourcing	Crowdsourcing	Crowdsourced information (field data, photos, videos)	He et al., 2018
		Detection, Monitoring	To present a conceptual framework for collecting weather photos	Crowdsourcing	User reports, photos, videos	Longmore et al., 2015
		Detection, Monitoring	To evaluate the occurrence of crowdsourcing for severe weather within European NMHSs	Crowdsourcing, Social Media	Surveys with European National Meteorological and Hydrological Services	Krennert et al., 2018
		Forecasting	To use social media as a new way of forecasting and generating traffic alerts due to weather hazards	Social media	Temporal, spatial, traffic, and meteorological data from Weibo	Lu et al., 2018
	Communication and Dissemination Mechanism	Warning dissemination	To study the use of codified hashtags relating to weather warnings in Italy	Social media	Twitter data	Grasso & Crisci, 2016
		Warning dissemination	To evaluate the use of a list of predefined codified hashtags for weather warnings in Italy	Social media	Twitter data	Grasso et al., 2017
Cyclone	Detection, Monitoring, Warning Services	Forecasting	To determine if social media and geo-location information can contribute to a more efficient early warning system and help with disaster assessment	Social media	Twitter data, Hurricane damage loss data	Wu & Cui, 2018
	Preparedness and Early Response Capacity	Response to warnings	To integrate local and scientific meteorological knowledge and actions within coconut farming communities in the Philippines	Local knowledge	Interviews with key stakeholders	Ton et al., 2017
Landslide	Disaster Risk Knowledge	Modelling	To present a crowdsourcing smartphone app for landslide reports which populates a landslide database	Crowdsourcing	Crowdsourced landslide reports from app users	Choi et al., 2018
		Modelling	To present a national landslide database in the UK which is partially populated with social media data to capture the impacts of landslides and for early detection of landslides	Social media	Twitter data	Pennington et al., 2015
Air quality	Detection, Monitoring, Warning Services	Forecasting	To explore the use of social media as a real-time data source for forecasting smog-related health hazards	Social media	Social media data and physical sensors data	Chen et al., 2017
Urban heat wave	Detection, Monitoring, Warning Services	Detection	To investigate the relationship between heat exposure and tweet volume over time	Social media	Twitter data	Jung & Uejio, 2017

detecting floods and capturing impacts from social media and crowdsourced data respectively. Jung and Uejio (2017) tested the effectiveness of measuring heat exposure on social media and consequently detecting urban heatwaves. Similarly, He and colleagues (2018) developed a crowdsourcing application to detect various weather hazards and to capture impacts to improve the decision-making of local governments. Henriksen and colleagues (2018) indicated the role of social media and crowdsourcing for both detection and forecasting of floods, while Rossi and colleagues (2018) assessed the feasibility of social media for flood detection and monitoring. Longmore and colleagues (2015) presented a conceptual crowdsourcing framework for collecting photos of severe weather hazards in the United States to improve weather monitoring by the National Weather Service. In Europe, Krennert and colleagues (2018) assessed the occurrence of crowdsourcing (either through specialised applications or social media) by national hydrological and meteorological services to capture severe weather observations and impacts for real-time warning verification and improvement.

VGI for forecasting alone was used for floods, cyclone damage, general severe weather traffic impacts, and air quality. Restrepo-Estrada and colleagues (2018) developed a methodology using social media for estimating rainfall runoff estimations and flood forecasting, while Smith, Liang, James, Lin, and Qiuhua Liang (2017) presented a real-time modelling framework to identify likely flooded areas using social media. Alternatively, Wu and Cui (2018) found that geo-located social media can help with disaster assessment, and for future forecasting. Lu and colleagues (2018) explored how social media might be used to forecast and generate traffic alerts due to severe weather. Likewise, Chen, Chen, Wu, Hu, and Pan (2017) explored social media for real-time forecasting of smog-related hazards.

Finally, three studies used VGI to monitor floods. Schnebele and Cervone (2013) crowdsourced from social media and other online media to monitor flood hazards and to create hazard maps, finding that the VGI is useful when satellite data is unavailable. Horita, de Albuquerque, Degrossi, Mendiondo, and Ueyama (2015) developed a framework to integrate crowdsourced flood observations with official sensor data. The authors found that the VGI made it possible to capture data from areas lacking flood sensors (Horita et al., 2015). Sadler, Goodall, Morsy, and Spencer (2018) crowdsourced street flooding reports to estimate flood severity for flood prediction, but the poor temporal and spatial coverage of the crowdsourced reports hindered the performance of the prediction model (Sadler et al., 2018).

Communication and Dissemination Mechanisms. Two studies were identified for the third EWS component, Communication and Dissemination Mechanisms. Both studies used VGI to assess warning dissemination via social media (namely Twitter) for general severe weather (Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017). Grasso and Crisci (2016) analysed codified hashtags of regions in Italy impacted by rainfall and found that codified hashtags for different regions effectively enable the sharing of useful information during severe weather events. Additionally, many tweets included geo-location information along with hazard information to update and complement official data. As such, the authors argued that institutions might adopt codified hashtags to improve the performance of systems for disseminating and retrieving information. Grasso and colleagues (2017) built on this work by adding more regions to their tweet analyses and emphasised the importance of institutions and warning services to promote codified hashtags for warnings to streamline message delivery and reach.

Preparedness and Early Response Capacity. For the last component, Preparedness and Early Response Capacity, only one study applied. Ton, Gaillard, Cadag, and Naing (2017) collected VGI in the form of local knowledge using interviews and questionnaires with farmers to understand their response to cyclone warnings. In this process, the farmers identified economic, physical, social, and natural impacts of cyclone hazards. The authors found that while farmers forecast weather conditions and impacts based on their local knowledge, their confidence in the lead-time of their forecasts has declined due to changing climate conditions. As such, the authors argued for the integration of local knowledge with scientific forecasts to verify local knowledge-based forecasts and increase confidence.

Multiple components. Two studies were found to fall into more than one EWS component. Allaire (2016) used VGI for Detecting, Monitoring, and Warning, assessing Communication and Dissemination Mechanisms, and for measuring Preparedness and Early Response capacities for flood hazards. Allaire (2016) found that social media was an effective tool for flood monitoring (falling in the Detection, Monitoring, and Warning component), for receiving and spreading flood information (as a Communication and Dissemination Mechanism), and for receiving and spreading preparedness information, leading to reduced impacts (informing Preparedness and Early Response Capacity). Alternatively, Fdez-Arroyable and colleagues (2018) developed a mobile application to obtain individual vulnerabilities to meteorological changes (thus informing Disaster Risk Knowledge) and to provide personalised alerts based on the individual vulnerabilities to meteorological conditions (informing Detection, Monitoring, and Warning services).

VGI Platforms and Data Types

In this review, we broadly define VGI to include participatory mapping, participatory GIS, geo-located social media, and location-based local knowledge (de Albuquerque, Eckle, Herfort, & Zipf, 2016). Figure 2 shows the distribution of platforms discussed in each of the selected studies and to which component of the EWS framework they apply. The following section provides definitions of the platforms displayed in Figure 2 along with a description of how the VGI is used for severe weather warnings.

Geo-located social media. Geo-located social media refers to VGI that is posted online by users of Facebook, Twitter, Sina Weibo, Flickr, YouTube, Instagram, and SnapChat that has geographical location information associated to it. The heavy representation of social media (15 studies) demonstrates the growing popularity of these platforms as a data source for severe weather events (Tkachenko et al., 2017). The results indicate that social media is a valid tool for measuring the effectiveness of warning dissemination by following Twitter hashtags (Allaire, 2016; Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017; Taylor, Kox, & Johnston, 2018). The online platforms are also useful for early hazard detection and for estimating

	Disaster Risk Knowledge	Detection, Monitoring, Warning Services	Communication and Dissemination Mechanism	Preparedness and Early Response Capacity	Total
Geo-located Social Media	2	9	3	1	15
Crowdsourcing	2	6			8
Crowdsourcing and Geo-located Social Media		3			3
Local Knowledge	1			1	2
Participatory Mapping/PGIS	4				4
Total	9	18	3	2	32

Figure 2. Distibution of VGI platforms used for each early warning system (EWS) framework component. Two studies fell into multiple components and have been counted for each EWS component that they apply to, which results in a total of 32, rather than 29.

event magnitude for early warnings (Chen et al., 2017; Jung & Uejio, 2017; Restrepo-Estrada et al., 2018; Tkachenko et al., 2017). Reasons for collecting social media data were to increase coverage of the dataset(s), the ease of access and quantity of data available, real-time or near-real-time monitoring and collection, and the multi-directional communication during disaster enabled by social media (Allaire, 2016; Chen et al., 2017; Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, & Pantaleo, 2017; Jung & Uejio, 2017; Pennington et al., 2015; Rossi et al., 2018; Saint-Martin et al., 2018; Smith et al., 2017; Wu & Cui, 2018).

Crowdsourcing applications and forms. Eight of the selected studies used crowdsourcing via mobile applications, reporting forms, or other active contributions (e.g., storm spotters). The crowdsourcing applications in the selected studies were used for hazard detection and monitoring and for developing personalised risk knowledge. These applications allow citizens to report the occurrence of hazards such as landslides (Choi et al., 2018; He et al., 2018) and to monitor hazards such as rainfall-induced floods (Horita et al., 2015) and storms (Krennert et al., 2018; Longmore et al., 2015). The ability to efficiently collect reports and monitor hazards in real-time, in a standardised format to ensure quality, and to increase the scale and resolution of hazard-related data were arguments made for using crowdsourcing as opposed to other VGI collection types (Choi et al., 2018; He et al., 2018; Henriksen et al., 2018; Horita et al., 2015; Longmore et al., 2015; Sadler et al., 2018; Sharma et al., 2016).

Participatory mapping and participatory GIS. In the selected studies, participatory mapping and participatory GIS were employed for severe weather risk assessments and hazard modelling. Lavers and Charlesworth (2018) engaged UK farmers in participatory mapping to identify flood impacts on their properties and subsequent opportunities for mitigation. Peters-Guarin et al. (2012) had locals in the Philippines map their historical knowledge of recurring floods and impacts for a risk assessment. In Taiwan, Hung and Chen (2013) consulted with locals and stakeholders to verify flood vulnerability maps. Participatory mapping and interviews were utilised by Rollason and colleagues (2018) to validate flood models using local knowledge and experiences. In all of these studies, the mapped information was entered into a GIS for further mapping and analysis, thus qualifying it as participatory GIS. Reasons for using participatory GIS and participatory mapping over other types of VGI were formally recognising and integrating local knowledge in a systematic way, and supporting local engagement (Hung & Chen, 2013; Lavers & Charlesworth, 2018; Peters-Guarin et al., 2012; Rollason et al., 2018).

Local knowledge. For the purposes of this paper, we consider local knowledge as information gathered in participatory processes containing knowledge of the participants' local area and geography, that may or may not be translated onto a map. Just one selected study included local knowledge. After evaluating local knowledge of cyclone hazards and response capabilities to scientific knowledge, Ton and colleagues (2017) argued that local knowledge should be integrated with scientific meteorological knowledge for verification and to increase confidence in forecasts. The choice of using local knowledge for this study was to begin a dialogue between the locals and the meteorologists towards building trust (Ton et al., 2017).

Discussion

The results show that VGI is useful in all components of the early warning system (EWS) framework, but some platforms are more useful for specific components than are others. Furthermore, the different types of VGI have implications for supporting people-centred EWSs, which is a guiding principle for EWSs under the Sendai Framework.

Volunteered Geographic Information in Severe Weather Early Warning Systems

The purpose of this study is to determine the current and potential uses of VGI for severe weather warnings. We used the EWS framework to guide the analysis of the results.

The results from this literature review show that VGI has value in all four components of an EWS for severe weather hazards (Basher, 2006), but some forms of VGI are more useful for specific EWS components than are others (see Figure 3). Figure 3 is an update of Figure 1 based on the findings from this literature review to better represent how the different types of VGI inform or support the EWS components. For example, the majority of included studies used social media and crowdsourcing for hazard detection, monitoring, and early warning, while all of the included participatory mapping and participatory GIS studies used VGI for building disaster risk knowledge.

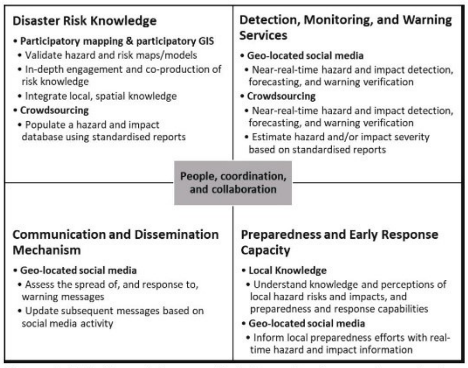

Figure 3. Volunteered Geographic Information for people-centred severe weather early warning systems.

The selected studies show that social media and crowdsourcing for severe weather are effective for early detection, monitoring, and verifying warnings (e.g., Harrison & Johnson, 2016; Henriksen et al., 2018; Krennert et al., 2018). The value of social media and crowdsourcing for EWSs lies in the real-time, or near-real-time, hazard and impact detection, forecasting, and warning verification (Henriksen et al., 2018; Kox, Kempf, Lüder, Hagedorn, & Gerhold, 2018; Krennert et al., 2018). However, the papers included in this scoping review lack forward-thinking for integrating these tools into official EWSs which is a challenge for warning services and emergency management services (Haworth, 2016; Henriksen et al., 2018; Kox et al., 2018). Despite this challenge, some national hydrological and meteorological services and emergency management agencies in Europe and North America collect information from social media for detection, monitoring, and warning verification (Harrison & Johnson, 2016; Henriksen et al., 2018; Krennert et al., 2018; Pennington et al., 2015).

Social media supports multi-directional communication, which allows for both crowdsourcing and broadcasting severe weather information. While most of the selected social media studies demonstrated the value of social media for detection and early warning, two studies also indicated its utility for disseminating warnings and assessing the spread of, and response to, warning messages (Grasso & Crisci, 2016; Grasso, Crisci, Morabito, Nesi, Pantaleo, et al., 2017). This allows warning services to gauge the reach of their message, understand the responses to their message, and update subsequent messages based on what they see on social media (Harrison & Johnson, 2016).

Before warnings are issued, knowledge of disaster risk is needed to be able to create tailored warnings. Participatory mapping and participatory GIS might be considered a long-term process for building knowledge and datasets for improving disaster risk knowledge as well as validating hazard and risk maps or models. While social media is valuable for real-time detection and communication, the participatory nature of participatory mapping enables more in-depth engagement with locals and communities in other areas of the EWS process to produce new knowledge (Haworth, 2018; Lavers & Charlesworth, 2018; Maskrey, Mount, Thorne, & Dryden, 2016; Peters-Guarin et al., 2012; Zolkafli, Brown, & Liu, 2017). Integrating local, spatial knowledge about disaster risk into an EWS through participatory mapping and participatory GIS fosters efforts towards people-centred EWSs as it translates local knowledge into usable and useful spatial data for risk analysis and for improved warnings (Basher, 2006; UNISDR, 2015).

These results support the findings from Marchezini and colleagues (2018), who presented a framework for bridging citizen science into EWSs. Like Marchezini and colleagues (2018), we found that VGI processes can bridge the gap between EWSs and audiences of warnings by incorporating local knowledge and personal experiences from stakeholders into the EWS components (see also Ton et al., 2017). This creates new data and unearths vulnerabilities at various scales (e.g., from the individual level to the community level; Haworth, 2018; Henriksen et al., 2018; Kox et al., 2018; Ton et al., 2017).

Implications for the different types of VGI. The results show that social media is a dominant platform for collecting VGI across severe weather hazards. Given the ease of access to, and the versatility of, social media (Harrison & Johnson, 2016), it is not surprising that social media is the most common platform used across hazards for collecting VGI (Granell & Ostermann, 2016). Social media is also now considered a "go-to" for collecting data because it is where the members of the public already are, thus groups or agencies looking to crowdsource do not have to do the heavy-lifting of creating a new app and attracting new users (Harrison & Johnson, 2016).

The perceived benefits of social media also come with some caveats. The data tend to be biased due to the uneven distribution of the social media user base (Granell & Ostermann, 2016; Harrison & Johnson, 2019). By relying on social media as a data source, those members of the public who are not present on social media are not represented in the data nor in the EWS process (i.e., the digital divide; Allaire, 2016; Harrison & Johnson, 2019). Additionally, tweet or post ambiguity and keyword selection for data-capture hinder data collection and analysis (Chen et al., 2017; Longmore et al., 2015; Tkachenko et al., 2017). Assimilating data of different formats into a database remains a challenge (Horita et al., 2015; Lu et al., 2018).

Capturing enough geo-located social media data is a constant challenge. It is widely known that only a small percentage of tweets contain geo-located information (Steed et al., 2019). Furthermore, the accessibility and availability of geo-located social media data are continuously limited. For example, Facebook does not offer an Application Programming Interface (API) to allow for researchers or media agencies to systematically collect Facebook posts, much less geo-located posts; it only offers an API for marketing and advertising agencies (Dubois, Zagheni, Garimella, & Weber, 2018; Thakur et al., 2018). In addition, in June 2019 Twitter announced plans to disable the geo-location feature for tweets due to its limited adoption by users and growing privacy concerns; however, the feature will still be available on photos taken within the Twitter mobile application (Benton, 2019; Khalid, 2019). While geo-located information on Instagram appears to be available for the moment (Arapostathis, 2019; Boulton, Shotton, & Williams, 2016), given the recent trends in the other major social media platforms, the continued availability and accessibility of this data in the future is uncertain.

A specialised crowdsourcing application can help to address some limitations found in social media. Crowdsourcing applications offer quality assurance, noise avoidance, application customisation, and citizen engagement (Choi et al., 2018; Longmore et al., 2015). On the other hand, crowdsourcing applications remain limited in the volume of participation due to public motivation to participate, the digital divide, and privacy concerns (Choi et al., 2018; Fdez-Arroyabe et al., 2018). Bias in reporting is also a concern, as contributors may over-exaggerate their personal experiences (Fdez-Arroyabe et al., 2018). Developing an application has the potential to streamline the integration of crowdsourced data into official processes, yet maintenance costs impede the willingness of officials to do so (Choi et al., 2018).

Capturing and representing local knowledge through participatory mapping and participatory GIS may help in bridging the digital divide, ensuring data quality, and enabling data integration. Participatory mapping and participatory GIS also enable community engagement (Haworth et al., 2016; Lavers & Charlesworth, 2018; Peters-Guarin et al., 2012). Participatory mapping and participatory GIS can be done using paper-mapping, as was done by Rollason and colleagues (2018), Lavers and colleagues (2018), and Peters-Guarin and colleagues (2012), or through digital-mapping (Haworth et al., 2016). In addition to the value of the resulting information and data itself, the process of engaging with and between locals provides another level of value in the social context by strengthening social networks, growing social capital, and increasing civic participation (Haworth et al., 2016).

Participatory GIS and participatory mapping do not come without their own limitations. For example, participatory GIS appears to be more effective with small-scale local projects. This is because most of the data collected is at a local or small scale, resulting in poor spatial distribution if scaled-up to a larger area. This could lead to underrepresentation and potential biases in the participatory GIS data (Rollason et al., 2018). Nevertheless, the rich quality and the ease of integrating this VGI into official processes may outweigh this limitation if the study is well-designed and the data is used appropriately (Brabham, 2013; Lauriault & Mooney, 2014). Within the EWS context, these perceived benefits further the movement towards people-centred EWSs by incorporating knowledge and information produced by the people into warnings that are ultimately for them (UNISDR, 2015).

Conclusion

This paper conducted a scoping literature review and explored 29 journal papers published in academic journals and conference proceedings retrieved from EBSCO Discovery and Scopus. The literature review found that VGI plays various roles for severe weather early warning systems (EWSs). The examples from the selected studies show that VGI furthers the development of people-centered EWSs; it brings people, their knowledge, and their experiences into EWSs. Still, the current research captured in this scoping review lacks forward-thinking for integrating these tools into official EWSs which is a challenge for warning services and emergency management services (Haworth, 2016; Henriksen et al., 2018; Kox et al., 2018).

In the always shifting EWSs landscape, a new type of severe weather EWS is emerging that is causing national meteorological and hydrological services and warning services to re-think their traditional warning practices. The World Meteorological Organization is advocating for the aforementioned services to adopt impact-based forecasts and warning systems (Fleming et al., 2015). Impact-based forecasts and warnings are meant to shift the focus from the physical hazard phenomena to the risk of impacts produced by the hazard, including communicating impacts in warning messages and building new warning thresholds based on risk of impact (Fleming et al., 2015; Morss, Cuite, Demuth, Hallman, & Shwom, 2018; Poolman, 2014; Potter et al., 2018; Robbins & Titley, 2018; Rogers, Kootval, & Tsirkunov, 2017; Sai et al., 2018). However, warning services have indicated a limited understanding of, and access to, the data required for developing impact-based forecasting and warning systems (Harrison et al., 2014; Kox et al., 2018; Obermeier & Anderson, 2014).

Future research would benefit from a systematic review of this topic area in the future. Additional research should investigate the data needs for impact-based forecasts and warnings and explore how VGI can help in meeting these data needs while also maintaining a people-centred focus. This would align with the goals of the World Meteorological Organization's High Impact Weather research programme (http://hiweather.net) which aims to improve the effectiveness of weather-related warnings in support of advances in weather prediction and forecasting (Zhang et al., 2019). While this literature review characterised the role of VGI within severe weather EWSs and demonstrated how it supports people-centred EWSs, future research can delve into the nature of the resulting data and how it might support impact-based forecast and warning systems. It should be noted that in spite of the popularity of collecting and using social media data, given the uncertainty of reliable access to social media data in the future (e.g., disestablishing the geolocation function on Twitter), it would be wise to minimise reliance on these platforms and consider additional VGI sources and collection processes to capture the desired information.

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Appendix L: Chapter Seven Publication

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'Where oh where is the data?': Identifying data sources for hydrometeorological impact forecasts and warnings in Aotearoa New Zealand

Sara E. Harrison [a,b,*], Sally H. Potter [b], Raj Prasanna [a], Emma E.H. Doyle [a], David Johnston [a]

[a] Massey University, New Zealand
[b] GNS Science, New Zealand

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ABSTRACT

Early Warning Systems are a key component to building preparedness and response capacities to hydrometeorological hazards that continue to affect people worldwide. Notable historic events have revealed gaps in current hazard-based warning systems. Impact Forecasts and Warnings (IFWs) have been proposed to fill these communication gaps by re-centring the warning thresholds and language around the consequences, or impacts, of the hazard(s), rather than just the physical characteristics. However, research has shown that implementing IFWs requires not just hazard data, but also data on impacts, vulnerability, and exposure to understand the risk of impacts.

Using Grounded Theory Methodology, we conducted a series of interviews with users and creators of hazard, impact, vulnerability, and exposure (HIVE) data to identify data sources and understand how these data are collected and created to support the implementation of IFWs. We focus the study on the New Zealand context to support the country's efforts towards implementing IFWs.

Our findings indicate that many sources for HIVE data exist that are collected for other uses (such as for disaster/emergency response efforts, and for research) and have relevant applications for IFWs. Our findings further suggest that priorities, motivation, and interest within organisations influence how well data is collected. Moreover, agencies tend to prefer official data, but official data has limitations that unofficial data may address, such as timeliness. To that end, a tension exists between the timeliness and trustworthiness of data needed for emergency response and warnings.

1. Introduction

The last two decades have seen a paradigm shift in disaster risk reduction from reactive post-disaster response and recovery to proactive preparedness and mitigation. Early Warning Systems (EWS) are a key component for better preparedness [1]. Past severe weather events exposed major communication gaps between meteorologists and warning services and target audiences, resulting in widespread losses including death, injuries, and damage. For example, following Typhoon Haiyan, which resulted in over 6,293 deaths, 28,689 injuries, and 1,061 missing people in the Philippines [2], it was found that 88% of warning recipients did not understand messages about 'storm surge' and 95% of warning recipients did not evacuate because they did not expect the storm to be so catastrophic [3]. It was recommended that "warning messages … should be conveyed in terms understood by the population at risk" ([3]; p. 34).

This communication gap is a result of both technical failings and human behaviour. The World Meteorological Organization (WMO) posited that meteorologists and warning services do not typically consider the warning audiences' current state of vulnerability and exposure at the time of the warning or at the expected time of impact [4]. Furthermore, warning audiences fail to understand and respond to the warnings effectively due to ambiguous terminology [3], lack of trust in the warning system and service provider [5], and warning fatigue [6]. As such, EWSs continue to evolve in attempts to reduce the effects of these factors.

In the hydrometeorological space, Impact Forecasts and Warning (IFW) systems are an advancement of traditional hazard-based EWSs.

* Corresponding author. Massey University, New Zealand.
E-mail address: s.harrison@massey.ac.nz (S.E. Harrison).

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IFW systems provide an opportunity to integrate knowledge and understanding of exposure, vulnerability, and impacts into an EWS to build new warning thresholds that better align with the position, needs, and capabilities of target audiences [7]. However, challenges have been identified around identifying and accessing the required data sources for IFWs [8]. [7] identified the specific needs and uses for hazard, impact, vulnerability, and exposure (HIVE) data in an IFW system. We continue this work by identifying sources for these required datasets. We next present a review of existing HIVE data sources from the literature, identifying data gaps that we explore further through a series of key-informant interviews.

1.1. Impact forecasting and warning data gaps and sources

Warning agencies and meteorologists are challenged with accessing appropriate data to support the decision-making required for IFW systems [9]. The lack of impact, vulnerability, and exposure data is a major obstacle to implementing IFWs [10]. Beyond IFWs, these data are also needed for enhancing our understanding of disaster risks and subsequent mitigation and reduction, as per the Sendai Framework for Disaster Risk Reduction [1].

The following literature review identifies some existing sources of HIVE data for IFWs. These data sources and datasets are summarised in Table 1 and described further in the following sections.

1.1.1. Hazards

For this study, hazard data refers to meteorological, hydrological, and hydrogeological data. For example, windspeeds and rainfall amounts may be considered meteorological hazard data, while river levels would be hydrological hazard data, and slope data are useful for landslide hazards (i.e., hydrogeological hazards).

Understanding of severe weather hazards primarily comes from hydrometeorological observations and measurements usually gathered quantitatively through specialised equipment, such as rain gauges, river gauges, and remote sensing. This information helps to estimate the timing, direction, and magnitude of the hazard for forecasts [11].

Forecasts are another form of hazard data. Multiple Numerical Weather Prediction (NWP) models are run using observational data to determine probabilities of future weather patterns based on running multiple simulations [12]. This probabilistic forecasting approach allows for the calculation of likelihoods of the weather phenomena to occur, and thus an overall confidence level of the forecast [12]. More observational data can increase the confidence of weather forecasts, however, this confidence decreases as forecast lead time increases [13].

In places where hydrometeorological monitoring network coverage is limited or lacking, crowdsourcing and citizen science projects have been used to fill these gaps (e.g. [14]). Eyewitness accounts and storm spotter reports also contribute to an understanding of severe weather hazards and phenomena [15].

1.1.2. Impacts

Impacts are the effects, outcomes, or consequences of hazardous events. During a severe weather event [16], identified impact information sources to include media coverage, fire stations upstream of a storm track that have already been affected, emergency calls, scout reports and ground-truthing, and emergency vehicle occupancy, to determine if enough capacities are on hand. Social media [17], crowdsourcing [18], and volunteered geographic information [19] are other near real-time sources of impact information. Near real-time impact data is usually collected by local emergency management (EM) agencies to produce situational reports which contain all available information about the developments and impacts of an event [16].

Post-event damage information is collected in the aftermath of an event in the form of damage surveys. Post-event data such as damage surveys allows forecasters to correlate damage levels produced from certain hazards, such as tornadoes, with the storm radar signature [17].

Table 1
Summary of data sources and datasets for hazard, impact, vulnerability, and exposure data identified from the literature review.

Data Type	Description	Data Sources	Datasets
Hazard	Hydrometeorological observations and measurements to formulate warnings.	Meteorological services, hydrological services, Law enforcement, Storm spotters, Responders, social media (Twitter, Facebook, Seina Webo, Flickr, Instagram, SnapChat), the public, online databases, crowdsourcing and citizen science projects.	Meteorological and hydrological observations (e.g., rain gauges, river gauges), satellite and radar imagery, aerial imagery, Natural Hazards Assessment Network (NATHAN), European Severe Weather Database, US Storm Database, public surveys, historic warning record, eyewitness interviews, public surveys, photos and videos.
Impact	Building situational awareness and informs situational assessments for response planning. After an event, impact/damage assessments are conducted to link radar signatures of upcoming or unfolding hazards with a historical database and formulate impact-based warnings based on the historic impacts of similar events. Feeds into vulnerability models and fragility functions for impact modelling.	Media reports, law enforcement, fire stations upstream already affected, the public, emergency responders, engineers, social media (Twitter, Facebook, Seina Webo, Flickr, Instagram, SnapChat), crowdsourcing applications, Google, hydrological services and flood managers, public health agencies, insurance industry, online databases, flood databases, research institutions, environmental protection agencies, storm spotters, emergency services, personal contacts, risk modelling.	Ground-truthing, in-situ observations, reports and emergency calls, situational reports, eye-witness interviews, photos/videos, commentary, incident reports, situational reports, hotline records, loss claims, Emergency Events Database (EM-DA), Natural Hazards Assessment Network (NATHAN), flood databases, digital mapping (e.g. Humanitarian OpenStreetMap, MissingMaps), Google Alerts, Google Analytics Records, technical reports, European Severe Weather Database, public surveys, eyewitness interviews, risk modelling outputs.
Exposure	Highly specific and small-scale nature, usually at the individual, activity, or community level, (e.g., Ferry routes and the locations of large trees overhanging power lines).	Government departments, land and resource management agencies, flood managers, mapping agencies/organisations, crowdsourcing, OpenStreetMap,	Census data (for population counts and density), transportation routes and schedules, infrastructure databases/datasets, land-use spatial layers, building/asset

(continued on next page)

Table 1 (*continued*)

Data Type	Description	Data Sources	Datasets
		Google Maps, infrastructure industry, risk model.	footprints, road network spatial layers, Digital Elevation Models, time-varying population data, river network spatial data, risk modelling outputs.
Vulnerability	Conveys the vulnerability of people, livelihood, and property and typically includes information about infrastructure, buildings, land-use, census data, ecological data, and economic data; feeds into vulnerability models and fragility functions for impact modelling.	Research Institutions, public health agencies, engineers, risk specialists, insurance industry.	Vulnerability assessments, Pacific Risk Information System (PacRIS), vulnerability functions/ fragility curves, vulnerability indices, asset characteristics (e. g., building structure information), public surveys.

If this impact information is stored in a historic database, forecasters can refer to the database to compare past storm radar signatures with current radar signatures and understand the level of damage and impacts the current storm may produce, allowing the forecaster to formulate impact-based warnings [17].

Impact data is also produced from risk/impact models for pre-impact, rapid-impact, and post-impact assessments. Data sources can include hazard, exposure and vulnerability information, geo-located social media data [20], satellite data [21], crowdsourced impact reports [18], and normalised damage functions [22].

Challenges still exist with collecting enough systematic, in-situ data (i.e., observed impacts) to build empirical models [23] and to validate models [8]. Furthermore, existing impact databases have been created with varying responsibilities for which agency collects information, and the methods and purposes of collection [24]. This limits the databases' use, particularly for analysis and verification. The classification of impacts appears to be subjectively done [25], proving it difficult to use datasets outside of the original purpose for which they were created.

1.1.3. Vulnerability

Vulnerability information is usually created through conducting vulnerability assessments [26]. This involves combining information about infrastructure, buildings, land-use, census data, ecological data [27], and socio-economic data [28]. These vulnerability assessments are typically presented as spatial maps [29].

Vulnerability assessments have traditionally focused on physical vulnerability, such as buildings and infrastructure, with less focus on social vulnerability [29]. Studies that have looked at social vulnerability tended to focus on physical impacts such as loss of life or physical injuries [30], and less so on nuanced social impacts resulting from less quantifiable social vulnerability factors such as "poor biophysical, social, and/or financial capital" in communities ([28]; p. 1482). This is because these vulnerability factors are easier to quantify [29]. To address these gaps [28], identified a range of underlying social vulnerability factors resulting from human behaviour and demonstrated the highly dynamic nature of social vulnerability, such as risk governance, land use, and individuals' status, all of which change over space and time.

In New Zealand [31], developed social vulnerability indicators for flooding using national Census population data. These indicators are based on social vulnerability dimensions such as exposure, age, health and disability status, financial security, social connectedness, knowledge of natural hazards, housing conditions, food and water security, and decision-making and participation [31]. Health indicators relating to certain health conditions such as cardiovascular disease, respiratory disease, and mental health issues were not completed due to time constraints [31]. The results of their study provide an opportunity for decision-makers to consider additional factors beyond economic impacts when planning mitigative actions towards flooding [31].

Vulnerability information may be obtained through partnerships with the insurance industry who conducts vulnerability assessments for insurance schemes [32]. Additionally, the Pacific Catastrophe Risk Assessment and Financing Initiative (PCRAFI) created the Pacific Risk Information System (PacRIS), which houses historical hazard data, and risk profiles for Pacific Island countries [32].

1.1.4. Exposure

The highly specific and small-scale nature of exposure makes it difficult to systematically collect and incorporate into an IFW system with the current tools and data available [4,33]. An example of one form of general exposure information is population counts of people living in areas where hazards frequently occur (e.g. population data overlaid onto floodplains data) [27]. Exposure data is typically created by mapping the locations of assets, such as buildings and infrastructure in proximity to a hazard [29].

Ferry routes and the locations of large trees overhanging power lines are other examples of exposure data that would be important to consider during a high wind event [4]. Building footprints (i.e., a spatial layer of building polygons) is another example of exposure if the building footprints layer is overlaid with a hazard layer (e.g., [34]). However, even national- or global-scale exposure datasets can be expensive [29], and remain difficult to create and use due to a lack of detailed asset information [35].

1.2. Data characteristics for Early Warning Systems

Data usability in disaster response is determined by many factors. For the purposes of this study, we focused on two factors: reliability and timeliness. These appear to be two of the most important factors for choosing data sources for disaster response [36]. The requirements for reliable and timely data for disaster response can also apply to EWSs, as warnings must be timely and accurate to incite early and appropriate action [37,38].

Data is perceived as more reliable if it comes from a trusted source and/or it can be vetted [39]. As such, there is a preference for official sources, such as emergency call centre reports, intel from responders themselves, etc. [16]. For this study, official data refers to data created by recognised officials involved in local disaster response management practices where the disaster is occurring, such as police and fire services, engineers, helicopter pilots, local and regional councils, as well as meteorological and hydrological agencies, and science agencies. Unofficial data refers to data created by external parties of the disaster management practices, such as social media users, contributors to OpenStreetMap, private external corporations (e.g., Google Maps), and media agencies.

This section identified various sources of HIVE data. These components (hazard, impact, vulnerability, and exposure, or HIVE) form the conceptual basis of severe weather IFWs. Meteorologists do not typically possess knowledge of impacts, vulnerability, and exposure [40]. As such, sources of these data need to be identified for IFWs [7,10]. Furthermore, understanding the characteristics of the available data sources in terms of reliability and timeliness will assist data users in determining appropriate datasets for their purposes.

The objectives of this research are to identify sources for HIVE data and to understand the inhibitors and facilitators for collecting and using these data, to support the implementation of an IFW system in New Zealand for severe weather hazards. We chose to focus on the New

Zealand context to support the country's efforts for fulfilling both the WMO's objectives and Sendai Framework priorities for improved documenting of disaster risk and loss data; a need identified in previous research [10,41]. We employed Grounded Theory [42] to meet the research objectives, described next.

2. Research method

We used a qualitative approach to address the research question, specifically employing the Evolved-Straussian Grounded Theory research strategy (ES-GT) for data collection and analysis. Interviews and workshops were the primary data collection methods. From November 2018 to April 2021, the lead author interviewed thirty-nine (n = 39) experts in weather forecasting, warning, response, risk modelling, and data collection and management, as shown in Table 2. Three virtual workshops were held in New Zealand (NZ). Two of these workshops involved EM practitioners, weather forecasters, communication and data specialists, and hydrologists, from Auckland Region (n = 4) and Southland Region (n = 5). The third workshop involved a portion of the NZ risk and hazard science community based at GNS Science (n = 11). Thus, in total 59 people participated in this research.

Interview questions and workshop activities focused on IFW data needs and sources. We asked for participants' general thoughts on IFWs; what impact, vulnerability, and/or exposure data they use or need, why, and how; the life path of the data; experienced and/or perceived challenges obtaining data required for IFWs and other uses; and thoughts on collecting and using alternative data sources (e.g. social media and crowdsourcing). Herein we report on data sources, collection, and creation.

This research was conducted under a 'low risk' ethics notification with the Massey University Human Ethics Committee prior to data collection in 2018. All interviewees remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by their area of expertise and/or practice, industry, location, or governance level (Table 2). Interviews were audio-recorded and transcribed verbatim.

Following ES-GT, we analysed the interview and workshop data using open coding and axial coding, supported by memo-writing and diagramming [43], in Nvivo 12 [44]. The coding paradigm introduced by [42] supported the axial coding stage whereby the codes created from open coding were related to the coding paradigm dimensions (Table 3) for increased density and precision.

3. Findings and discussion

This section will first present data sources for HIVE data as identified by the participants, followed by an investigation into the causal conditions, intervening conditions, and subsequent action/interaction strategies for collecting the HIVE data.

3.1. Data sources

The interviews and workshops identified several sources for hazard, impact, vulnerability, and exposure data. These data sources are described next. The following sections are organised by data type (hazard, impact, vulnerability, and exposure). Herein, each section will provide an overview, with accompanying summary tables, of the data sources and their characteristics related to IFWs. The accompanying tables present the data or dataset (e.g., weather stations, radar data), whether the data is official or unofficial, who collects or creates the data (e.g., the creator may be a member of the public by posting a report on social media, and the collector may be an EM agency who collects social media posts for situational awareness), the timescale of the data (e.g., "[Near] real-time" is data collected in real-time or near real-time, such as observational data, social media reports, etc.; "Current" is data that is static in time, was created prior to the event, but has been maintained and kept up-to-date; "Forecasted" is data created from forecasting models; and "Historic" is data created after an event and is not kept up-to-date), the type of hazard and/or impact (e.g., meteorological, hydrological, hydrogeological, social, infrastructural, urban, rural, environmental, health, property, built environment), and uses within and outside of the Impact Forecasting and Warning Value Chain [7].

3.1.1. Hazard data

Hazard data refers to meteorological, hydrological, and hydrogeological data. Table 4 provides a summary of the hazard data sources identified by our participants. With regards to uses in the Warning Value Chain, each hazard data source listed in Table 4 was found to be used for Observation, Monitoring, and Detecting; Hazard Forecasting; Impact Forecasting; Impact Warning.

Our findings indicate that hazard data is quite systematically collected, documented, and used in New Zealand for many purposes by a select group of official agencies (see Table 4). For example, meteorological data, such as rainfall, windspeed, radar data, and forecast data are mostly produced, used, and housed by the Meteorological Service of New Zealand (herein referred to as the NZ MetService) and the National Institute of Water and Atmospheric Research (NIWA). The NZ MetService is NZ's appointed National Meteorological Service (NMS) [46], and NIWA is NZ's Crown Research Institute (CRI)[6] for atmospheric and oceanic science [48]. NIWA maintains the national climate database with all the rainfall records and hydrological databases. Fire and Emergency New Zealand (FENZ) was also found to collect observational meteorological data for their own operations, which helps them plan responses to wildfires and other weather-related emergencies (EM. NZ. Nat. I).

The NZ MetService has made some of their observation and satellite data freely available [49]; Met. Private NZ. L) for commercial use by private weather forecasting companies, and for stakeholder agencies and researchers to conduct their own analyses, such as risk modelling. Following an impactful event on the Wellington South Coast where large swells and waves damaged houses and evacuations of five properties, arrangements have been made for the NZ MetService and their oceanographic branch (the MetOcean), and NIWA, to provides swell data, wave data, and wave forecast data to the regional EM office for a Significant Wave Warning programme (EM. NZ. Reg. L; [50]).

Findings from our interviews indicate that hydrological data is collected, created, and used primarily by local and regional councils in New Zealand. This aligns with the mandated role of local and regional councils under the Resource Management Act 1991, the National Civil Defence Emergency Management Plan 2015, and the Local Government Act 2012, wherein local and regional councils are assigned the responsibility of managing, monitoring, forecasting, and warning for flood hazards, with support from NIWA, the MetService, and EM Groups [51]. Hydrological data includes river height and flow gauges, river camera feeds, river network and watershed data (e.g., spatial shapefiles of rivers, floodplain footprints), overland flow paths, river flow and flood forecast models, etc.

The MetService also forecasts pollen counts for those with allergies. Pollen data is desirable for the public health sector (Health NZ. Reg. A) because pollen was found to play a significant factor in thunderstorm-related asthma attacks [52]. While the MetService provides qualitative pollen forecasts (e.g., "Pollen Levels: Moderate, Type is Plantain"), a public health official from the Waikato Region in NZ expressed a need for quantitative pollen data to model the risk of asthmatic attacks due to pollen and spring thunderstorms (Health NZ Reg. A; [7]). This need was echoed by a NZ-based pollen scientist for climate change risk assessments (see [53]).

Our interviews identified other creators of relevant hazard data alongside the MetService, NIWA, local/regional councils, and FENZ.

[6] Crown Research Institutes (CRIs) are government owned companies that conduct scientific research in New Zealand [47].

Table 2
Participant Codes. All participants remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by the area of expertise and/or practice, industry, location, or governance level.[11]

Interview Code	Position	Classification	Location	Government Level
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ	National
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ	National
Data Management Private NZ. B	Geospatial Specialist	Data Management	NZ	
Data Management Research NZ. C	GIS Specialist	Data Management	NZ	
Data Management Private NZ. D	GIS Specialist	Data Management	NZ	
Data Management Gov. NZ. Nat. E	Head of Data	Data Management; Governance	NZ	National
EM. NZ. Reg. A	Director	Emergency Management	NZ	Regional
EM. NZ. Reg. B	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. C	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ	Regional
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ	Regional
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ	National
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Nat. I	First Responder	Emergency Management	NZ	National
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ	National
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ	Regional
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ	Regional
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ	Regional
Hyd. Gov. NZ. Reg. A	Flood EWS Programme manager	Hydrology; Governance	NZ	Regional
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ	Regional
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ	
Met. Int. A	Science Manager	Meteorology	International	National
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	International	National
Met. Int. C	Senior Policy Officer	Meteorology	International	National
Met. Int. D	Senior Social Scientist	Meteorology	International	National
Met. Int. E	Consultant Meteorologist	Meteorology	International	National
Met. NZ. F	Senior Meteorologist	Meteorology	NZ	National
Met. NZ. G	Communications	Meteorology	NZ	National
Met. NZ. H	Public Relations	Meteorology	NZ	National
Met. Int. I	Division Chief/Meteorologist	Meteorology	International	National
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ	National
Met. NZ. K	Senior Meteorologist	Meteorology	NZ	National
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ	
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ	National

Table 3
Summary of the coding paradigm dimensions that supported the axial coding analysis in this study.

Coding Paradigm Dimension	Description
Causal Conditions	A set of events that influence the phenomena or result in the appearance or development of a phenomenon [42,45].
Phenomena	The subject or object under study [42].
Contextual Conditions	The specific set of conditions and characteristics surrounding the phenomena and resulting in action/interaction strategies taken to address the phenomena [42,45].
Intervening Conditions	Unexpected events or factors leading to action/interaction strategies (e.g., time, space, culture, socioeconomic status, technological status, history) [42,45].
Action/Interaction Strategies	Purposeful and deliberate acts taken to address the phenomena [42,45].
Consequences	Predicable or unpredictable, intended or unintended outcomes of the action/interaction strategies [42,45].

Land Information New Zealand (LINZ), the public service department charged with handling geographic information in New Zealand, collects sea level data from float gauges (as do port companies), which is useful for coastal flood hazards (Data Management Gov. NZ. Nat. A); and holds slope data, useful for landslide hazard management and mitigation (Data Management Gov. NZ. Nat. A). LINZ and the Ministry for Environment (MfE) also hold river network data.

Unofficial data sources were also identified by participants for monitoring hydrometeorological hazards and building situational awareness. For example, the MetService, Civil Defence and Emergency Management (CDEM) Groups, and Local/Regional Councils monitor social media for reports or observations of hydrometeorological hazards (Met. Int. E; EM. NZ. Reg. B, C). From our interviews, we found that none of our participating agencies collect or store social media data for future analysis, citing resource limitations as a key barrier (Met. NZ. F, G, H; EM. NZ. Reg. A, E). Rather, the social media platforms are monitored onscreen for staff to pick up posts or events of interest for further investigation (Met. Int. E; EM. NZ. Reg. B, C). Additionally, one CDEM Group described how they actively request social media users to verify impacts if they can safely do so (EM. NZ. Reg. A). Notable posts may be captured and included in situational reports, but the data usually does not have a use beyond that (EM. NZ. Reg. A, C).

Crowdsourced data was found to be collected through specially designed applications and platforms. In NZ, the West Coast CDEM group crowdsourced hazard and impact reports using the Esri Story Maps platform (EM. NZ. Reg. C, F). Similarly, the NZ Flood Pics Esri Story Map[7] was set up by a volunteer to collect flood and impact photos during flood events in Auckland and has since been expanded to the rest of NZ (Data Management Private NZ. D). In the USA, the meteorological service collects precipitation data and associated impacts through the mobile application mPing[8] (Met. Int. I). Similarly, in Austria and

[7] http://www.nzfloodpics.co.nz/.
[8] https://mping.nssl.noaa.gov/.

Table 4
Summary of hazard data sources in New Zealand, identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, type of hazard, and non-IFW uses.[21]

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	Type of Hazard	Non-IFW Uses
Weather stations (rain gauges, anemometers, etc.)	Official and unofficial	MetService, FENZ, NIWA, councils, volunteers	[Near] real-time	Meteorological	Research
Radar data	Official	MetService, NIWA, Private	[Near] real-time	Meteorological	Research
Satellite imagery & observations	Official	MetService, NIWA, LINZ	[Near] real-time	Meteorological	Research
River height and flow gauges	Official	Regional councils, NIWA	[Near] real-time	Hydrological (e.g. flood)	Research
Float gauges/Sea level data	Official	LINZ, port companies, regional councils, NIWA	[Near] real-time	Hydrological (e.g. flood)	Research
River networks	Official	NIWA, LINZ, Ministry for the Environment, Councils	[Near] real-time	Hydrological (e.g. flood)	Research
Vertical Rain Radar	Official	MetService, Private, Healthy Waters Auckland Council	[Near] real-time	Meteorological	Research
Regionwide floodplains footprints/ shapefiles	Official	Councils	[Near] real-time	Hydrological (e.g. flood)	Research
Overland flow paths	Official	Councils	Current	Hydrological (e.g. flood)	Research
Coastal inundation Maps	Official	Councils	Forecasted	Hydrological (e.g. flood)	Research
Pollen Counts	Official	MetService	Forecasted	Health	Research; Response: Preparedness
Slope	Official	LINZ, Councils	Current	Hydrogeological (e.g. landslide)	Research
Camera feeds	Official	Councils, NZTA, Ski fields, Police	Real-time	Meteorological, Hydrological, Hydrogeological (e.g. landslide)	Response; Preparedness; Public Awareness
Social media (Tweets, Facebook post comments)	Unofficial	Creators: public/social media users Collectors: MetService, EM, Researchers, Councils, NZGIS4EM	[Near] real-time	Meteorological, Hydrological, Hydrogeological	Research; Response; Situational Awareness
Crowdsourcing (e.g., volunteer rain gauges, NZ Flood Pics, mPing, WeatheX, European Weather Observer)	Unofficial	Creators: public/social media users Collectors: EM, Researchers, Councils, NZGIS4EM, Volunteers (e.g., NZ Flood Pics)	[Near] real-time	Meteorological, Hydrological, Hydrogeological	Research; Response; Situational Awareness
Forecast data	Official	MetService, MetOcean, NIWA, Councils	Forecasted	Meteorological, Hydrological, Marine/Coastal	Research; Response: Preparedness
National Climate Database	Official	NIWA	Historical	Meteorological, Hydrological	Research

Australia, the European Weather Observer[9] (Met. Int. E) and WeatheX[10] (Met. Int. B, C) applications respectively are used to collect severe weather reports. These applications gather hazard (and some impact) reports from the public, who have not received any training. The Story Map data usually contains photos with an optional description for the CDEM Group to build their situational awareness (EM. NZ. Reg. F). Alternatively, the specialised applications used in the USA, Austria, and Australia collect more structured data using reporting forms (Met. Int. B, C, E, I). The benefits of the crowdsourced data are that it is timely (Met. Int. E), it may fill in sensor gaps (Met. Int. I), and the applications may increase public awareness and engagement in severe weather hazards (Met. Int. B, C, I). However, maintaining engagement is a challenge and agencies may struggle with receiving reports once contributors have lost interest (Met. Int. E). A gamification element is being considered to maintain interest for contributors of the European Weather Observer (Met. Int. E). Other challenges include quality control and getting buy-in from scientists on the validity of crowdsourced data (Met. Int. E, I).

Meteorological services in the USA and Austria regularly collect reports from storm spotters. The storm spotters can receive training from the meteorological services to increase their credibility. In Austria, the meteorological services offer training and certificates with identification numbers for storm spotters to then register and receive a quality control rating for their reports based on their level of training (Met. Int. E). The meteorological service can then discern the trustworthiness of incoming spotter reports (Met. Int. E). This data is considered highly credible among scientists (Met. Int. E). Furthermore, engagement and awareness are quite high with the "weather enthusiasts" (Met. Int. E). However, connecting with spotters for training remains a challenge (Met. Int. E). The data is also limited in its application for warnings because it is not real-time, thus it cannot be used for real-time warning verification (Met. Int. E). Lastly, storm spotter reports may overlook meteorological phenomena that produce small impacts, a need identified by the US National Weather Service (Met. Int. I).

As reported in a related study [7], much of these datasets are used for steps in the Value Chain for warnings, particularly hydrometeorological Observation, Monitoring, and Detection, Hazard Forecasting, and in some cases Impact Forecasting and Impact Warning. For example, the MetService uses radar and rainfall data to observe, monitor, and detect rainfall amounts, which is then used by regional and local councils to forecast flood hazards (Met. NZ. G). Flood forecasts may then be used to forecast the impacts of the flood, in a quantitative model-based approach, or in a qualitative discussion-based approach, or both [7]. Local/regional councils and CDEM Groups may then use these forecasts to inform their flood warning messages, wherein they might include impact-oriented messages (EM. NZ. Reg. H; [40]).

3.1.2. *Impact data*

A plethora of impact data was identified in our interviews that are created, collected, and used by different groups for different purposes, as

[1] The acronyms and abbreviations in Table 2 are as follow: Emergency Management (EM), New Zealand (NZ), Geographic Information Systems (GIS), Regional (Reg), Government (Gov.), Early Warning System (EWS), International (Int.).
[9] https://www.essl.org/cms/european-severe-weather-database/ewob/.
[10] https://weathex.app/.

Table 5
Summary of impact data sources. identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, uses in the IFW Value Chain, type of impact, and non-IFW uses.[31]

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
Tweets	Unofficial	Public/social media users	MetService, CDEM, Researchers, Councils, NZGIS4EM	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Facebook Post comments	Unofficial	Public/social media users	MetService, CDEM, Researchers, Councils, NZGIS4EM	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
SnapChat Heat Maps	Unofficial	Public/social media users	MetService, CDEM, Researchers, NZGIS4EM	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Crowdsourced Photos via Story Maps (e.g., NZ Flood Pics)	Unofficial	Public/social media users	MetService, CDEM, Researchers, Councils, NZGIS4EM, Volunteers (e.g., NZ Flood Pics)	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Crowdsourcing/ Public Reporting	Unofficial	Public	Councils, CDEM, Volunteers	Current, maybe near real-time	Observation, Monitoring, and Detecting; Hazard Forecasting; Impact Forecasting; Impact Warning	Built environment, infrastructure	Response; Situational Awareness; Recovery; Planning; Mitigation; Public Awareness/ Engagement/ Education
Red Cross Chained Crowdsourcing	Unofficial	Public	Red Cross	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Response; Situational Awareness
Emergency call centre reports	Official	Public	Police, FENZ	[Near] real-time & Historic?	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Community volunteer radio calls	Unofficial	Designated community volunteers	EM, Councils	[Near] real-time	Observation, Monitoring, and Detecting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Response; Situational Awareness
Damage surveys (e.g. aerial surveys, building surveys via Survey123, QuickCapture, RiACT, Kobo 2, etc.)	Official	Councils, Researchers (NIWA, GNS Science, Universities), CDEM	Councils, Researchers (NIWA, GNS Science, Universities), CDEM	Historic	Impact Forecasting; Impact Warning	Urban, Rural, Infrastructural	Research; Response; Situational Awareness; Recovery; Mitigation; Land use planning and development policies
Media reports	Unofficial	Media outlets	Councils, Researchers (NIWA, GNS Science), CDEM, MetService	[Near] real-time	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Research; Response; Situational Awareness
Tacit knowledge, experience, intuition	Official	Councils, CDEM, MetService	Councils, CDEM, MetService	Available in real-time, based on historic knowledge and experience	Impact Forecasting; Impact Warning	Urban, Rural, Environmental	Response; Situational Awareness
Health & Injury Data	Official	District Health Boards, ACC, Stats NZ	District Health Boards, ACC, Stats NZ	Historic	Impact Forecasting; Impact Warning	Health	Research; Response; Recovery; Planning and Mitigation
Wellbeing Surveys	Official	CDEM, Councils	EM, Councils	Historic		Social, Health, Property	Response; Situational

(continued on next page)

Table 5 (*continued*)

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
					Impact Forecasting; Impact Warning		Awareness; Recovery
Post-event interviews and surveys	Official	Researchers (e.g. NIWA, GNS Science, other), EM	Researchers (e.g. NIWA, GNS Science, other), EM	Historic	Impact Forecasting; Impact Warning	Social	Response; Mitigation; Preparation
Insurance claims	Official	Insurance companies, EQC, ICNZ	Insurance companies, EQC, ICNZ	Historic	Impact Forecasting; Impact Warning	Property, Health, Economic	Research; Recovery; Mitigation
"Boots on the ground"	Official	Councils, CDEM	Councils, CDEM	[Near] real-time	Impact Forecasting; Impact Warning	Urban, Rural, Environmental	Response; Situational Awareness
Lifelines Sectors (e.g. power companies, NZTA)	Official	Lifelines Services (e.g., NZTA, Transpower, KiwiRail), councils, wastewater services	Lifelines Services (e.g., NZTA, Transpower, KiwiRail), councils, wastewater services	[Near] real-time	Impact Forecasting; Impact Warning	Infrastructural	Response; Situational Awareness; Recovery; Business As Usual; Research
Council Requests For Service (RFS)	Official	Public	Councils	[Near] real-time	Impact Forecasting; Impact Warning	Infrastructural; Property; Urban; Rural; Environmental	Situational Awareness; Response; Recovery
Situational Reports	Official	CDEM, Councils	CDEM, Councils	Current	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Built Environment	Response; Situational Awareness; Recovery; Research
Post-event reports	Official	NEMA, CDEM Groups, Councils	NEMA, CDEM Groups, Councils	Historic	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Built Environment	Recovery; Mitigation and Planning; Research
Operations Reports (Council)	Official	Councils	Councils	Historic	Impact Forecasting; Impact Warning	Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Built Environment	Response; Situational Awareness; Recovery; Research
Flood event reporting	Official	Councils, Healthy Waters Auckland Council/Councils	Councils, Healthy Waters Auckland Council/Councils	Historic	Observation, Monitoring, and Detecting; Impact Warning	Infrastructural, Urban, Rural Environmental	Response; Situational Awareness; Research; Mitigation; Land use planning and development policies
Injuries and fatalities (e.g., cause of death)	Official	ACC, Coronial Services of New Zealand, Stats NZ	ACC, Coronial Services of New Zealand, Stats NZ	Historic	Impact Forecasting; Impact Warning	Health	Response; Situational Awareness; Research; Mitigation
Cultural and heritage/historical impacts	Official	Councils	Councils	Historic	Impact Forecasting; Impact Warning	Social, Cultural	Research; Planning; Mitigation
Impact Model outputs	Official	GNS Science, NIWA, Researchers	GNS Science, NIWA, Researchers	Historic, Rapid	Hazard Forecasting; Impact Forecasting	Social, infrastructure, built environment, hydrological, hydrogeological, urban, rural, Property, Economic	Response; Research; Planning; Mitigation
NEMA National Loss Database	Official	CDEM Groups	NEMA	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Sendai Framework Reporting
NIWA NZ Historic Events Catalogue	Unofficial	Media outlets	NIWA	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Research; Mitigation
Local Council Databases	Official	Councils	Councils	Historic	Impact Forecasting; Impact Warning	Hydrological, Hydrogeological, Property, Urban, Rural,	Response; Situational Awareness;

(*continued on next page*)

Table 5 (*continued*)

Data	Official or Unofficial	Data Creators	Data Collectors	Timescale	IFW Value Chain Uses	Type of Impact	Non-IFW Uses
						Infrastructural, Built Environment	Recovery; Mitigation
Storm Data (USA)	Official	Meteorological services, Responders, Emergency Services, Storm Spotters, media outlets	National Centers for Environmental Information	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Research; Mitigation
European Severe Weather Database	Official	Meteorological services, Responders, Emergency Services, Storm Spotters, media outlets	European Severe Storms Laboratory	Historic	Impact Forecasting; Impact Warning	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Health, Property, Economic, Built Environment	Research; Mitigation

shown in Table 5. Impact data is available in a range of official and unofficial capacities.

Impact data is collected, created, and used in an official capacity by CDEM Groups, local/regional councils, FENZ, the lifelines sector (e.g., transportation, power, water/wastewater/stormwater services), the insurance sector (e.g., the Earthquake Commission (EQC), the Accident Compensation Corporation (ACC), the Insurance Council of NZ), and the research sector (e.g., GNS Science, NIWA). The primary purpose of collecting the impact data is not for severe weather forecasts and warnings, but for response, recovery, mitigation, and planning. Depending on the quality of the data, it could be used for additional purposes such as impact forecasting and warning. For example, emergency call centre (i.e., 111 calls in NZ) reports incite responses from the appropriate authorities (e.g., FENZ, police). Afterwards, weather-related emergency reports can be used for post-event analysis to verify and improve warnings (Met. NZ. G; [54]).

Insurance claims from property damage and injuries are used for recovery and produce rich datasets for future analysis such as risk/loss modelling (Loss Modelling Research NZ. A), which may inform impact forecasts. Likewise, impact assessments conducted by CDEM Groups are primarily used for building situational awareness to inform response efforts (EM. NZ. Reg. H [55]); and can also be used for warning verification and warning updates in real-time (EM. NZ. Reg. H).

Impact assessments for CDEM Groups in NZ have evolved with the advancements of GIS-based technology for improved data capture and management (EM. NZ. Reg. C, H, F; Data Management Private NZ. B). An overview of how GIS tools were used for a flood event in NZ's West Coast region was provided by [56]. Officials used rapid data collection tools such as Survey123[11] and QuickCapture[12] to collect impact information. QuickCapture was primarily used for collecting photos from aerial and ground assessments, while Survey123 was used to complete form-based assessments [56]. The value of these tools lies in the seamless integration process of the field data directly into a GIS layer for real-time viewing in an Emergency Operations Centre (EOC) (EM. NZ. Reg. C, H, F; Data Management Private NZ. B). However, the pitfalls of these collection methods are that information overload can occur with applications like QuickCapture if the trained staff take a large volume of photographs, and gaps in training can lead to errors in the data, which may skew datasets (EM. NZ. Reg. F).

Tacit knowledge and experience refer to knowledge held by official staff from past experiences who apply this knowledge when planning for or responding to events. NZ participants described how senior EM staff know from past events that certain river levels and peaks will lead to respective levels or types of impacts (EM. NZ. Reg. A, B). This knowledge is passed on verbally either just before or during an event to help with response planning and coordination (EM. NZ. Reg. A, B). The same was found to be true for the Lifelines sector, who "have a good amount of data but … more importantly …, their staff have a very good historical knowledge" (Lifelines NZ. Reg. A). This information is highly trusted as it is based on years of experience. It allows agencies to learn from past events and better prepare for current or future events (EM. NZ. Reg. B).

In many cases, this tacit knowledge and experience is not formally documented and there is a risk of losing this knowledge when staff move on (EM. NZ. Reg. A, C; Lifelines NZ. Reg. A). As one participant identified: "[hazard and impact forecasting are] primarily based on history and knowledge. And with that comes the risk … if you have key people out of the equation or people move on … in life, then you have the knowledge gap until such time as that's filled" (EM. NZ. Reg. C). Upon identifying this vulnerability, this participant indicated that their agency has begun some historical cataloguing (EM. NZ. Reg. C).

Unofficial impact data/information also helps EMs "build a picture of

[2] The acronyms and abbreviations in Table 4 are as follows: Fire and Emergency New Zealand (FENZ), National Institute of Water and Atmospheric Research Ltd (NIWA), Land Information New Zealand (LINZ), New Zealand Meteorological Service (MetService), New Zealand Transport Agency (NZTA), Emergency Management (EM), New Zealand Geographic Information Systems for Emergency Management (NZGIS4EM), MetOcean Solutions (MetOcean).

[3] The acronyms and abbreviations in Table 5 are as follows: Fire and Emergency New Zealand (FENZ), National Institute of Water and Atmospheric Research Ltd (NIWA), New Zealand Meteorological Service (MetService), New Zealand Transport Agency (NZTA), Emergency Management (EM), New Zealand Geographic Information Systems for Emergency Management (NZGIS4EM), Insurance Council of New Zealand (ICNZ), Accident Compensation Corporation (ACC), Institute of Geological and Nuclear Sciences Limited (GNS Science), Statistics New Zealand (Stats NZ), Earthquake Commission (EQC), National Emergency Management Agency (NEMA) Real-time Individual Asset Attribute Collection Tool (RiACT).

[11] Survey123 is a location-based application developed by Esri [57] that is used for completing assessment forms such as impact assessment forms, building assessment forms, and welfare needs assessment forms (EM. NZ. Reg. F).

[12] QuickCapture is another location-based field observation application developed by Esri [58] that is particularly useful for taking photographs of damage/impacts and uploading in real-time to be viewed on a dashboard in the Emergency Operations Centre (EM. NZ. Reg. F).

what's happening" (EM. NZ. Reg. C). Unofficial data includes social media posts, crowdsourced and citizen science data, media reports, and community volunteer radio calls. Interviewees were found to obtain information from Facebook, Twitter, and SnapChat. In most cases, the interviewees indicated that they do not collect or store social media data, but only monitor it for situational awareness and real-time verification. The value of social media appears to lie in its ability to indicate potential hot spots early on in an event and building situational awareness (Met. Int. E; EM. NZ. Reg. C). Social media sentiment analysis can also help to understand the cultural impacts of severe weather and communicate the warnings better (Met. Int. D). However, interviewees use social media data with caution, indicating that while social media data is timely and quantitatively rich, it is difficult to verify, verify (EM. NZ. Reg. B). Relying solely on social media risks missing or overlooking impacted people who are not on social media, such as areas without power or internet access (EM. NZ. Reg. B). Thus, social media data should be used complementarily with other data (Met. Int. D).

Impact databases were also found to exist or be under development. In NZ, the National Emergency Management Agency (NEMA) is developing a national loss database in fulfilment of the Sendai Framework priorities [1]. Data is pulled from EM impact assessments, situational reports, and post-event reports (EM. Gov. NZ. Nat. G). NIWA hosts a catalogue of historic severe weather events in NZ using media reports (Met. Research NZ. J), primarily for research purposes. Storm Data in the USA and the European Severe Weather Database contain data sourced from storm spotters and impact assessments from storms in the USA and Europe (Met. Int. E, I). These American and European databases are highly credible as only vetted and trusted information goes in (Met. Int. E, I). Unfortunately, the databases are not updated in real-time due to the rigorous quality control measures and may have gaps for small impact events (Met. Int. E, I).

Most of the data sources described above capture direct and physical impacts such as damages to the built and natural environment and do not capture social human impacts or indirect impacts. This is a major gap identified in a previous study [7]. Wellbeing surveys and post-event surveys from research studies capture indirect impacts on people's health and social/cultural wellbeing (EM. NZ. Reg. F, H; Risk Modelling NZ. B, C). Wellbeing surveys (also referred to as Needs Assessments and Welfare surveys) are conducted by CDEM Groups and/or health agencies to understand the needs and impacts of people affected by an emergency [59,60]. Furthermore, District Health Boards, ACC, and Stats NZ collect and house health, injury, and mortality data for their own purposes (EM. Gov. NZ. Nat. G; Loss Modelling Research NZ. A). In the context of severe weather IFWs, these data, along with the Wellbeing surveys conducted by EM/councils, could be useful for understanding indirect and social and cultural impacts to inform impact warning messages (EM. Gov. NZ Nat. G; Loss Modelling Research NZ. A; [7]).

3.1.3. *Vulnerability data*

Our participants identified some vulnerability data sources, as shown in Table 6. As stated in our literature review, vulnerability data is more difficult to obtain or create, as vulnerability changes over space and time. On their own, many of the identified data sources in Table 6 do not provide an indication of vulnerability. Rather, these data sources are inputs into vulnerability assessments and risk models. For example, census data and health data may be used to conduct a social vulnerability assessment, while building damage assessments are inputs into vulnerability functions for risk modelling [7,61]. The results of the vulnerability assessment or risk model then help analysts identify vulnerable areas:

> Everything's built off the models … we've identified … issues with care homes and areas, hotspots in the community which could potentially … be at risk … We've got them in … behind the stop

Table 6
Summary of vulnerability data sources. identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, uses in the IFW Value Chain, type of impact, and non-IFW uses.[41]

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	IFW Uses (from the Value Chain)	Type of Impact	Non-IFW Uses
Vulnerability Assessment and Risk Modelling Outputs	Official	Councils, Researchers (NIWA, GNS Science), CDEM, Hired contractors	Historic	Impact Forecasting; Impact Warning	Property, human, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Planning; Mitigation; Research
Asset Information	Official	Councils, Researchers (NIWA, GNS Science), CDEM, Hired contractors	Historic	Hazard Forecasting; Impact Forecasting; Impact Warning	Property, human, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Planning; Mitigation; Research
Building damage assessments	Official	Councils, Researchers (NIWA, GNS Science), CDEM, Hired contractors	Historic	Hazard Forecasting; Impact Forecasting; Impact Warning	Property	Response; Situational Awareness; Recovery; Research; Mitigation
Census data	Official	Stats NZ	Historic	Hazard Forecasting; Impact Forecasting	Human	Research; Business As Usual (BAU)
Tacit knowledge, experience, intuition	Official	Councils, CDEM	Available in real-time, based on historic knowledge and experience	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Response; Situational Awareness; Preparedness; Mitigation; BAU
Lab-based experiments	Official	Researchers (NIWA, GNS Science, universities)	Historic	Hazard Forecasting; Impact Forecasting	Built environment	Research
Health Data, New Zealand Health Survey	Official	MOH, DHBs	Historic	Impact Forecasting. Impact Warning	Health	Research; Recovery
Infrastructure	Official	Councils, Hired contractors	Historic	Hazard Forecasting; Impact Forecasting; Impact Warning	Built environment, infrastructure	Response; Situational Awareness; Recovery; Planning; Mitigation
Soil/land stability	Official	GNS Science	Historic?	Observation, Monitoring, and Detecting; Hazard Forecasting; Impact Forecasting	Hydrogeological; Built environment, infrastructure, Environment, Property	Planning; Mitigation; Research

banks, bungalows, probably not the best place for them but they're there. So just being aware of those [vulnerable areas] (Hyd. Gov. NZ Reg. A).

Asset information refers to characteristics of the asset for which the vulnerability is being assessed. These can be people, buildings, roads, stop banks, the environment, etc. The asset information of buildings would include data on the age of the building, the construction material, and the number of floors (Risk Modelling NZ. B). This information is collected through building assessments by building engineers (Risk Modelling NZ. B). Alternatively, asset information of people consists of demographic data, health data, socioeconomic data, etc. (Risk Modelling NZ; [28]), available from Stats NZ and the Ministry of Health. Asset information about stop banks includes age and condition and is held by local and regional councils (Hyd. Gov. NZ. Reg. A).

Physical vulnerability of the built environment is captured through building damage assessments, lab-based experiments, infrastructure vulnerability assessments, and the tacit knowledge, experience, and intuition of engineers (Risk Modelling NZ. A). Assessments of building damage and lab-based experiments are typically conducted by engineers hired within or contracted by agencies like local/regional councils, GNS Science, NIWA, and CDEM Groups (Risk Modelling NZ. B). Infrastructure vulnerability assessments are conducted or contracted by the Lifelines Sector (e.g. [62]), and other researchers. While much work has been made in the risk modelling space for the built environment, a gap remains in NZ around the asset information of buildings: "We don't have good building data. We've got [data on] where buildings are, but we don't necessarily know what they're made of and that kind of stuff" (Risk Modelling NZ. A).

Social or human vulnerability is even more difficult to capture and assess and there is a need to capture the dynamic nature of social human vulnerability for IFWs [7]. This need is also echoed for response efforts: "[emergency response agencies are] more focused on the emergency response, so they need to know [who needs] more help, so it's better to break down all the gender … and age difference (sic) … " (Risk Modelling NZ. B). The census is a clear choice for obtaining social/human vulnerability data. However, our participants identified surprising challenges with obtaining and using census data, such as in the example below:

> We have vulnerability data. The problem with that data is that … in Argentina we make a national census … every ten years … So, the vulnerability information that we have now is old! We have other information but, you know, this strong, national census gives you a lot of information about vulnerability. So that's a problem (Met. Int. D).

In New Zealand, low response rates of the 2018 national census created problems with the dataset [63], which significantly delayed the release of the data and frustrated risk modellers who were waiting on the data to use in their models (Risk Modelling NZ. A).

An additional challenge with using census data identified by our participants is the spatial scale. The NZ census data is at the meshblock[13] scale, but risk modellers want to model at the building scale. Participating risk modellers questioned how they can interpolate the census data with the building level (Risk Modelling NZ. A, B).

Health data is another indicator of human vulnerability. The impacts of severe weather events can exacerbate underlying health conditions. For example, people with asthma may experience exacerbated symptoms while cleaning up damaged and contaminated sites after a flood (Risk Modelling NZ. C), or during thunderstorms (Health NZ. Reg. A; [7]). In NZ, District Health Boards (Health NZ. Reg. A) and the Ministry of Health house this data. The Ministry of Health conducts an annual national Health Survey of NZ.

Like impact data, vulnerability data is also present as tacit knowledge and experience. As previously mentioned, infrastructure engineers and other asset managers possess a wealth of knowledge and experience around the performance capacities of a building, levy, or another piece of infrastructure. In the risk modelling space, this tacit knowledge, or expert opinion is a valid resource for building vulnerability functions:

> If you are an asset manager and you know about your port or your wharf … and you just intuitively think about … if a six-meter wave came in what do you think would happen? … you can elicit information that way. And there's a lot of vulnerability functions out there that are done that way because you don't need an event to happen. And I guess there is a certain level of knowledge and intuition that can go into these things … So you can do some kind of estimate (Risk Modelling NZ. A).

CDEM Groups possess tacit knowledge around vulnerable areas, people, and communities within their jurisdiction (Hyd. Gov. NZ. Reg. A; Auckland Workshop), but our participants indicated that they still need to know "who is where and what their mobility/health/access considerations are" (Auckland Workshop). Some of this information is available through pre-existing networks with EM services that manage relationships with vulnerable communities, such as the "Caring for Communities" government work programme that was established in response to COVID-19,[14] and through Welfare coordination groups (Auckland Workshop). However, there is a risk of missing people who are not "in the system" (Auckland Workshop). Furthermore, privacy concerns exist when considering alternative uses for the data beyond its initial purpose, which is usually to support response and recovery (Auckland Workshop; EM. NZ. Reg. H; EM. Gov. NZ. Nat. G). Yet, even this tacit knowledge can still help EM groups formulate their warning messages (EM. NZ. Reg. H).

All datasets listed in Table 6 are produced and housed in an official capacity. Our interviews did not find any instances where crowdsourcing or other unofficial methods were used for producing vulnerability data. Some research has been done to use crowdsourcing applications for capturing vulnerability. For example, in Kazakhstan [65] developed a mobile application (OxyAlert) where users can answer questions about their health status relative to their geographic location and atmospheric conditions to characterise individual vulnerability to meteorological changes [66]. presented a new participatory mapping methodology for incorporating stakeholder's participation, local knowledge, and locally spatial characteristics for vulnerability assessments of flood risk. These studies demonstrate the untapped opportunity to use crowdsourcing and other engagement activities to produce localised or individualised vulnerability assessments.

3.1.4. Exposure data

The dynamic nature of exposure data also makes it difficult to collect and maintain. However, our participants identified some existing and potential sources of exposure data for different uses and with different time scales, summarised in Table 7. Most of the data sources are classified as official, as they are produced by official agencies.

Asset footprints refer to the geographical location of assets, such as buildings, historically and culturally significant sites, etc. These data are

[4] The acronyms and abbreviations in Table 6 are as follows: National Institute of Water and Atmospheric Research Ltd (NIWA), Emergency Management (EM), Institute of Geological and Nuclear Sciences Limited (GNS Science), Statistics New Zealand (Stats NZ), Ministry of Health (MOH), District Health Boards (DHBs).

[13] According to [64]; "[a] meshblock is defined by a geographic area, which can vary in size from part of a city block to a large area of rural land."

[14] https://ipanz.org.nz/Article?Action=View&Article_id=150258.

Table 7
Summary of exposure data sources identified in interviews. This table presents the data set, whether it is official or unofficial, the data creators and collectors, timescale, uses in the IFW Value Chain, type of impact, and non-IFW uses.[51]

Data	Official or Unofficial	Data Creators and/or Collectors	Timescale	IFW Uses (from the Value Chain)	Type of Impact	Non-IFW Uses
Asset footprints (e.g., building, cultural and historical site locations)	Official and unofficial	Councils, Google Maps, OpenStreetMap, LINZ, FENZ, Heritage NZ, Iwi	Historic	Hazard Forecasting; Impact Forecasting	Property, Cultural, Social	Response; Research; BAU; Mitigation
Infrastructure networks, e.g., transportation networks, traffic flows, power & water supplies	Official	Lifelines Services (e.g., NZTA, Transpower, KiwiRail), local & regional councils	Current	Hazard Forecasting; Impact Forecasting	Infrastructural	Response; Situational Awareness; BAU
Census data	Official	Stats NZ	Historic	Hazard Forecasting; Impact Forecasting	Human	Research; BAU
Population movement via cell phone data	Official	DataVentures/Stats NZ	Historic and [Near] real-time?	Hazard Forecasting; Impact Forecasting; Impact Warning	Human	Research
Tacit knowledge, experience, intuition	Official	Councils, CDEM	Available in real-time, based on historic knowledge and experience	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Social, Infrastructural, Urban, Rural, Environmental, Property, Economic, Built Environment	Response; Situational Awareness; Preparedness; Mitigation; BAU
Topographical data, e.g., digital elevation models	Official	LINZ, Landcare Research, Universities, GNS Science, NIWA	Historic	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Rural, Urban, Environmental	Response; Situational Awareness; Research; BAU
Land-use	Official	Councils, LINZ	Historic	Hazard Forecasting; Impact Forecasting	Meteorological, Hydrological, Hydrogeological, Rural, Urban, Environmental	Response; Situational Awareness; Research; BAU
Community events	Official	MBIE, Stats NZ, Local and regional cultural and tourism agencies (e.g., Auckland Unlimited)	[Near] real-time	Hazard Forecasting; Impact Forecasting; Impact Warning	Cultural, Social	Response; Situational Awareness; BAU

officially produced by local/regional councils, LINZ, and FENZ. They are also available on unofficial platforms like Google Maps and OpenStreetMap.[15] This location-based data helps EMs and researchers identify assets that are potentially exposed to a hazard.

Exposure is typically determined by overlaying the asset information with hazard information (Risk Modelling NZ. C). This is common practice for disaster and climate change mitigation. For example [34], created a national-scale built environment exposure model to extreme sea-level rise for NZ by overlaying buildings, infrastructure, and built land area with a Digital Elevation Model and coastal flood maps. Similarly [67], compared urban and rural exposure to coastal hazards using demographic data overlaid with building, infrastructure, and land assets. Their results provided counts of people, buildings, infrastructure, and land assets located in areas exposed to coastal hazards. While these exposure models and their outputs help to locate and quantify exposed people and assets to a given hazard, the results of these models represent one point in time. Thus, they do not accurately represent the dynamic nature of exposure.

Other data sources can capture dynamic exposure, such as live traffic flows from transportation agencies (e.g., the New Zealand Transport Agency) (Data Management Gov. NZ. Nat. A; Met. NZ. K). Cell phone data was also discussed for capturing population shifts (Risk Modelling NZ. A; Data Management Gov. NZ. Nat. E). For example, Data Ventures, a commercial data brokerage branch of Stats NZ, used cell phone data to produce population densities at the Statistical Area 2 level (a higher scale than the Meshblock level) for a given time range[16].

This product became useful in the COVID-19 response where Data Ventures provided near real-time population movements to the National Crisis Management Centre which "provided [a] very close to real-time view of whether or not people were following the advice" (Data Management Gov. NZ. Nat. E), which informed advice to the Prime Minister's COVID-19 advisory group "about whether or not we move or shift down levels of lockdown" (Data Management Gov. NZ. Nat. E). Through this, they were also able to determine "whether or not people were moving from one region to another because that's really how you have that wider contagion risk" (Data Management Gov. NZ. Nat. E). This has potential application in an IFW system for identifying the "catchment of individuals" (Data Management Gov. NZ. Nat. E) in near real-time for more contextualised warnings. However, this data alone does not provide an overall risk indication; "you have to put other layers of information to go 'well if it's a … category 5 [ex-tropical cyclone] then are the buildings of a particular standard and … how many people are in the areas that those buildings are present in'" (Data Management Gov. NZ. Nat. E). Hence the need for vulnerability information as previously discussed.

Knowledge of dynamic human exposure can also come from knowing about community events (Auckland Workshop). A regional EM official in NZ identified the need for a "real-time understanding of what is going

[15] OpenStreetMap is a form of geographic crowdsourcing in which volunteers digitize features of the earth onto an online map of the world. This data is produced under a Creative Commons license, thus making it open-source and freely available for download.

[16] See https://population-density.dataventures.nz/explorer2/help/index.html for more.

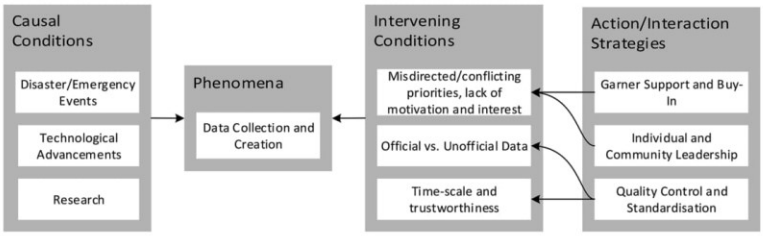

Fig. 1. Results of applying the coding paradigm to understand the causal conditions, intervening conditions, and action/interaction strategies for HIVE data creation, collection, and use phenomenon as defined in Table 3. Causal conditions are the drivers of the phenomena. Intervening conditions are conditions that inhibit or facilitate the phenomena. Action/interactions strategies are strategies that were identified to address the intervening conditions.

on in the community (i.e., sports events, hotel capacity, etc.)" (Auckland Workshop). In this case, the regional council's economic and cultural department possesses this knowledge and information (Auckland Workshop) and should be shared with the EMs and other agencies such as the MetService who would need to be aware of events if severe weather were to occur.

3.2. *Data creation, collection, and use*

Discussions with participants revealed several inhibitors and facilitators to collecting, creating, and using the data. Using the ES-GT coding paradigm, we identified the causal conditions driving data collection, creation, and use, intervening conditions to this phenomenon, and actions and strategies that have been used to address those intervening conditions (Fig. 1). The causal conditions are presented next.

3.2.1. *Causal conditions*

Causal conditions were identified as drivers for agencies collecting and using HIVE data in general for different purposes and via different methods. The main causal conditions identified by participants are (1) Disaster/emergency events, (2) technological advancements, and (3) Research.

Other factors can also be attributed to HIVE data collection, such as existing policies and plans (e.g., the National Disaster Resilience Strategy) within NZ, and international initiatives such as the Sendai Framework. For the purposes of this study, we have decided to focus these current findings on the causal conditions that participants identified more directly.

3.2.1.1. Disaster/emergency events. Our participants gave examples of how the creation, collection, and use of HIVE data has been driven by past disaster/emergency events. Following the 2010–2011 Canterbury earthquake sequence there was a need for data on the damaged buildings, such as their age, construction material, and level of damage to inform recovery (Risk Modelling NZ. B). At the time, no database existed for building characteristics (e.g., history, age, construction material) (Risk Modelling NZ. B). Consequently, engineers had to "go through one by one to record the location and age … of the material" before they could conduct the damage assessments (Risk Modelling NZ. B). This experience where decision-makers were caught scrambling for data revealed a need for building up databases for future events (Risk Modelling NZ. B; EM. NZ. Reg. H).

[5] The acronyms and abbreviations in Table 7 are as follows: Fire and Emergency New Zealand (FENZ), National Institute of Water and Atmospheric Research Ltd (NIWA), New Zealand Transport Agency (NZTA), Institute of Geological and Nuclear Sciences Limited (GNS Science), Statistics New Zealand (Stats NZ), Ministry of Business, Innovation, and Employment (MBIE).

This and other major events resulted in the formation of a Technical Advisory Group (TAG) by the Ministry of Civil Defence and Emergency Management (now the National Emergency Management Agency or NEMA), in 2017 [68]. The TAG conducted a Ministerial Review and provided several recommendations for better intelligence gathering (i.e., data collection) [69]. A participating regional EM official cited this review as a driver for their council and EM Group attempting to improve their data collection efforts for disaster response (EM. NZ. Reg. H). Additionally, in response to two back-to-back ex-tropical cyclones that resulted in disastrous flooding, the Bay of Plenty region EM Group now updates exposure maps for tropical cyclone hazards annually (EM. NZ. Reg. A).

3.2.1.2. Technological advancements. Technological advancements, particularly the implementation of geospatial technologies such as Geographic Information Systems (GIS), cloud-based services, and the proliferation of mobile devices with cameras and an internet connection have also driven efforts for better collection of HIVE data. For example, one participant described Esri's ArcGIS Online product as the "catalyst" for using geospatial technologies for emergency response (EM. NZ. Reg. H). The cloud-based aspect of the ArcGIS Online product supports rapid development and sharing of maps and other geospatial applications, which is seen as the most valuable feature for emergency response (EM. NZ. Reg. H). As such, "the strength of the NZGIS4EM [New Zealand Geographic for Emergency Management] community really … is built upon that. And … there's … been continual growth with event after event" (EM. NZ. Reg. H). Furthermore, this cloud-based technology used in combination with mobile devices using applications like QuickCapture and Survey123 allowed for the redevelopment of how rapid impact assessments are conducted for more efficient and timely data collection. For example, with Survey123, "the fieldworker hits submit, that assessment will instantly show up on the map [in the Emergency Operations Centre]" to display the level of damage and safety of the buildings (EM. NZ. Reg. H).

3.2.1.3. Research. Research has also driven the collection of HIVE data. For example, NIWA's NZ Historic Events Catalogue[17] was initially developed for research interests, where "people realised that it would be really good to have this database for people and researchers, and just sort of give an idea of what historically has happened … And I think it's been quite useful" (Met. Research NZ. J). Other HIVE data has been collected to support the research and development of risk models (Risk Modelling NZ. B).

3.2.2. *Intervening conditions for data creation, collection, and use*

Intervening conditions were found to affect whether HIVE data is

[17] https://hwe.niwa.co.nz/.

collected, and the choice for which data source is used. Herein we focus on three intervening conditions: (1) Priorities, motivation, and interest; (2) Official and unofficial data; (3) Timescale and trustworthiness.

3.2.2.1. Priorities, motivation, and interest. Conflicting priorities and a lack of motivation or interest in data creation and maintenance was a barrier identified by several participants for gathering HIVE data (EM. Gov. NZ. Nat. G; Data Management Gov. NZ. Nat. A; Data Management Private NZ. B; Data Management Research NZ. C; EM. NZ. Reg. D). Management priorities and the personal interests of key staff within an organisation appear to either inhibit or enable data collection and creation, as one NZ risk modeller summarised: "it just depends on who's here and who's leading the team" (Risk Modelling NZ. A).

The National Emergency Management Agency (NEMA) for New Zealand reports losses and impacts to the UNDRR in fulfilment of Sendai Framework priorities. Their goal is to develop a national loss and impact database (EM. Gov. NZ. Nat. G). However, progress on this front is slow as NEMA is continuously busy responding to other events and so is unable to direct resources towards developing a national loss and impact database (EM. Gov. NZ. Nat. G). This may be due to the reactive nature of the EM sector [16], where agencies lack the time or resources to establish proper data collection and management practices (EM. Gov. NZ. Nat. G; Loss Modelling Research NZ. A; EM. NZ. Reg. A, B, H; Data Management Private NZ. B; Hyd. Gov. NZ. Reg. A).

3.2.2.2. Official and unofficial data. The leading mandate of many of the participating agencies is to preserve life and property, be it through designing and issuing warnings (e.g., NMSs, warning services) or coordinating emergency response plans and actions (EM agencies). A key role for these agencies is providing the voice of truth during a severe weather event. These agencies must maintain a high level of credibility and trustworthiness amongst the public and stakeholders to ensure that their messages are heeded (NMS. Int. C, D, E; NMS. NZ). Since these agencies use a plethora of data to communicate critical information and alerts to the public, trust in the supporting information underpinned all discussions with participants.

Official and unofficial datasets and sources were discussed and compared with interviewees. Interviewees showed a preference for official datasets and sources because of their role as an authoritative voice in saying "this is what happened" or may happen (NMS. Int. C). However, collecting and using official data is not always possible. For example, agencies who possess the data may be unable or unwilling to share (NMS. Int. C), or agencies may need real-time data, which is rarely official or trusted (NMS. Int. D). In these cases, agencies may need to turn to unofficial data sources such as crowdsourcing and social media (NMS. Int. C).

3.2.2.3. Time scale and trustworthiness. Forecasting impacts in real-time or near real-time for early warning is an operational goal [8,70]. Thus, our participants identified a need for real-time or near real-time data (Met. Int. E; EM. NZ. Reg. H; Risk Modelling NZ. C, D; Data Management Private NZ. B). Potential real-time data sources that were identified are crowdsourcing, social media, and mobile tracking data. Aside from the mobile tracking data, these sources are unofficial data sources, resulting in decreased perceptions of trust and credibility in the data (Met. NZ. H; Met. Int. D, I). As such, our results indicate trustworthiness, and the timescale needs appear to be two intervening conditions in the choice and use of a data source. A tension appears to exist between these two conditions, as officials (e.g., warning agencies, emergency managers, responders) need both timely and trustworthy data, but often have to compromise on either factor [71].

Distrust is a critical obstacle to warning adherence [72]. Thus, it is not surprising that trust in the data and in the sources to support IFWs is a primary driver in deciding which impact, exposure, and vulnerability dataset/source to use. It is important that warning officials perceive the data as trustworthy [73], as this will ensure that public trust in the agency and in the warnings is maintained. Different uses of impact, exposure, and vulnerability data require varying levels of trustworthiness.

The timescale needed also determines the most appropriate dataset. We found that some data sources, like crowdsourcing and social media, fill a gap in the need for real-time or near real-time data for verification, situational awareness, and response. This finding supports those of a recent survey of European NMSs [40]. However, these data may be less useful for defining impact thresholds and informing impact/risk models due to the perceived limited quality and trustworthiness. For example, social media data appeared to be less trustworthy amongst participants because it is difficult to vet and lacks the structure needed for forecasting and modelling (Met. NZ. G, H). However, social media remains useful for building situational awareness quickly and updating alerts (EM NZ Reg. C; [54]).

3.2.3. Action/interaction strategies

Action/interaction strategies were found to address the intervening conditions previously identified. The three strategies we focused on here are: (1) Garnering support and buy-in, (2) Individual and community leadership, and (3) Quality control and standardisation.

3.2.3.1. Garnering support and buy-in. Garnering support and buy-in was found to be an action/interaction strategy for overcoming conflicting management priorities or a lack of motivation and interest. One regional EM official has been pushing for a GIS-based approach for improved intelligence gathering, management, sharing, etc., but has faced resourcing challenges. The first "informal" (EM. NZ. Reg. H) stage of this project "didn't turn out to be sustainable because we had a lot of issues with trying to carve out time from people to actually contribute to it" (EM. NZ. Reg. H). As such, they developed a "more formal" (EM. NZ. Reg. H) strategy to approach decision-makers for support for resource allocation across regional stakeholders/agencies (EM. NZ. Reg. H). Efforts for garnering support are still underway (EM. NZ. Reg. H).

3.2.3.2. Individual and community leadership. Individual and community leadership was found to be another action/interaction strategy for overcoming misdirected management priorities and lack of motivation or interest. Some regional agencies have improved their own data collection practices based on the leadership of their in-house GIS and EM experts. For example, the West Coast CDEM group regularly develops innovative ways for using GIS-based technology to carry out impact assessments (EM. NZ. Reg. C, F; see [56]). Furthermore, the emergence of the NZGIS4EM[18] group has been identified by participants as a major driver for technological advancement and for pushing the needle forwards on creating, sharing, and accessing geospatial data and tools for emergency response (EM. NZ. Reg. H; Data Management Gov. NZ. Nat. A; Data Management Private NZ. B; EM. NZ. Reg. D).

This innovative GIS-based work is credited to specific individuals within the sector who possess a passion and expertise to drive these efforts (Data Management Private NZ. B; EM. NZ. Reg. B, F). Furthermore, the innovation may also be due to available resources and support from management.

Our findings align with the Policy Capacity Framework [74] which outlines three levels of capacity development and implementation: individual, organisation, and systemic; and three dimensions: analytical, managerial, and political. The individuals accredited with driving the GIS4EM movement in NZ appear to possess analytical, managerial, and political acumen capacity at the individual level by possessing

[18] NZ Geographic Information Systems for Emergency Management (NZGIS4EM) is a grassroots community of GIS specialists and EM practitioners in NZ that began working together in the mid-2010's to identify how they could build and use geospatial tools for better emergency response (EM. NZ. Reg. H).

analytical, technical, communication, and leadership skills to drive technological innovation within their sector. Agencies like the West Coast CDEM Group possess technical and administrative capacity at the organisational level by providing and coordinating the resources needed to allow the individuals to implement their innovative solutions. More investigation is needed to understand the policy capacities at the systemic level and political dimension within the NZ EM and severe weather warning space. However, it appears that the GIS movement within NZ's EM sector has reached central government decision-makers with the recent release of the *Impact Assessments Director's Guideline for Civil Defence Emergency Management Groups [DGL 22/20]* by [55]. This guidance document outlines the role of GIS and supporting spatial tools for undertaking impact assessments.

3.2.3.3. Quality control and standardisation. Participating agencies emphasised the importance of applying quality control measures to increase the perceived trustworthiness of the data. Some quality control measures that came up in the conversations included vetting the source (s) of the data, training storm spotters, cross-validating between sources for accuracy, timing, and location. For example, the NMSs in the USA and Austria train and vet storm spotters so that they can trust incoming ground observations (Met. Int. E, I; [40,75]). Standardised post-event damage/impact assessments collected by those trained to, and entered into a database for further analysis, may be more suitable for needs that do not require real-time data [40].

4. Conclusions and limitations

Documenting hazard, impact, vulnerability, and exposure data fulfil needs for IFWs and meets Sendai Framework priorities for improved understanding of disaster risks and subsequent mitigation and reduction. The New Zealand focus of this research further supports an identified need for better risk data for modelling and natural hazard management in New Zealand.

In this exploratory study, we identified sources for hazard, impact, vulnerability, and exposure data for implementing severe weather IFW systems. Our findings indicate that many sources for hazard and impact data exist that are collected for other uses (such as for response, and research) and have relevant applications for IFWs. Furthermore, underlying datasets for vulnerability and exposure exist and are available. Technological advancements have also enabled the collection and creation of HIVE data, such as GIS-based tools and mobile devices.

We also identified intervening conditions, and action/interaction strategies for collecting HIVE data, as shown in Fig. 1. Our findings suggest that priorities, motivation, and interest within organisations influence how well data is collected and used. Furthermore, agencies tend to prefer official data, but official data has limitations that unofficial data can sometimes address, such as timeliness. To that end, a tension exists between the timeliness and trustworthiness of data needed for emergency response and warnings.

To address these intervening conditions, we identified some action/interaction strategies using Grounded Theory. Garnering support and buy-in from decision-makers and upper management within an agency can redirect priorities and increase motivation and interest in collecting HIVE data. Individual and community leadership within the field of practice also provides a bottom-up approach for driving industry priorities and practices for collecting HIVE data. Furthermore, measures for quality control and data standardisation may improve the perceived trustworthiness of the data.

The qualitative nature of data collection and analysis herein limits the generalisability of results beyond the interviewees. However, the qualitative approach offers an in-depth understanding of a problem not readily available from quantitative approaches [76–78]. Furthermore, participant recruitment and data collection methods were affected by the COVID-19 pandemic response, as many individuals and agencies targeted for recruitment were involved in the response. As such, some perspectives may be missing from the qualitative dataset.

Discussions with colleagues in the field pointed towards the value of mātauranga Māori (Māori knowledge) in understanding disaster risk and impacts in New Zealand. Considerations about cultural ownership of such knowledge and its use in an impact forecasting and warning system is thus an important area for future research.

Findings from this research provide insight into the drivers and barriers for collecting hazard, impact, vulnerability, and exposure data in New Zealand. Sources of such data were identified such that practitioners and researchers may seek out these datasets if so desired. Further questions remain around how the data can be accessed and acquired for use in an IFW system. Future research should explore the data acquisition process for these datasets.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix M: Chapter Eight Publication

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'Sharing is caring': A socio-technical analysis of the sharing and governing of hydrometeorological hazard, impact, vulnerability, and exposure data in Aotearoa New Zealand

Sara E. Harrison [a,b,*], Sally H. Potter [b], Raj Prasanna [a], Emma E.H. Doyle [a], David Johnston [a]

[a] Joint Centre for Disaster Research, Massey University, Wallace Street, Mount Cook, Wellington 6021, New Zealand
[b] GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5011, New Zealand

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ABSTRACT

There has been a growing recognition of the need to collect disaster and risk data over the last two decades. Accordingly, better collection and management of disaster data was identified as a priority of the Sendai Framework for Disaster Risk Reduction. The introduction and implementation of Impact Forecasts and Warnings (IFWs) have further highlighted this need to collect and access hazard, impact, vulnerability, and exposure (HIVE) data. However, challenges have been met with reporting and using disaster data, which have resulted in an identified need to establish principles for data collection, recording, reporting, exchange/sharing, and comparability. This introduces the concept of data governance and management for disaster data, particularly with regards to data custodianship, stewardship, and sharing.

Using Grounded Theory, a series of interviews were conducted with users and creators of HIVE data to develop further understanding around managing and accessing it for severe weather hazards in New Zealand. A socio-technical lens guided the analysis to identify the organisational and technical intervening conditions and action/interaction strategies for accessing and sharing HIVE data in NZ.

Findings indicated that there is a need to establish data governance principles for HIVE data in New Zealand. An additional need was identified for nurturing partnerships to continue building trust between stakeholders for sharing data. Furthermore, integration challenges continue to interfere with the use of various sources of HIVE data for effective risk and impact assessments for IFWs and beyond. Systematic and standardised data collection approaches using GIS-based tools can support integration.

1. Introduction

There has been a growing need to collect disaster and risk data over the last two decades (e.g., [32]). Accordingly, better collection and management of disaster data was identified as a priority of the Sendai Framework for Disaster Risk Reduction [81]. In response, global initiatives now exist with the objective of developing technical guidance for building up disaster and risk data, such as the Integrated Research on Disaster Risk (IRDR) programme and subsequent workshops [12,25]. The introduction and implementation of Impact Forecasts and Warnings (IFWs) for hydrometeorological hazards (e.g., [84,88]) has further highlighted the need to collect and access relevant disaster data for mitigation and prevention; namely hazard, impact, vulnerability, and exposure (HIVE) data [35,70]. However, challenges have been met with reporting and using disaster data, such as the fact that many stakeholders are involved in the collection, creation, and use of disaster data, making it difficult to integrate different data sources and perform comparative analyses [18]. These challenges have resulted in an identified need to establish principles and standards for data collection, recording, reporting, exchange/sharing, and comparability [25]. This

Abbreviations: IFW, Impact Forecast and Warning; HIVE, Hazard, Impact, Vulnerability, and Exposure; DRR, Disaster Risk Reduction; IRDR, Integrated Research on Disaster Risk; EWS, Early Warning System; NHP, Natural Hazards Partnership; LINZ, Land Information New Zealand; NZTA, New Zealand Transport Agency; NMS, National Meteorological Service; ES-GT, Evolved-Straussian Grounded Theory; CDEM, Civil Defence and Emergency Management; EM, Emergency Management; NEMA, National Emergency Management Agency; GNS Science, Institute of Geological and Nuclear Sciences Limited; NIWA, National Institute of Water and Atmospheric Research Limited; NZGIS4EM, New Zealand Geographic Information Systems for Emergency Management; GIS, Geographic Information Systems; COP, Common Operating Picture; CAP, Common Alerting Protocol; FENZ, Fire and Emergency New Zealand; IDSS, Impact-based Decision Support System.

* Corresponding author at: GNS Science, 1 Fairway Drive, Avalon, Lower Hutt 5011, New Zealand.
E-mail addresses: s.harrison@gns.cri.nz s.harrison@massey.ac.nz (S.E. Harrison), s.potter@gns.cri.nz (S.H. Potter), r.prasanna@massey.ac.nz (R. Prasanna), e.e.hudson-doyle@massey.ac.nz (E.E.H. Doyle), d.m.johnston@massey.ac.nz (D. Johnston).

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introduces the concept of data governance for disaster data [12,45,56], particularly with regards to data custodianship, stewardship, and sharing [69,86].

Building on recent research where we identified the data needs, uses, and sources of HIVE data for implementing hydrometeorological IFW systems in Aotearoa-New Zealand (see [34,35]), we aim to develop further understanding around managing and accessing these data sources. We begin by presenting background on data governance and management, and data access and sharing, where data accessibility can affect data sharing [64].

1.1. Data governance

Data governance is an emerging field of research, with no agreed-upon definition [1]. We adopt the definition provided by Benfeldt et al. [7] where "data governance refers to the organisation and implementation of rules and responsibilities, which enforce decision making and accountabilities regarding an organisation's data assets" (p. 299). This is different from data management, which focuses on defining the data element, and how it is stored, structured, and moved [1]. Thus, data governance is argued to be a higher level of "planning and control over data management" ([1], p. 841).

There has been little mention of governance for disaster loss data in the disaster risk reduction (DRR) literature, except when it is pointed to as a need to improve data quality, access, sharing, and interoperability (e.g., [12,45,56]). Clarke et al. [12] proposed that data governance and independence be established for "strengthening and protecting data quality through national statistical offices that are functionally autonomous from other government agencies" (p. 4). Migliorini et al. [56] identified a lack of appropriate data governance arrangements to be impeding data access for DRR. Similarly, Li et al. [45] identified issues around data governance when using population health data for disaster risk research. In Aotearoa-New Zealand, Crawford et al. [14] identified challenges with risk data collection due to unclear roles and responsibilities for doing so. Beyond these examples, we could not find studies that specifically investigated disaster data governance, despite the apparent need to establish appropriate data governance measures for improved data quality, sharing, and integration.

One element of data governance involves assigning roles and responsibilities, including decision rights and accountabilities, around how the data is managed, secured, validated, and made available [1,2,7]. Two such roles are data stewardship and data custodianship [86]. Often these roles may be confused or merged, however, they have distinct roles and responsibilities, discussed next.

1.1.1. Data stewardship and custodianship

Data stewardship and data custodianship relate to roles for managing data. In the context of health data, data stewardship consists of developing methods for "acquisition, storage, aggregation, deidentification, and procedures for data release and use" ([72], p. 1444). Similarly, the New Zealand (NZ) Government defines a data steward as an agency that operates at the systems and strategic level and promotes good practice to manage the data over its lifecycle, including planning and adjusting for technological obsolescence and long-term preservation and access [50,73]. Related, but distinct roles, are data custodians. For NZ government data these custodians are agencies that implement the data management practices stipulated by data stewards in daily practice [73] to ensure the quality and accessibility of the data [50].

In Aotearoa-New Zealand, several agencies have a data stewardship and/or custodianship role. Toitū Te Whenua Land Information New Zealand (LINZ; the government agency responsible for managing land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, etc.) provided a *Steward and Custodian Framework for New Zealand Fundamental Geospatial Themes and Datasets*, to outline the responsibilities and expectations of appointed custodians and stewards of fundamental geospatial data (see [50]). LINZ also provided a partner document outlining the process of identifying and selecting fundamental geospatial data (see [49]). In summary, datasets are proposed to the New Zealand Geospatial Office for evaluation against a set of criteria to classify it as a fundamental geospatial dataset [49]. Fundamental geospatial datasets are "datasets that provide the minimum core set of nationally-significant data that are critical to the effective running of [Aotearoa-New Zealand], and work together to help support growth in the economy" ([49], p. 4). Most of these fundamental geospatial datasets are not considered disaster datasets as they do not convey disaster losses, impacts, or risks. However, much of these underlying datasets can inform vulnerability and risk assessments when used in risk models and overlaid with hazard data to determine exposure (see [34,35]).

The fundamental geospatial datasets identified by LINZ are labelled as either Suggested (i.e., the agency suggested by LINZ has not yet agreed to the role and may not have been approached yet), Proposed (i.e., the suggested agency has agreed to the role but the commitment has not yet been formalised), Appointed (i.e., the proposed agency has formally committed to the role), or Not Evaluated (i.e., the datasets were proposed as fundamental datasets but were not yet evaluated to determine their status) [49]. For example, the Waka Kotahi New Zealand Transport Agency (NZTA) is the proposed custodian for the leadership and delivery of the national road network, while local government and territorial authorities are the suggested respective leadership and delivery custodians for council roads. Leadership Custodians ensure that appropriate data management policies and standards are developed while Delivery Custodians are "responsible for the continued physical existence, availability, and integrity of the dataset" for as long as is required by the leadership custodian ([50], p. 25).

Like disaster data governance, there is little mention of the stewardship of disaster data in the literature. This gap has been identified by Fakhruddin et al. [24] who identified the need for building capacity in data collection and stewardship to support reporting to the Sendai Framework, an international accord outlining global priorities for disaster risk reduction (DRR) [81]. Another challenge faced in DRR is accessing and sharing the required data [23] for emergency/disaster response, risk analysis (e.g., risk modelling and risk assessments), vulnerability assessments, and supporting IFWs [14,34,35].

1.2. Data access and sharing

Many stakeholders are involved in DRR who collect, produce, and manage their datasets. Access to and sharing of these datasets is necessary for DRR [24]. For example, in places like Europe with many countries sharing borders, it is important to be able to share data across borders [16]. Within a country, sharing data is important since, in many cases, disaster and risk data are collected by different agencies [34,35]. Data access refers to the retrieval and storage of data provided by the data holder and may be subject to technical, legal, and/or organisation requirements [64]. Data sharing is the voluntary provision of data by the data holder, including commercial and non-commercial conditional data sharing agreements [64]. Data accessibility is a spectrum, ranging from closed data to open data, and affects data shareability [64]. Data sharing is a socio-technical activity as it involves various parties forming data-sharing partnerships and technical systems to support integrating multiple datasets.

1.2.1. Organisational aspects of data access and sharing

Sharing disaster and risk data requires building partnerships between data stakeholders [23]. The Natural Hazards Partnership (NHP) is an example of a formal partnership developed in the UK between public agencies to improve disaster management across the country, including sharing data between the various agencies [36]. Building the NHP required extensive time, coordination, communication, and interaction between agencies [36].

Multi-organisational collaboration is wrought with challenges [74]. Building trust and increasing the willingness of organisations to participate is the first hurdle to overcome [74]. After this, new challenges include mutually identifying goals and objectives and agreeing on timelines, uses of differing terminology and epistemologies, legal issues around intellectual property, and developing workflows and communication standards [74]. These early stages of scouting and building trust can take years [74]. Sustaining collaboration (e.g., maintaining interest and securing funding sources) remains an ongoing challenge [36,74]. In addition to building partnerships to share data, technical solutions are needed to enable data integration.

1.2.2. Technical aspects of data access and sharing

Data integration and interoperability are important, yet challenging, technical factors that support data sharing for DRR [23]. Disaster and risk data are available in countless formats, making integration difficult [39]. Thus there is a need to understand the various data sources and how they can be effectively and efficiently used [39].

Interoperability is a familiar challenge for both Early Warning Systems (EWSs) and data sharing and integration [10,38]. Interoperability issues for EWSs emerged as technological advancements led to a plethora of warning delivery mechanisms [10]. The Common Alerting Protocol (CAP) was proposed to set standards for warning design and delivery [10]. The CAP relies on standardising warning data for sharing across platforms [63,71]. The introduction of IFWs further adds to the challenge of standardised data exchanges [41,70].

In Aotearoa-New Zealand the Canterbury earthquakes from 2010 to 2011 laid bare gaps in interoperability for data sharing during and after the disaster, and the need for standards-based interoperability for improved information and data management [79]. Furthermore, the NZ Civil Defence and Emergency Management (CDEM) sector is striving towards a Common Operating Picture (COP) in which all agencies and stakeholders involved in an event can access and view the same information [17]. This involves developing standards and capabilities for enabling access to and sharing of datasets [79].

Harrison et al. [34,35] identified and reported the various sources for HIVE data for hydrometeorological hazards in Aotearoa-New Zealand. While the data sources were identified, more understanding is needed around managing and accessing these data both for IFW systems and for general DRR [34,35].

The objectives of this research are to identify and understand the governance and acquisition process for hazard, impact, vulnerability, and exposure (HIVE) data for hydrometeorological hazards in Aotearoa-New Zealand, to support efforts to fulfil the Sendai Framework priorities around disaster data access and to support the implementation of a hydrometeorological IFW system.

2. Research methods

We used a qualitative approach to address the research question, specifically employing the Evolved-Straussian Grounded Theory (ES-GT) research strategy for data collection and analysis [13]. Interviews, workshops, and key documents were the primary data sources. Between November 2018 and April 2021, the lead author interviewed thirty-nine ($n = 39$) experts in weather forecasting, warning, emergency management, risk modelling, and data collection and management (see [35] for more information on the participant details). Three virtual workshops were held in Aotearoa-New Zealand. Two of these workshops involved Emergency Management (EM) practitioners, weather forecasters, communication and data specialists, and hydrologists from the Auckland ($n = 4$) and Southland ($n = 5$) Regions. The third workshop involved a portion of the NZ risk and hazard science community based at GNS Science ($n = 11$). Thus, 59 people participated in this research.

Interview questions and workshop activities focused on themes regarding IFW data needs and sources. We asked for participants' general thoughts on IFWs; what impact, vulnerability, and/or exposure data they use or need, why, and how; the life path of the data; experienced and/or perceived challenges obtaining data required for IFWs and other uses; and thoughts on collecting and using alternative data sources (e.g., social media and crowdsourcing). Findings around data governance and acquisition are reported in this paper.

This research was collected under a 'low risk' ethics notification with the Massey University Human Ethics Committee. All interviewees remain anonymous and are assigned an alphabetic code (A, B, C, etc.), being identified only by the area of expertise and/or practice, industry, location, or governance level (Table 1). Interviews were audio-recorded and transcribed verbatim, and qualitative analysis (including coding and memo-writing) followed the axial coding paradigm according to the ES-GTM [13], using NVivo 12 qualitative analysis software [8].

Per ES-GT, analysis of the interviews, workshops, and documents followed the open coding (assigning concepts and categories to an instance of the data by line or by word), axial coding (relating categories to each other with optional guidance from the coding paradigm), and selective coding (relating all categories to a core category) stages [77]. The coding paradigm introduced by Strauss and Corbin [77] supported the axial coding stage whereby the codes created from the open coding stage were related to the coding paradigm dimensions (Table 2) for increased density and precision.

Additional techniques were used to support the ES-GT analysis, including regular memo-writing, diagramming, and constant comparison [29]. When the lead author noticed common themes in the interview and workshop data, a memo was written to identify the theme and discuss its relation to other concepts or themes (i.e. constant comparison) [13,29]. Diagramming was used to draw out linkages or relationships between the emerging themes. This was an iterative process that occurred during the data collection and analysis.

From the axial coding process (summarised in Table 2), two phenomena related to data management and acquisition of hazard, impact, vulnerability, and exposure data were identified. Phenomena are the subjects or objects under study [77]. Impact forecasts and warnings and HIVE data were identified as the overarching phenomena being studied in this research. As data collection and analysis progressed, the two phenomena that became the focal point of this manuscript were identified from the themes that emerged in the interviews, memo-writing, diagramming, and constant comparison techniques previously described. These two phenomena are: (1) The Roles and Responsibilities of Data Custodianship, and (2) Data Access and Sharing. These are discussed next.

3. Findings and discussion

The two phenomena (The Roles and Responsibilities of Data Custodianship and Data Access and Sharing) were succinctly summarised by an NZ-based risk modeller, who said:

> I think it really comes down to … sharing and collaboration … and I think there are good efforts, but … often things get snagged in … a privacy or confidentiality or legal issues with the datasets, who owns them, who maintains them, how can you rely on them … And the amount of work that is required to produce and maintain a reliable dataset is massive, it's just so much work that people don't want to do it. It costs money, it costs time, and … being a custodian of a dataset is not really an enviable position, necessarily. I think that's probably one of the biggest barriers (Risk Modelling NZ. A).

These two phenomena (the roles and responsibilities of data custodianship, and data access and sharing) will each be discussed in turn.

3.1. The roles and responsibilities of data custodianship

Amongst participating agencies and countries, it remains unclear as to who is responsible for maintaining datasets for IFWs:

> … it's a little bit about our traditional remits just being on the hazards information and so insurance companies and other areas are associated with damage and loss. And now … the challenge is accessibility to the data. So, we don't necessarily need to or want to become custodians of new data sets, we're just keen, if someone's got it organised and has it, to be able to … bring it together with our hazard information and our

Table 1
Interviewee codes.

Interview Code	Position	Classification	Location	Government Level
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ	National
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ	National
Data Management Private NZ. B	Geospatial Specialist	Data Management	NZ	Private
Data Management Research NZ. C	GIS Specialist	Data Management	NZ	Private
Data Management Private NZ. D	GIS Specialist	Data Management	NZ	Private
Data Management Gov. NZ. Nat. E	Head of Data	Data Management; Governance	NZ	National
EM. NZ. Reg. A	Director	Emergency Management	NZ	Regional
EM. NZ. Reg. B	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. C	Controller	Emergency Management	NZ	Regional
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ	Regional
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ	Regional
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ	National
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Nat. I	First Responder	Emergency Management	NZ	National
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ	National
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ	Regional
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ	Regional
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ	Regional
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ	Regional
Hyd. Gov. NZ. Reg. A	Flood EWS Programme manager	Hydrology; Governance	NZ	Regional
Interview Code	Position	Classification	Location	Government Level
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ	Regional
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ	Private
Met. Int. A	Science Manager	Meteorology	International	National
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	International	National
Met. Int. C	Senior Policy Officer	Meteorology	International	National
Met. Int. D	Senior Social Scientist	Meteorology	International	National
Met. Int. E	Consultant Meteorologist	Meteorology	International	National
Met. NZ. F	Senior Meteorologist	Meteorology	NZ	National
Met. NZ. G	Communications	Meteorology	NZ	National
Met. NZ. H	Public Relations	Meteorology	NZ	National
Met. Int. I	Division Chief/Meteorologist	Meteorology	International	National
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ	National
Met. NZ. K	Senior Meteorologist	Meteorology	NZ	National
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ	Private
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ	National
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ	National

forecasting capability (Met. Int. B).

The responsibility and cost of collecting and storing HIVE data were concerns for participants. Many of the agencies' remits do not include data custodianship, and it would be a costly undertaking, with the uncertainty of maintaining funding (Met. Int. B; Met. NZ. F).

While the literature has pointed to Emergency Management (EM) agencies for collecting impact information (e.g., [44,70]), we found that the participating NZ-based EM agencies indeed collect impact information, but they often do not systematically collect it or store it (EM. NZ. Reg. A, B). These findings corroborate those of Crawford et al. [14], who found that EM agencies and councils in Aotearoa-New Zealand were not clear on who was responsible for collecting risk data. For example, regarding the NZ National Loss Database under development by the National Emergency Management Agency in Aotearoa-New Zealand (NEMA), our participant indicated that NEMA is not a designated data custodian in NZ, and as such, they have been grappling with learning proper data management protocols (EM. Gov. NZ. Nat. G). This raises questions around who is most suitable for managing and acting as the steward and/or custodian of the data.

Several data custodians were identified in passing during our interviews, which align with some that have been identified by LINZ [49], such as LINZ, the NZTA, and local councils. For example, a risk modeller who was involved in collecting building asset information for the 2011 Canterbury earthquake recovery described how maintenance responsibilities for these data were transferred to LINZ due to privacy concerns:

> because there's some personal information in the database … that we didn't pay attention [to] previously … but to protect us from now on, we say 'okay this is the data we give [to] LINZ, you guys take the data … and you … decide if you want to share the data or not' (Risk Modelling NZ. B).

Similarly, for the development and management of the NZ National Loss Database, NEMA has turned to Statistics New Zealand (typically referred to as Stats NZ, New Zealand's national statistics agency) for guidance on proper data management protocols:

Table 2
Coding paradigm summary(from Harrison et al., In Press).

Coding Paradigm Dimension	Description
Causal Conditions	A set of events that influence the phenomena or result in the appearance or development of a phenomena [77,82].
Phenomena	The subject or object under study [77].
Contextual Conditions	The specific set of conditions and characteristics surrounding the phenomena and resulting in action/interaction strategies taken to address the phenomena [77,82].
Intervening Conditions	Unexpected events or factors leading to action/interaction strategies (e.g., time, space, culture, socioeconomic status, technological status, history) [77,82].
Action/Interaction Strategies	Purposeful and deliberate acts taken to address the phenomena [77,82].
Consequences	Predictable or unpredictable, intended or unintended outcomes of the action/interaction strategies [77,82].

> Stats NZ … have helped us think about this, but it's their business. So, for example, we talked about data management, and they talked about, 'okay if you're holding that data then you need to run an integrity test, that your data hasn't become corrupted, and you do that every [so often]. And you've got enough backups' and all that … but we haven't got an explicit data management policy around ensuring it's not corrupt, its integrity … change controls, and all that tracking; that's not what we do (EM. Gov. NZ. Nat. G).

In addition to being the national statistics agency for Aotearoa-New Zealand, Stats NZ also became the lead agency for government-held data in 2017 [75]. In this leadership role Stats NZ acts as a facilitator to support government agencies in building their capabilities and data management practices [75]. Thus, their help in guiding NEMA towards proper data management practices for the National Loss Database aligns with their role as the lead for government data. The Stats NZ website[1] provides further guidance on principles for safe and effective use of data and analytics, data stewardship, data standards, open data, etc.

Several of the HIVE datasets that were identified by Harrison et al. [34] have been classed as fundamental geospatial datasets by LINZ and have an appointed, proposed, or suggested data custodian and steward. Table 3 presents the Suggested (S), Proposed (P), or Appointed (A) Stewards and Custodians of the HIVE data sets identified by Harrison et al. [34] from our interviews as designated by LINZ [49]. The results in Table 3 are based on an analysis of two LINZ documents regarding data custodianship (see [49,50]).

The results in Table 3 show that stewardship/custodianship for most of the underlying datasets for hazards, vulnerability, and exposure have been identified by LINZ and are either Suggested (S), Proposed (P), or Appointed (A), while there is a clear a gap in the stewardship/custodianship of impact data, as shown by the number of 'N/A' entries for these datasets. This, in conjunction with our interviews, shows the need for establishing data management protocols and practices for impact data, including identifying potential data stewards and custodians for these data, such that the data can be accessed by and shared with other relevant users.

3.2. Data access and sharing

Data access and sharing was the next phenomenon identified in our data analysis. The ES-GT coding paradigm was applied to understand the causal and intervening conditions, and action/interaction strategies for data access and sharing, as shown in Fig. 1. As discussed by Harrison et al. [34],[2] disaster/emergency events, technological advancements, and research were identified as the causal conditions to data collection and data access and sharing. For example, sharing data was required for the response to the 2019 Pigeon Valley fires in Nelson, NZ, yet organisational and technical issues impeded the data sharing process (Data Management Gov. NZ. Nat. A). However, as shown in Fig. 1, intervening conditions can inhibit data sharing and access while several action/interaction strategies have been identified as capable of addressing these intervening conditions. These conditions and strategies will be discussed next.

3.2.1. Organisational aspects of data access and sharing

Trust and distrust, and privacy and security were identified as organisational intervening conditions affecting data sharing. Building partnerships was identified as an organisational action/interaction strategy to address these intervening conditions. These will be discussed next.

3.2.1.1. Trust and distrust as intervening conditions. Trust is a key element to data use and access. While Harrison et al. [34] identified the importance of trust in the data for IFWs, here we found the need for trust between agencies to be an important condition for data access and sharing, as summarised by an NZ risk and data specialist:

> There's a lot of suspicion between institutions in New Zealand as to what people are doing things for and why and with this comes patch protection. This is an important point and that it inhibits risk awareness, collaboration and our risk management as a country (Data Management Private NZ. D).

The management of the NZ Flood Pics[3] crowdsourcing platform and access to its resulting data is an example of an initiative established to avoid suspicion and lack of institutional trust, according to one of our interviewees (Data Management Private NZ. D). They described that NZ Flood Pics was developed independently from any institutions, and there is an aversion to tying the platform to any single institution even though that would make available the resources needed to sustain the platform. This aversion stems from the need for the data to remain open and separate from any "ulterior motives" (Data Management Private NZ. D). They indicated that institutionalising the platform may give the impression that there is an agenda with the use of the data, which could make people wary to contribute to it. At the time of conducting this interview, the costs and resources needed to sustain the platform remained such that the participant was seeking collaborating support and buy-in from multiple sectors with the requirement of keeping the data openly accessible. An update has since been provided by this participant that NZ Flood Pics is now in the process of being institutionalised with the Natioanl Institute for Water and Atmospheric Research (NIWA; a Crown Research Institute in New Zealand) with an agreed set of principles for how the data will remain open and accessible for "anybody to add value" (Data Management Private NZ. D).

Institutional involvement and open access to and sharing of citizen science data are growing areas of interest in citizen science research. The type of organisation involved in citizen science projects appears to influence people's willingness to participate and contribute their data [3]. For example, Martin et al. [51] found that contributors to a marine citizen science project in Australia showed a very high willingness to share data with research organisations, but less so with private research companies or consultants. Additionally, contributors seem to care about how the data they contribute is shared: Ganzevoort et al. [27] found that surveyed citizen scientists do no support unconditional data sharing, rather their acceptability of sharing the data with third parties depends on the goals of the data user. Moreover, Groom et al. [31] argue that the motivations of citizen scientists to contribute their data should align with the accessibility of the data for other uses. Thus, it is important to invest in data policies and transparency efforts to protect the interests of the contributors and ensure their continued engagement [3].

Participants indicated that some agencies who collect impact data were also found to be averse to sharing the data due to its sensitive nature and distrust in how such data could be used (Met. Int. D; Risk Modelling NZ. A; Loss Modelling Research NZ. A). As one loss modelling participant from Aotearoa-New Zealand outlined, not all agencies are willing to publicly share their data, such as a public insurance group that formed after the 2010–2011 Canterbury earthquake sequence (Loss Modelling Research NZ. A). As such, there is no guarantee that government/public organisations will want to, or can, make any of their data publicly available (Loss Modelling Research NZ. A).

This could be due to the sensitive nature of the data (Met. Int. D; Risk Modelling NZ. A). Certainly, in Aotearoa-New Zealand there are concerns around how releasing impact information could influence property values (Risk Modelling NZ. A). In Argentina, our participant described how a provincial government would not share their impact data with the National Meteorological Service (NMS) because of the political nature of the data:

[1] https://www.stats.govt.nz/about-us/data-leadership. Accessed 20 December 2021.

[2] The results of Harrison et al. [34] are presented in a similar fashion using the ES-GTM Coding Paradigm to analyse the causal conditions, intervening conditions, and action/interaction strategies pertaining to the Data Collection phenomenon. As such, a similar figure is presented here, but pertaining instead to the Data Access and Sharing phenomenon.

[3] www.nzfloodpics.co.nz. Accessed 20 December 2021.

Table 3
Suggested (S), Proposed (P), or Appointed (A) Stewards and Custodians of the HIVE data sets identified by Harrison et al. [34] from our interviews as designated by LINZ [49]. N/A is used for datasets that were not proposed as fundamental datasets (note that any person or agency can propose a fundamental geospatial dataset [49]), and thus a steward and custodian was not identified. The number of N/A entries demonstrates a lack of direction for managing impact data.

	Dataset	Status	Steward	Leadership Custodian	Delivery Custodian
Hazard Data	Weather stations (rain gauges, anemometers, etc.)	N/A	N/A	N/A	N/A
	Radar data	N/A	N/A	N/A	N/A
	Satellite imagery & observations	Fundamental, Not evaluated	LINZ (A)	LINZ (S), NZDF (S), TAs (S), Police (S)	LINZ, NZDF, TAs, Police, MfE, Landcare (S)
	River height and flow gauges	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S)	RCs (S)
	Float gauges/Sea level data	N/A	N/A	N/A	N/A
	River networks	Fundamental	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S)
	Vertical Rain Radar	N/A	N/A	N/A	N/A
	Regionwide floodplains	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S), GNS (S), RCs (S), TAs (S)
	Overland flow paths	N/A	N/A	N/A	N/A
	Coastal inundation Maps/Hazards	Not evaluated	Steward Committee (S) or MPI (S), DoC (S)	MfE (S)	RCs (S), GNS (S)
	Pollen Counts	N/A	N/A	N/A	N/A
	Slope	N/A	N/A	N/A	N/A
	Camera feeds	N/A	N/A	N/A	N/A
	Social media (Tweets, Facebook post comments)	N/A	N/A	N/A	N/A
	Crowdsourcing (e.g., volunteer rain gauges, NZ Flood Pics)	N/A	N/A	N/A	N/A
	Dataset	Status	Steward	Leadership Custodian	Delivery Custodian
Impact Data	Social media (Tweets, Facebook post comments, SnapChat)	N/A	N/A	N/A	N/A
	Crowdsourced Photos via Story Maps (e.g., NZ Flood Pics)	N/A	N/A	N/A	N/A
	Crowdsourcing/Public Reporting	N/A	N/A	N/A	N/A
	Red Cross Chained Crowdsourcing	N/A	N/A	N/A	N/A
	Emergency call centre reports	N/A	N/A	N/A	N/A
	Community volunteer radio calls	N/A	N/A	N/A	N/A
	Damage surveys	N/A	N/A	N/A	N/A
	Media reports	N/A	N/A	N/A	N/A
	Tacit knowledge, experience, intuition	N/A	N/A	N/A	N/A
	Health & Injury Data	N/A	N/A	N/A	N/A
	Wellbeing Surveys	N/A	N/A	N/A	N/A
	Post-event interviews and surveys	N/A	N/A	N/A	N/A
	Insurance claims	N/A	N/A	N/A	N/A
	"Boots on the ground"	N/A	N/A	N/A	N/A
	Lifelines Sectors (e.g., power companies, NZTA)	N/A	N/A	N/A	N/A
	Situational Reports	N/A	N/A	N/A	N/A
	Post-event reports	N/A	N/A	N/A	N/A
	Operations Reports (Council)	N/A	N/A	N/A	N/A
	Flood event reporting	N/A	N/A	N/A	N/A
	Injuries and fatalities (e.g., cause of death)	N/A	N/A	N/A	N/A
	Cultural and heritage/historical impacts	N/A	N/A	N/A	N/A
	Impact Model outputs	N/A	N/A	N/A	N/A
	NZ National Loss Database	N/A	N/A	N/A	N/A

	Dataset	Status	Steward	Leadership Custodian	Delivery Custodian
Vulnerability Data	Vulnerability Assessment and Risk Modelling Outputs	N/A	N/A	N/A	N/A
	Asset information - Building footprints	Fundamental	LINZ (A)	MBIE (S)	TAs (S), NZFS (S), MBIE (S)
	Asset information - Historically and Culturally Significant Sites	Not evaluated	Steward Committee (S) consisting of LINZ (S), LGNZ (S), Emergency Services (S)	LINZ (S), LGNZ (S)	LINZ (S), TAs (S), Private Sector (S)
	Building damage assessments		N/A		
	Census data - meshblocks	Fundamental	Stats NZ	Stats NZ	Stats NZ
	Tacit knowledge, experience, intuition	N/A	N/A	N/A	N/A
	Lab-based experiments	N/A	N/A	N/A	N/A
	Health Data, New Zealand Health Survey	N/A	N/A	N/A	N/A
	Soil/land stability	Fundamental	No Steward	LINZ (S), GNS (S), Landcare (S)	LINZ (S), GNS (S), Landcare (S)
	Infrastructure - NZ Road Network	Not evaluated	Ministry of Transport	NZTA (P)	NZTA (P)
	Infrastructure - Council roads	Not evaluated	Ministry of Transport	LGNZ (S)	TAs (S)
	Infrastructure - Water	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S), LINZ (S), RCs (S), TAs (S)

	Dataset	Status	Steward	Leadership Custodian	Delivery Custodian
Exposure Data	Asset information - Building footprints	Fundamental	LINZ (A)	MBIE (S)	TAs (S), NZFS (S), MBIE (S)
	Asset information - Historically and Culturally Significant Sites	Not evaluated	Steward Committee (S) consisting of LINZ (S), LGNZ (S), Emergency Services (S)	LINZ (S), LGNZ (S)	LINZ (S), TAs (S), Private Sector (S)
	Infrastructure - NZ Road Network	Not evaluated	Ministry of Transport	NZTA (P)	NZTA (P)
	Infrastructure - Council roads	Fundamental	Ministry of Transport	LGNZ (S)	TAs (S)
	Infrastructure - Power - Electricity	Not evaluated	No Steward	Transpower (S)	Transpower, Lines Companies
	Infrastructure - Utility Networks	Not evaluated	No Steward	MCDEM/NEMA (S)	Utility Companies (S)
	Infrastructure - Water	Not evaluated	Steward Committee (S) or MPI (S), MfE (S)	MfE (S), LINZ (S)	NIWA (S), LINZ (S), RCs (S), TAs (S)
	Census data - meshblocks	Fundamental	Stats NZ	Stats NZ	Stats NZ
	Population movement via cell phone data	N/A	N/A	N/A	N/A
	Tacit knowledge, experience, intuition	N/A	N/A	N/A	N/A
	Topographical data, e.g. digital elevation models	Not evaluated	No Steward	MfE (S), LINZ (S)	Landcare (S), LINZ (S)
	Land-use and planning zones	Not evaluated	No Steward	LGGA (S), LGNZ (S)	TAs (S), RCs (S)
	Land-use maps	Fundamental	No Steward	MfE (S)	MfE (S)
	Community events	N/A	N/A	N/A	N/A

The acronyms in Table 3 are as follows: Land Information New Zealand (LINZ), New Zealand Defence Force (NZDF), Territorial Authorities (TAs), Ministry for the Environment (MfE), National Institute of Water and Atmospheric Research Limited (NIWA), Ministry of Primary Industries (MPI), Institute of Geological and Nuclear Sciences Limited (GNS Science), Regional Councils (RCs), Department of Conservation (DoC), Ministry of Business, Innovation and Employment (MBIE), Local Government New Zealand (LGNZ), Statistics New Zealand (Stats NZ), New Zealand Transport Agency (NZTA), National Emergency Management Agency (NEMA, formerly MCDEM), Local Government Geospatial Alliance (LGGA)

> I was working with the province of [redacted] … and we implement[ed] this [data collection] form as a final project, and when I [said] 'okay, I want the data' they [told] me 'okay, we will give you the infrastructure data but no data about deaths' … And I was like 'hey, no. That's not fair.' Why? Because it's political data! Who live and who die during a storm: that's political data, because it has to do with vulnerability and people here [are] very vulnerable. That's why I say that impact data is political data (Met. Int. D).

This finding aligns with those from Harrison and Johnson [33], where Canadian emergency managers showed concern about displaying heavily damaged areas online via crowdsourcing platforms for emergency response. However, as shown in the above quote, the political nature by which the impact data in Argentina is perceived adds another layer beyond simply showing concern for the privacy and security of people and assets during an emergency. Viewing impact data as a threat to how government response agencies and their response capabilities are perceived indeed introduces a political element that inhibits the global movement for open and collaborative data sharing for improved DRR.

The consequences of restrictive data access and lack of information sharing for DRR can lead to disastrous consequences, as was seen in the USA following the landfall of Hurricane Katrina in 2005 [68]. Yet, our findings show that data creators and users remain reluctant to share critical

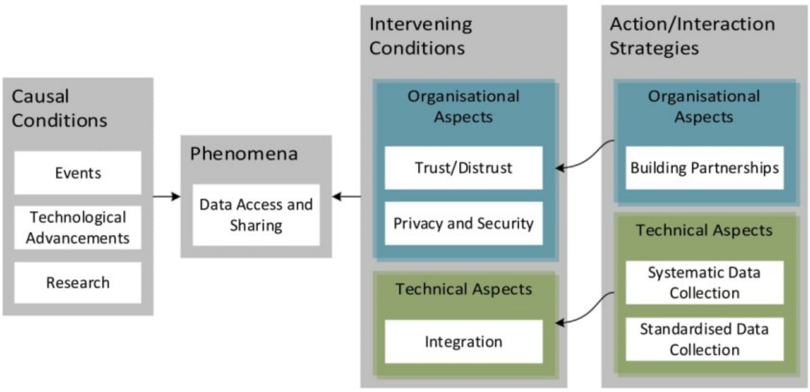

Fig. 1. Summary of findings relating to the causal conditions, intervening conditions, and action/interaction strategies relating to data access and sharing, identified using the ES-GTM coding paradigm. Blue boxes represent organisation aspects and green boxes represent technical aspects.A socio-technical lens was applied to the analysis to identify both organisational aspects to the intervening conditions and action/interaction strategies and the technical aspects. The following results are separated accordingly, and further partitioned into intervening conditions (i.e., Trust/Distrust, and Privacy and Security as organisational intervening conditions, and Integration as a technical intervening condition), and action/interaction strategies (i.e., Building Partnerships as an organisational action/interaction strategy, and Systematic and Standardised Data Collection as technical action/interaction strategies). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

information. In addition to the concerns around the political nature of the data as described above, this aversion to sharing may be due to interagency competition over resources, influence, and autonomy [68], and/or loss of control over the datasets [6].

Trust is an essential factor in multi-agency collaboration and data sharing, especially for disaster response [21]. Our findings further illustrate the importance of trust to facilitate data access and sharing through interagency collaboration for DRR [42]. The importance and value of opening and sharing disaster-related data cannot be denied, and it is possible to establish open data access and sharing for DRR. For example, local, provincial, and national agencies, and regional and national academic and research institutions in Argentina worked together to establish an open data platform for flood impact reduction, "with a view to socializing knowledge for early alerts" ([15], p. 86). Thus, agencies must continue to build and nurture trust between each other to facilitate data and information sharing.

Traditional media outlets may be one party not tied to the political influence and privacy and security concerns of sharing data, and play a major role in disseminating information during a disaster [30,59]. For example, in Aotearoa-New Zealand, the MetService usually has "a conversation with media" about their official warning message and provides examples of impacts along with the warning message to add meaning and context to the warning. The media then passes on this information to the public (Met. NZ. G, K).

Media outlets and reports can be a timely data stream for information during a disaster [59]. They can even provide new information that might not otherwise be picked up or observed elsewhere. For example,

> there might be a report of … a motorcyclist blown off a piece of road or something. But there might not be any weather observations for miles in any direction that support that. So, then you have to go and look for corroborating evidence somewhere else, and how much do you trust the source? (Met. NZ. K).

However, as this example suggests, while media reports can bring new information to light, the new information still needs to be verified, as it might not always be accurate or true. Media outlets are both heavily reliant and influential on perceptions of trust and distrust during disasters [57]. In another example, a regional EM agency in Aotearoa-NZ received crowdsourced reports on their public online story map of a van "stuck in the centre of the Hokitika River" (EM. NZ. Reg. F). The media picked up this report and publicised that "there's people trapped" (EM. NZ. Reg. F). The van was empty, and the EM agency had to re-upload the report themselves to include a note that the van was empty (EM. NZ. Reg. F).

The literature indicates that agencies elsewhere have reported difficulties with communicating with media outlets e [4,59]. In Aotearoa-New Zealand, the continuous conversations between the NZ MetService and the media described above exemplify a working relationship that ensures a unified message for informing people. In another example, the media provided "quite active and quite positive support" in the response and evacuation of a large-scale flood in Edgecumbe, Bay of Plenty by providing ample media coverage of the event and of the messages issued by the EM agency (EM. NZ. Reg. A). For media outlets and their resulting reports to be effectively used by their audiences, it is thus critical for them to build trusted relationships with those audiences, including members of the public, hydrometeorological services, and EM agencies. This could include developing a process or protocols for sharing data and information effectively.

3.2.1.2. Building partnerships as an action/interaction strategy. While NMSs are not typically responsible for collecting non-meteorological data, EM and flood management agencies, amongst others, collect or produce various types of impact data for their own purposes. Findings from the interviews, in support of existing literature (e.g., [36,84]), suggest that either formal or informal partnerships support data sharing for DRR. Continued collaboration to build and nurture partnerships has a positive relationship with trust [42], an important factor for sharing data. Under the NHP, previously describted in section 1.2.1 [36], the UK MetOffice can access useful datasets such as traffic count data from the transportation agency, for their impact models (Met. Int. A;).

In Aotearoa-New Zealand and other participating countries, no such formal partnership was found to exist that is comparable to the NHP in the UK. However, evidence of informal partnerships was found in Aotearoa-New Zealand and Australia. In both Aotearoa-New Zealand and Australia, NMS and EM officials frequently contact each other informally during an event to exchange more targeted forecasting information such as levels of uncertainty, and worst-case scenarios to help with planning responses (Met. Int. B; Met. NZ. F, K; EM. NZ. Reg. A, B, C, D, E, F; [35]). For example, as reported by Harrison et al. [35], the NZ MetService works together with local and regional EM groups and hydrologists to determine the most appropriate warning level. These informal partnerships are particularly useful for information-sharing and decision-making on-the-fly during an event.

A need remains for more formal partnerships to facilitate data sharing after response events (Risk Modelling NZ. A). However, progress in this space will be slow:

> there's lots of talk about data sharing and I think there's a general attitude in New Zealand moving towards greater collaboration, greater sharing. [But] a sort of central repository for any of this stuff within the next decade is absolutely not going to happen, or if ever … It's hard to get people to work together (Risk Modelling NZ. A).

The participant listed data ownership and proprietary licensing as key limitations to sharing data. Perhaps in the context of sharing HIVE data via a central repository as mentioned by the risk modeller (Risk Modelling NZ. A), progress will indeed be slow as this requires more in-depth understanding and legal groundwork to establish data ownership rights and protection of proprietary data (e.g., [11]; Risk Modelling NZ. A). However, like the informal partnerships between the MetService, EM groups, and council hydrologists to share hydrometeorological information for warnings, another informal partnership has been established to fill a gap in EM practice in Aotearoa-New Zealand, the NZ Geographic Information Systems for Emergency Management (NZGIS4EM) group.

The NZGIS4EM group formed in the mid-2010s to boost the use of geospatial tools, such as Geographic Information Systems (GIS) within the EM sector (EM. NZ. Reg. H; [34]). NZGIS4EM is a grassroots community of GIS specialists and EM practitioners in Aotearoa-New Zealand that work together to share data and tools during responses and to innovate the use of geospatial technologies for EM (EM. NZ. Reg. H; Data Management Private NZ. B; [34]). The community was formed from the leadership of one skilful individual who identified the need for geospatial innovation in the NZ EM sector, to enhance practices from relying on paper maps to using modern tools and technology (Data Management Private NZ. B).

The NZGIS4EM is credited with fostering a community of practice within the EM and GIS sectors, where relationships across agencies have been built and strengthened for a more coordinated disaster response effort (EM. NZ. Reg. H; Data Management Private NZ. B). In turn, this has driven innovation, knowledge sharing, and data sharing across Aotearoa-New Zealand (EM. NZ. Reg. H; Data Management Private NZ. B). Direct outcomes of this group's work are seen in the recent *Director's Guideline for Civil Defence Emergency Management Groups [DGL 22/20]* [60] and *Technical Standard [TS05/20] National Impact Assessments Data Set and Dictionary* [62], published by NEMA. In these documents, the use of GIS is heavily referenced, and NZGIS4EM aided in defining the standards presented in the *Technical Standard [TS05/20] National Impact Assessments Data Set and Dictionary* ([62]; Data Management Private NZ. B).

Our findings suggest that informal partnerships are developed to fulfil an immediate need, such as communicating hydrometeorological information for warning decision-making or building a community of practice for coordinated disaster response. This finding aligns with the ad hoc informal partnerships that formed in the response and recovery to the 2010–2011 Queensland floods, where such partnerships formed between public and private agencies for information sharing [5]. Furthermore, interorganisational networks facilitated by groups like the NZGIS4EM can be voluntary or mandated [43]; in the case of the NZGIS4EM group, it is a voluntary effort. Success factors of such networks have been identified as effective communication, trust and social capital, and learning and adaptation [43].

Formal partnerships appear to be less common, and not as easy to establish, as indicated previously (Risk Modelling NZ. A), particularly for severe weather hazards. However, formal partnerships have been developed in Aotearoa-New Zealand in the form of science advisory panels for natural hazard perils, such as the New Zealand Volcanic Science Advisory Panel [61], and the New Zealand Tsunami Advisory Group. The New Zealand Volcanic Science Advisory Panel works with area-specific volcanic advisory groups to coordinate planning for volcanic activity [61]. These groups were formed from a specific need that was either identified from local/national or international events (EM. Gov. NZ. Nat. J), to better communicate science advice by bringing the expertise from various scientific agencies together [20]. For example, the New Zealand Tsunami Advisory Group was established in response to the 2011 Tōhoku and 2004 Indian Ocean earthquakes and tsunami (EM. Gov. NZ. Nat. J). These groups differ from the UK NHP in that practitioners are not formally included in them and some of the groups' roles in response and providing formal advice are unclear. Partnerships and multi-agency collaboration are not new concepts in the EM literature (e.g., [65]). It is promising to see these growing examples of successful partnerships both within and outside of Aotearoa-New Zealand, be it formal and informal. However, more clarity is needed to establish the roles of these NZ-based groups for response and formal advice.

Strategies for building and nurturing partnerships and collaboration include networking (EM. Gov. NZ. Nat. J), professional development (EM. NZ. Reg. K; [21]), cohabitation [36], and multi-disciplinary collaboration (Risk Modelling NZ. C; [28]), which may or may not be supported by funding and top-down mandates (EM. Gov. NZ. Nat. J; [67]). Participants indicated that a mix of both bottom-up and top-down approaches to building and nurturing partnerships is applicable in the Aotearoa-New Zealand context (EM. Gov. NZ. Nat. J). For example, cohabitation between agencies like the MetService, CDEM Groups, and local/regional councils can be organised from the bottom-up between the agencies in question. However, some political direction such as a national mandate might be more effective at inciting nation-wide cohabitation practices (EM. Gov. NZ. Nat. J). Further exploration of these strategies will be explored in future research.

3.2.1.3. Privacy and security as an intervening condition. When it comes to sharing data for emergency response purposes, our participant from Fire and Emergency New Zealand (FENZ) identified the importance of protecting the response data. Much of their response data comes from NZ Police, who have very structured and careful security systems protecting their information (EM. NZ. Nat. I). As such, parties are working with the Privacy Commissioner to show that they can ensure the appropriate controls to protect the information, and in turn, there are also cultural challenges around the views of sharing information (EM. NZ. Nat. I). Our FENZ participant indicated that it is a matter of knowing staff members' behaviours and educating staff on why it is important to keep the data safe, while also safely sharing the information for effective response.

Safe and secure mechanisms for sharing the data are needed but are not always feasible. For example, our participant from Argentina indicated that they set up a Google Form to facilitate standardised data collection and sharing between the NMS and local government agencies, but they "have concerns … because … it is sensitive data [and] I don't trust … sending information through Google" (Met. Int. D). However, Google Forms was the most easily accessible tool that the local government agencies could handle (Met. Int. D). This demonstrates the need to have controls in place to maintain privacy and ensure data security.

3.2.2. Technical aspects of data access and sharing

Challenges around data integration were identified as a technical intervening condition affecting data sharing. Systematic Data Collection and Standardised Data Collection were identified as technical action/interaction strategies to address this intervening condition. These will be discussed next.

3.2.2.1. Data integration as an intervening condition. Sharing data is only successful when the data can be integrated seamlessly into existing systems and practices [56]. Findings from Harrison et al. [34] show that a wide variety of HIVE data for severe weather events exists. In many cases, the challenge lies not in identifying the data sources but in integrating all sources and types of data in a meaningful way (NMS. Int. A, E; NMS. NZ; EM. NZ Regional. A, B, E). This is summarised by an NZ risk modeller, "although we all complain about a lack of data, a lot of the time, there is quite a bit of data out there that could be used and isn't being used very well" (Risk Modelling NZ. A). For example, this participant identified struggles with integrating building data, which is typically stored as spatial point data, with meshblock data, which is stored as spatial polygons. They stated that matching these point and polygon data together

> can be the bigger barrier than the fact that the data does or doesn't exist. Because … it turns out it's really not easy to put those points in a polygon because … there's no basic way of doing that, it's complicated (Risk Modelling NZ. A).

Furthermore, our UK-based participant described how they would like to see

> an integration of different approaches [like] the use of satellite, the use of social media, the use of citizen science, the use of media, and the integration of media to help understand better the differences and the causes for different types of impact (NMS. Int. A).

Some data integration methods have been successfully implemented. For example, the NZ MetService receive council rainfall data and share warning data files to integrate into hydrological models. In Aotearoa-New Zealand, the West Coast EM agency primarily works online so they can share information in near-real-time with other agencies. But this is not standard practice across the country; gaps still exist in developing formal systems for data sharing and integration. A regional EM official elaborated on their challenges of linking up and integrating various data sources:

> I would like to see … some research in understanding what are the tools and systems that can be used for this? Because on one hand … if you sit around and everyone goes 'yeah, … we must share data' and … if we're going to plan for the future and everyone, different agencies hold different data about the same event, but how we're sharing that data? So, what is the system to do that? (EM. NZ Regional. A).

The Common Operating Picture (COP) is a solution currently under development in Aotearoa-New Zealand to allow cross-agency intelligence and data sharing during a response. The COP, a recommendation made following the 2010–2011 Canterbury earthquakes and other notable events (see [78]), is based on the idea of "everyone contributing to the scenario so that they've got to share, so that everyone's got access to that information" (EM. NZ. Reg. A); in other words, it is "a graphical visualisation of all the data available to make a decision" (Data Management Private NZ. B).

Phase one of the NZ COP programme began in late 2019 led by NEMA, when agencies involved identified the core national datasets needed for EM, and brainstormed how some of those datasets are shared, particularly geospatial datasets (EM. NZ. Reg. H). This required agencies to collaborate to identify different needs, highlighting the need for building trust and partnerships between agencies to facilitate data sharing.

Other solutions have been proposed and developed for improving data interoperability for integration. Horita et al. [38] developed a spatial decision support system (DSS) to integrate official and unofficial data for flood risk management in Brazil, showing that integration "provides more complete, accurate and updated information about the situation in the affected areas" ([38], p. 91).

Impact-based decision support systems (IDSS) offer a way for warning services to make effective decisions. An IDSS is "the provision of relevant information and interpretative services that enable partners to prepare for and respond, as planned, to extreme weather, water, and climate events for the protection of lives and livelihoods" ([80], p. 1928). In a case study comparison of two historic severe winter weather events in the USA with and without a formal IDSS, the IDSS was found to enable quicker and more complete forecast updates, such that emergency managers could relay information to appropriate agencies to take mitigative actions [40]. The IDSS also allowed for improved crafting of public and partner messaging, and for preparing public officials to decide to shut down infrastructure.

Similarly, an integrated analysis of social vulnerability to extreme precipitation in Colorado was carried out by Wilhelmi and Morss [83] using Geographic Information Systems (GIS). The process involved integrating radar-derived rainfall data and watershed boundaries with national census data and historical impact data. Challenges were faced with the differences in spatial-temporal scales between meteorological and social datasets, as well as the various formats in which the meteorological data were available [83].

3.2.2.2. Systematic data collection as an action/interaction strategy. Systematic data collection is a need highlighted by many participants as an action/interaction strategy for better data sharing and integration. Non-systematic data collection occurs when data is collected in various formats and stored in different places (e.g., [52]). Thus, we refer to systematic data collection as having a system in place to process data from raw state to a usable format and storing the data in one place for easy access.

Our participants indicated that systematic data collection would support evidence-based planning and decision-making for warnings and planning (Met. Int. A; Met. NZ. F; EM. NZ. Reg. B). For example, our participating UK-based NMS official highlighted the need for systematic impact, exposure, and vulnerability data collection to be able to understand the causes of impacts with empirical evidence and to be able to compare different impact models (Met. Int. A). In Aotearoa-New Zealand, a lack of systematic data collection severely impacted the organisation of intelligence and data gathered from event responses. For example, "back in 2011 [Canterbury earthquakes] … the capture of the data was so unstructured" (Data Management Gov. NZ. Nat. A); photos of buildings and letterboxes were not associated with dates or addresses, nor were they associated with damage and impact assessment forms used to capture information about the person and/or building (Data Management Gov. NZ. Nat. A). Consequently, an individual was "employed … for 18 months, just to take that photo and that building form and that welfare form and try to bring together a file on that family" (Data Management Gov. NZ. Nat. A). Had the data been collected in a more systematic way, "that information … would have been more informative at the time of the response and recovery" (Data Management Gov. NZ. Nat. A). Furthermore, systematic data collection would allow the sector to learn from past events and forecast potential future events by identifying impacts from events with similar meteorological signatures (Met. NZ. F; EM. NZ. Reg. B).

The COP previously mentioned provides a streamlined system for collecting, sharing, and managing impact data. However, much of this data does not have a shelf life beyond its initial purpose of building situational awareness for decision making during a response, because "from a Civil Defence perspective, whether it's local or regional, we don't need to keep the data, really. We'd probably keep it for two years and then say right, we're going to dispose of it because we don't need it" (EM. NZ. Reg. H). This also applies to welfare/wellbeing assessments, which are "very challenging, because there is a lot more private and personally identifiable information collected" (EM. NZ. Reg. H). As such, the EM agency will "probably … be even more aggressive about deleting that information once the event is over, to protect the people's privacy" (EM. NZ. Reg. H).

3.2.2.3. Standardised data collection as an action/interaction strategy. Standardised collection of data was another need highlighted by many interviewees. Standardised data collection facilitates systematic data collection by providing a set of standards at which the raw data is collected such that it can be seamlessly integrated into a database with minimal processing [16,26]. Standardised data collection would ensure all data is collected consistently for rigour and comparability [16,26]. Our interviewees identified a need to be able to compare datasets and warnings across countries and regions, such as in Europe (Met. Int. E). Likewise, data collection practices within Aotearoa-New Zealand, Argentina, and Australia differ regionally, making it difficult for regions to share data. In Australia, EM agencies collect post-event impact assessments, but the Australian NMS official indicated that this data lacks necessary fields for forecasting purposes (Met. Int. E). In Argentina, the NMS is working with EM agencies to build a process for collecting standardised impact data using Google Forms to benefit both agencies; the EM agencies will have trustworthy data, while the meteorological service will have data to support IFW implementation (Met. Int. D).

Our investigation into Aotearoa-New Zealand practice showed that several types of standard data collection forms are available for different purposes, whereby the standards/forms were designed by different agencies for various uses. For example, in 2006, the Hawke's Bay Regional Council commissioned the development of *Templates for Consistent Hazard Event Reporting* (herein referred to as the *Template*) with a focus on capturing the impacts of the hazard for use by EM agencies for research, risk modelling, and developing a hazards and impacts database [22]. Standardised data collection provided from this template would better facilitate the organisation and storage of impact and hazard data for further use and analysis. However, it is unclear whether this form is used by EM agencies or councils across Aotearoa-New Zealand, as no participants identified it as a resource that they use, yet it has potential for development going forward.

NEMA published an *Impact Assessments Director's Guideline for Civil Defence Emergency Management Groups* outlining the preparation requirements for conducting effective and efficient rapid impact assessments by response agencies to enable a coordinated approach across multiple agencies (see [60]). This document identifies the agencies responsible for conducting impact assessments for various purposes and at various phases. For example, EM agencies or local authorities are responsible for planning rapid impact assessments, while FENZ is "likely to be one of the first responding agencies to conduct a rapid impact assessment" ([60], p. 15) due to their specialised capabilities for collecting and sharing field data [60]. NEMA also provided forms for completing an initial situation overview, initial damage assessment, and impact report form. These assessments support response planning and coordination (EM. NZ. Reg. H). Furthermore, a companion document called the *Technical Standard [TS05/20] National Impact Assessments Data Set and Dictionary* [62] provides more technical information to support the consistent collection and recording of impact assessment data for easy cross-agency sharing and integration.

Our participants identified welfare needs assessments as another form of impact assessment (EM. Gov. NZ. Nat. G; EM. NZ. Reg. H; Data Management Gov. NZ. Nat. A; Data Management Private NZ. B), focusing on "understanding the needs of people affected by an emergency" ([55], p. 1). Guidelines have been published outlining the welfare needs assessment process (see [55]). These guidelines indicate that data is collected using "customised [EM agency]/local authority forms" ([55], p. 11).

For the built environment, the Ministry for Business, Innovation and Employment (MBIE) published field guides, assessment forms, and other learning resources for rapid building damage assessments for flooding, earthquakes, and geotechnical hazards such as landslips (see [54]). These resources are an outcome of lessons learned from the 2010–2011 Canterbury earthquake sequence, the 2011 Nelson storm, and the 2016 Hurunui/Kaikōura earthquake, and other international events [53]. These assessments are primarily used by councils via contracted building engineers to assess the building and land safety and usability immediately after an earthquake or flood (Risk Modelling NZ. B; EM. NZ. Reg. H; [54]), but are not suitable for impact/risk modelling because they are not designed for this purpose and are not sufficiently comprehensive (Risk Modelling NZ. B).

Alternatively, our risk modelling participant indicated that developing a "master building database" containing building attribute data pre- and post-disaster would be "ideal" (Risk Modelling NZ. B). The participant envisions the database holding building data for all purposes, populated before an event, and updated with damage information to the respective buildings using a unique identifier post-disaster (Risk Modelling NZ. B). Efforts on this project are currently underway at GNS Science in Aotearoa-New Zealand (see [48]).

The above assessments can be completed on paper, as has traditionally been done. However, a recent technological overhaul of the NZ CDEM sector (Data Management Private NZ. B) has introduced new tools for streamlining the collection and integration of these datasets (EM. NZ. Reg. F; EM. NZ. Reg. H; Data Management Private NZ. B). Much of the system has become location-based (Data Management Private NZ. B) using GIS technology [60]. For example, the "welfare system [has] moved from being quite a database and table-based system to a location-based system" (Data Management Private NZ. B), and now utilises tools like Survey123[4] for welfare needs assessments (EM. NZ. Reg. H). The West Coast example outlined by Stowell [76] provides more detail on how GIS has been used to streamline the CDEM impact assessment process.

Outside of impact data and the CDEM sector, other agencies have developed their own applications for conducting standardised information. For example, the Real-time Individual Asset Attribute Collection Tool (RiACT) was developed by risk modellers to capture real-time, geolocated, standardised asset information, such as building attributes (Risk Modelling NZ. B; [47,48]). The goal of this tool is to support an exposure data development framework whereby exposure data is systematically collected and stored for improved access, management, and use (Risk Modelling NZ. B; [47,48]).

While various standardised forms have been developed to capture hazard and impact data for various purposes, it would be beneficial to continue the systematic process of integrating the resulting data into a data repository for ease of access, sharing, and use beyond its initial purpose, depending on licensing and proprietary restrictions (e.g., [11]). Global efforts in the hydrometeorological hazard space are underway for building data repositories. For example, the HIWeather Value Chain Project under the World Weather Research Programme (WWRP) is currently building a catalogue of hydrometeorological events and their impacts to evaluate the end-to-end warning value chain [37]. Additionally, the World Meteorological Organisation (WMO) has established an initiative for cataloguing hazards and events through its members [19].

Strategies for building an integrated and multi-disciplinary data collection approach rely, again, on building and nurturing partnerships and collaboration. Collaboration allows data collectors and users from various disciplines to jointly define and scope problems for which the data is being collected, and identify the data types that are of interest to the problem [28]. For example, Harrison et al. [35] identified the need for including social scientists when designing post-impact assessments for risk modelling such that the modelling can extend into social and cultural impacts. For the aforementioned HIWeather Value Chain Project, an international multi-disciplinary task team of social scientists, meteorologists, and risk scientists was formed to co-develop the data collection template for the event catalogue [37]. Consideration of emergent technology would also help with identifying efficient data collection and integration tools, such as GIS-based technology (e.g., Survey123), mobile devices, unmanned aerial vehicles (e.g., drones), etc. [46,85].

4. Conclusions and limitations

This exploratory study built further understanding around the management, acquisition, and sharing of hazard, impact, vulnerability, and exposure (HIVE) data for severe weather hazards in New Zealand, towards supporting Sendai Framework priorities and implementing Impact Forecasts and Warnings (IFWs). While the qualitative nature of data collection and analysis herein limits the generalisability of results beyond the interviewees, this approach offers an in-depth understanding of a problem not readily available from quantitative approaches, which is appropriate for an exploratory study such as this [9,58,66].

We employed a socio-technical lens to our analysis to identify the organisational and technical intervening conditions and action/interaction strategies for accessing and sharing HIVE data in Aotearoa-New Zealand.

We found that there is a need for data governance of HIVE data. This involves identifying and appointing stewards and custodians of the relevant datasets such that the datasets can be maintained and available for further use beyond their initial purpose.

We also found a need for building and nurturing stronger partnerships to continue building trust between stakeholders for sharing data. Trust is an important factor for facilitating data sharing between agencies, and for people to share their data with hazards and impact monitoring crowdsourcing/citizen science projects.

Furthermore, integration challenges continue to interfere with the use of various sources of HIVE data for effective risk and impact assessments for IFWs and beyond. Systematic and standardised data collection approaches using GIS-based tools can support integration. Many templates for standardised data collection were found to exist in Aotearoa-New Zealand but the resulting data has not been systematically collected into one place for easier access and use. Depending on licensing and proprietary restrictions, it may be beneficial to aggregate these data into a central repository for continued use.

This research provides empirical evidence supporting the need for establishing roles and practices for governing HIVE data in Aotearoa-New Zealand. This is in support of both meeting the Sendai Framework priorities and implementing an IFW system for severe weather hazards in Aotearoa-New Zealand. Building partnerships remains key to improving data collection, access, and sharing practices for DRR. Further research can investigate how these partnerships can be built and strengthened.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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