International Journal of Disaster Risk Reduction 66 (2021) 102619

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

'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*

ARTICLE INFO

Keywords:
Impact-based warnings
Severe weather
Risk data
Impacts
Vulnerability
Exposure

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).

https://doi.org/10.1016/j.ijdrr.2021.102619
Received 1 July 2021; Received in revised form 29 September 2021; Accepted 30 September 2021
Available online 5 October 2021

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.

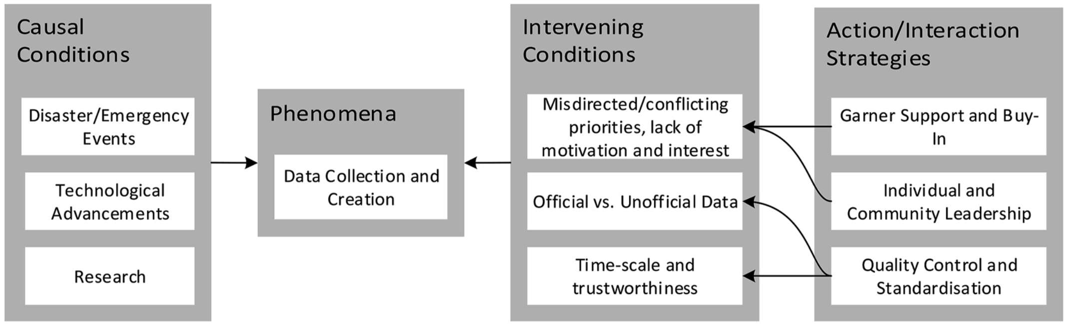

Fig. 1. Results of applying the coding paradigm to understand the causal conditions, intervening conditions, and action/interaction strategies for HIVE data creation, collection, and use phenomenon as defined in Table 3. Causal conditions are the drivers of the phenomena. Intervening conditions are conditions 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).

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

[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).

[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.

Acknowledgements

This research was funded by New Zealand's Ministry of Business, Innovation & Employment via the GNS Science Strategic Science Investment Fund and Resilience to Nature's Challenges Kia manawaroa – Ngā Ākina o Te Ao Tūroa. The authors thank the participants of the research for providing their invaluable time and insights, and the New Zealand MetService – Te Ratonga Tirorangi for their insightful conversations and advice over the course of this research. The authors also thank the reviewers whose feedback improved this manuscript.

References

[1] UNDRR, Sendai Framework for Disaster Risk Reduction 2015 - 2030, UNDRR, 2015. https://www.undrr.org/publication/sendai-framework-disaster-risk-reduction-2015-2030.
[2] M. McPherson, M. Counahan, J.L. Hall, Responding to Typhoon haiyan in the Philippines, Western Pac. Surveill. Response J. 6 (2015) 1–4, https://doi.org/10.5365/WPSAR.2015.6.4.HYN_026.
[3] P.K. Ching, V. Carr de los Reyes, M.N. Sucaldito, E. Tayag, An assessment of disaster-related mortality post-Haiyan in Tacloban City, Western Pac. Surveill. Response J. 6 (2015) 34–38, https://doi.org/10.5365/WPSAR.2015.6.2.HYN_005.
[4] WMO, WMO guidelines on multi-hazard impact-based forecast and warning services (9789263111500). https://www.wmo.int/pages/prog/www/DPFS/Meetings/ET-OWFPS_Montreal2016/documents/WMOGuidelinesonMulti-hazard Impact-basedForecastandWarningServices.pdf, 2015.
[5] A.L. Taylor, T. Kox, D. Johnston, Communicating high impact weather: improving warnings and decision making processes, Int. J. Disaster Risk Reduct. 30 (2018) 1–4, https://doi.org/10.1016/j.ijdrr.2018.04.002.
[6] B. Mackie, Warning Fatigue: Insights From the Australian Bushfire Context, Doctor of Philosophy in Media and Communication, University of Canterbury, 2013, https://ir.canterbury.ac.nz/handle/10092/9029.
[7] Harrison, S. E., Potter, S. H., Prasanna, R., Doyle, E. E. H., & Johnston, D. M. (submitted for publication). Identifying the Data Uses and Gaps for Severe Weather Impact Forecasts and Warnings. Weather, Climate, and Society.
[8] R. Hemingway, J. Robbins, Developing a hazard-impact model to support impact-based forecasts and warnings: the Vehicle OverTurning (VOT) Model, Meteorol. Appl. (2019) 1–17, https://doi.org/10.1002/met.1819.
[9] J. Harrison, C. McCoy, K. Bunting-Howarth, H. Sorensen, K. Williams, C. Ellis, Evaluation of the National Weather Service Impact-Based Warning Tool, 2014.
[10] S.H. Potter, S.E. Harrison, P. Kreft, The benefits and challenges of implementing impact-based severe weather warning systems: perspectives of weather, flood, and emergency management personnel, Weather, Clim., Soc. 13 (2) (2021) 303–314, https://doi.org/10.1175/wcas-d-20-0110.1.
[11] P. Heinselman, D. LaDue, D.M. Kingfield, R. Hoffman, Tornado warning decisions using phased-array radar data, Weather Forecast. 30 (2015) 57–78, https://doi.org/10.1175/WAF-D-14-00042.1.
[12] T. Gneiting, A.E. Raftery, Weather forecasting with ensemble methods, Science 310 (5746) (2005) 248–249, https://doi.org/10.1126/science.1115255.
[13] P.A. Hirschberg, E. Abrams, A. Bleistein, W. Bua, L.D. Monache, T.W. Dulong, J. E. Gaynor, B. Glahn, T.M. Hamill, J.A. Hansen, D.C. Hilderbrand, R.N. Hoffman, B. H. Morrow, B.P. Philips, J. Sokich, N. Stuart, A weather and climate enterprise strategic implementation plan for generating and communicating forecast uncertainty information, Bull. Am. Meteorol. Soc. (2011) 1651–1666, https://doi.org/10.1175/BAMS-D-10-00073.1.

[14] M.C. Fava, G. Santana, D.A. Bressiani, A. Rosa, F.E.A. Horita, E.M. Mendiondo, *Integration Of Information Technology Systems For Flood Forecasting with Hybrid Data Sources* 6th International Conference on Flood Management, Sao Paulo, Brazil, 2014.
[15] T. Krennert, G. Pistotnik, R. Kaltenberger, C. Csekits, Crowdsourcing of weather observations at national meteorological and hydrological services in Europe, Adv. Sci. Res. 15 (2018) 71–76, https://doi.org/10.5194/asr-15-71-2018.
[16] T. Kox, C. Lüder, L. Gerhold, Anticipation and response: emergency services in severe weather situations in Germany, Int. J. Disaster Risk Sci. 9 (2018) 116–128, https://doi.org/10.1007/s13753-018-0163-z.
[17] S.E. Harrison, A. Silver, B. Doberstein, Post-storm damage surveys of tornado hazards in Canada: implications for mitigation and policy, Int. J. Disaster Risk Reduct. 13 (2015) 427–440, https://doi.org/10.1016/j.ijdrr.2015.08.005.
[18] J.M. Sadler, J.L. Goodall, M.M. Morsy, K. Spencer, Modeling urban coastal flood severity from crowd-sourced flood reports using Poisson regression and Random Forest, J. Hydrol. 559 (2018) 43–55, https://doi.org/10.1016/j.jhydrol.2018.01.044.
[19] S.E. Harrison, S.H. Potter, R. Prasanna, E.E.H. Doyle, D. Johnston, Volunteered Geographic Information for people-centred severe weather early warning: a literature review, Australas. J. Disaster Trauma Stud. 24 (1) (2020). http://trauma.massey.ac.nz/issues/2020-1/AJDTS_24_1_Harrison.pdf.
[20] L. Smith, Q. Liang, P. James, W. Lin, C. Qiuhua Liang, Assessing the utility of social media as a data source for flood risk management using a real-time modelling framework, J. Flood Risk Manag. 10 (3) (2017) 370–380, https://doi.org/10.1111/jfr3.12154.
[21] G. Cervone, E. Schnebele, N. Waters, M. Moccaldi, R. Sicignano, Using social media and satellite data for damage assessment in urban areas during emergencies, in: P. Thakuriah, N. Tilahun, M. Zellner (Eds.), Seeing Cities through Big Data, Springer Geography, 2017, pp. 443–457, https://doi.org/10.1007/978-3-319-40902-3_24.
[22] R.P. Crompton, K.J. McAneney, Normalised Australian insured losses from meteorological hazards: 1967-2006, Environmental Science & Policy II, 2008, pp. 371–378, https://doi.org/10.1016/j.envsci.2008.01.005.
[23] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, P. Mancarella, Power system resilience to extreme weather: fragility modeling, probabilistic impact assessment, and adaptation measures, IEEE Trans. Power Syst. 32 (5) (2017) 3747–3757, https://doi.org/10.1109/TPWRS.2016.2641463.
[24] J.C. Robbins, H.A. Titley, Evaluating high-impact precipitation forecasts from the Met Office Global Hazard Map using a global impact database, Meteorol. Appl. (2018) 548–560, https://doi.org/10.1002/met.1720. July 2017.
[25] S. Doocy, A. Daniels, S. Murray, T.D. Kirsch, The human impact of floods: a historical review of events 1980-2009 and systematic literature review, PLoS Currents (2013), https://doi.org/10.1371/currents.dis.f4deb457904936b07c09daa98ee8171a. APR 2013.
[26] F. Sai, L. Cumiskey, A. Weerts, B. Bhattacharya, Towards impact-based flood forecasting and warning in Bangladesh: a case study at the local level in Sirajganj district, Nat. Hazards Earth Syst. Sci. Discussions(February) (2018) 1–22, https://doi.org/10.5194/nhess-2016-122.
[27] E.R. Poolman, A Probabilistic Impact-Focussed Early Warning System for Flash Floods in Support of Disaster Management in South Africa, Doctor of Philosophy in Meteorology, University of Pretoria, Pretoria, 2014, http://hdl.handle.net/2263/44331.
[28] G. Terti, I. Ruin, S. Anquetin, J.J. Gourley, Dynamic vulnerability factors for impact-based flash flood prediction, Nat. Hazards 79 (2015) 1481–1497, https://doi.org/10.1007/s11069-015-1910-8.
[29] I. McCallum, W. Liu, L. See, R. Mechler, A. Keating, S. Hochrainer-Stigler, J. Mochizuki, S. Fritz, S. Dugar, M. Arestegui, M. Szoenyi, J.-C.L. Bayas, P. Burek, A. French, I. Moorthy, Technologies to support community flood disaster risk reduction, Int. J. Disaster Risk Sci. 7 (2) (2016) 198–204, https://doi.org/10.1007/s13753-016-0086-5.
[30] E. Enarson, Chapter 13: identifying and addressing social vulnerabilities, in: W. L. Waugh, K. Tierney (Eds.), Emergency Management: Principles and Practices for Local Government, second ed., ICMA Press, 2007, pp. 257–278.
[31] K. Mason, K. Lindberg, C. Haenfling, A. Schori, H. Marsters, D. Read, B. Borman, Social vulnerability indicators for flooding in aotearoa New Zealand, Int. J. Environ. Res. Publ. Health 18 (8) (2021), https://doi.org/10.3390/ijerph18083952.
[32] D.P. Rogers, H. Kootval, V.V. Tsirkunov, Early warning, resilient infrastructure and risk transfer, in: Bridging Science and Policy Implication for Managing Climate Extremes, 2017, pp. 65–79. www.gfdrr.org.
[33] GFDRR, Implementing Multi-Hazard Impact-Based Forecast and Warning Services, 2016.
[34] R. Paulik, S. Stephens, R. Bell, S. Wadhwa, B. Popovich, National-scale built-environment exposure to 100-year extreme sea levels and sea-level rise, Sustainability 12 (4) (2020), https://doi.org/10.3390/su12041513.
[35] S.L. Lin, J. Ungaro, J.T. Nimau, S. Singh, K. Raqisia, Development of pacific exposure dataset for use in catastrophe risk assessment. Natural Hazards, 2020, https://doi.org/10.1007/s11069-020-04290-4.
[36] A. Mansourian, A. Rajabifard, M.J. Valadan Zoej, I. Williamson, Using SDI and web-based system to facilitate disaster management, Comput. Geosci. 32 (3) (2006) 303–315, https://doi.org/10.1016/j.cageo.2005.06.017.
[37] WMO, Multi-hazard Early Warning Systems: A Checklist, in: The First Multi-Hazard Early Warning Conference, 2018 (Cancun, Mexico).
[38] D. Zhang, L. Zhou, J.F.J. Nunamaker, A knowledge management framework for the support of decision making in humanitarian assistance/disaster relief, Knowl. Inf. Syst. 4 (2002) 370–385, https://doi.org/10.1007/s101150200012.
[39] S.E. Harrison, P.A. Johnson, Challenges in the adoption of crisis crowdsourcing and social media in Canadian emergency management, Govern. Inf. Q. 36 (2019) 501–509, https://doi.org/10.1016/j.giq.2019.04.002.
[40] R. Kaltenberger, A. Schaffhauser, M. Staudinger, "What the weather will do" – results of a survey on impact-oriented and impact-based warnings in European NMHSs, Adv. Sci. Res. 17 (2020) 29–38, https://doi.org/10.5194/asr-17-29-2020.
[41] M.H. Crawford, K. Crowley, S.H. Potter, W.S.A. Saunders, D.M. Johnston, Risk modelling as a tool to support natural hazard risk management in New Zealand local government, Int. J. Disaster Risk Reduct. 28 (January) (2018) 610–619, https://doi.org/10.1016/j.ijdrr.2018.01.011.
[42] A.L. Strauss, J.M. Corbin, Basics of Qualitative Research: Grounded Theory Procedures and Techniques, Sage Publications, 1990.
[43] J. Corbin, A. Strauss, in: V. Knight, Y. McDuffee, L. Barrett, M. Markanich (Eds.), Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory, fourth ed., SAGE Publications Inc, 2015.
[44] M. Bergin, NVivo 8 and consistency in data analysis: reflecting on the use of a qualitative data analysis program, Nurse Res. 18 (3) (2011) 6–12, https://doi.org/10.7748/nr2011.04.18.3.6.c8457.
[45] M. Vollstedt, S. Rezat, An introduction to grounded theory with a special focus on axial coding and the coding paradigm, in: G. Kaiser, N. Presmeg (Eds.), Compendium for Early Career Researchers in Mathematics Education, Springer International Publishing, 2019, pp. 81–100, https://doi.org/10.1007/978-3-030-15636-7_4.
[46] M. Williamson, Meteorological Service Contract, New Zealand Government, Wellington, New Zealand, 1998. Retrieved from, https://www.beehive.govt.nz/feature/meteorological-service-contract.
[47] MBIE, Crown research Institutes, 10 May from, https://www.mbie.govt.nz/science-and-technology/science-and-innovation/agencies-policies-and-budget-initiatives/research-organisations/cri/, 2021.
[48] T. Steiner, J.R. Martin, N.D. Gordon, M.A. Grant, Commercialisation in the provision of meteorological services in New Zealand, Meteorol. Appl. 4 (1997) 247–257.
[49] MetService, Open access data, Retrieved 22 June from, https://about.metservice.com/our-company/about-this-site/open-access-data/, 2021.
[50] WREMO, Significant Wave Hazards Project: Closeout Report, April 2021, W. R. E. M. Office, 2021.
[51] H. Rouse, Flood risk management research in New Zealand Where are we, and where are we going? (2012/04), GNS Sci. (2011).
[52] G. D'Amato, C. Vitale, M. D'Amato, L. Cecchi, G. Liccardi, A. Molino, A. Vatrella, A. Sanduzzi, C. Maesano, I. Annesi-Maesano, Thunderstorm-related asthma: what happens and why, Clin. Exp. Allergy 46 (3) (2016) 390–396, https://doi.org/10.1111/cea.12709.
[53] M. Sharpe, Hay fever sufferers beware: the great yellow clouds of swirling dust are upon us, Stuff. Retrieved, https://www.stuff.co.nz/national/health/122418563/hay-fever-sufferers-beware-the-great-yellow-clouds-of-swirling-dust-are-upon-us, 2020. (Accessed 10 May 2021).
[54] S.E. Harrison, P.A. Johnson, Crowdsourcing the disaster management cycle, Int. J. Inf. Syst. Crisis Response Manag. 8 (4) (2016) 17–40, https://doi.org/10.4018/ijiscram.2016100102.
[55] NEMA, Impact assessments Director's guideline for Civil defence emergency management groups *[DGL 22/20]*. (DGL 22/20). Wellington, NZ: New Zealand government, Retrieved from, https://www.civildefence.govt.nz/cdem-sector/guidelines/impact-assessments-directors-guideline-and-national-impact-assessment-data-set-and-dictionary-technical-standard/, 2020.
[56] J. Stowell, West Coast flooding event, Retrieved 24 April 2021 from, https://storymaps.arcgis.com/stories/e3769bfe5c8a4138b21f20c215a57f6b, 2020.
[57] Esri (n.d.-b), ArcGIS Survey123, from, https://survey123.arcgis.com/. (Accessed 20 May 2021).
[58] Esri (n.d.-a), ArcGIS QuickCapture, from, https://www.esri.com/en-us/arcgis/products/arcgis-quickcapture/overview. (Accessed 20 May 2021).
[59] MCDEM, Part II section 7 needs assessnent welfare services in an emergency Director's guideline [DGL 11/15]. (DGL 11/15). Wellington, NZ: New Zealand government, Retrieved from, https://www.civildefence.govt.nz/assets/Welfare-Services-in-an-Emergency/Welfare-Services-in-an-Emergency-Directors-Guideline.pdf, 2015.
[60] Nielsen, Wellbeing survey. https://www.cph.co.nz/wp-content/uploads/CantyWellbeingSurveyJun2017.pdf, 2017.
[61] C. Tarbotton, F. Dall, D. Dominey-Howes, J. Goff, The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: comparative review and summary of best practice, Earth Sci. Rev. 142 (2015) 120–134, https://doi.org/10.1016/j.earscirev.2015.01.002.
[62] NZLC, New Zealand critical lifelines infrastructure national vulnerability assessment. New Zealand lifelines council. http://www.nzlifelines.org.nz/site/assets/files/1019/nzlc_nva_2020_full_report.pdf, 2020.
[63] M. Jack, C. Graziadei, Report of the independent review of New Zealand's 2018 census. https://www.stats.govt.nz/assets/Uploads/Report-of-the-Independent-Review-of-New-Zealands-2018-Census/independent-review-report.pdf, 2019.
[64] Stats Nz, Meshblock 2021 (generalised), from, https://datafinder.stats.govt.nz/layer/105176-meshblock-2021-generalised/#:~:text=A%20meshblock%20is%20the%20smallest,large%20area%20of%20rural%20land, 2021. (Accessed 12 May 2021).
[65] P. Fdez-Arroyabe, L. Lecha Estela, F. Schimt, Digital divide, biometeorological data infrastructures and human vulnerability definition, Int. J. Biometeorol. 62 (5) (2018) 733–740, https://doi.org/10.1007/s00484-017-1398-x.
[66] H.-C. Hung, L.-Y. Chen, Incorporating stakeholders' knowledge into assessing vulnerability to climatic hazards: application to the river basin management in

Taiwan, Climatic Change 120 (1–2) (2013) 491–507, https://doi.org/10.1007/s10584-013-0819-z.

[67] R. Bell, R. Paulik, S. Wadhwa, Coastal Hazard and Climate-Change Risk Exposure in New Zealand: Comparing Regions and Urban Areas. FIG Working Week 2016 Recovery from Disaster, 2016 (Christchurch, New Zealand).

[68] G. Treadgold, J. Gunn, P. Morton, S. Chambers, *Developing a Regional Approach and Strategy for Geographical Information Systems for Emergency Management* ISCRAM Asia-Pacific, 2018 (Wellington, New Zealand).

[69] Technical Advisory Group, Ministerial Review Better Responses To Natural Disasters And Other Emergencies, Departmenr of the Prime Minister and Cabinet, 2017. https://dpmc.govt.nz/sites/default/files/2018-01/ministerial-review-better-responses-natural-disaster-other-emergencies.pdf.

[70] T. Aldridge, O. Gunawan, R.J. Moore, S.J. Cole, D. Price, *A Surface Water Flooding Impact Library for Flood Risk Assessment* FLOODrisk 2016 - 3rd European Conference on Flood Risk Management, 2016 (Lyon, France).

[71] A.M. Mehta, A. Bruns, J. Newton, Trust, but verify: social media models for disaster management, Disasters 41 (3) (2017) 549–565, https://doi.org/10.1111/disa.12218.

[72] V. Covello, P.M. Sandman, Risk communication: evolution and revolution, in: Solutions to an Environment in Peril, John Hopkins University Press, 2001, pp. 164–178.

[73] G. Terti, I. Ruin, M. Kalas, I. Láng, A. Cangròs, V. Lorini, ANYCaRE: a role-playing game to investigate crisis decision-making and communication challenges in weather-related hazards, Nat. Hazards Earth Syst. Sci. 19 (2019) 1–43.

[74] X. Wu, M. Howlett, M. Ramesh, Policy capacity: conceptual framework and essential components, in: Policy Capacity and Governance: Assessing Governmental Competences and Capabilities in Theory and Practice, Springer Nature, 2018, pp. 1–28, https://doi.org/10.1007/978-3-319-54675-9.

[75] T. Krennert, R. Kaltenberger, G. Pistotnik, A.M. Holzer, F. Zeiler, M. Stampfl, Trusted Spotter Network Austria – a new standard to utilize crowdsourced weather and impact observations, Adv. Sci. Res. 15 (2018) 77–80, https://doi.org/10.5194/asr-15-77-2018.

[76] H. Blumer, Symbolic Interactionism: Perspective and Method, first ed., University of California Press, 1969.

[77] M.B. Miles, A.M. Huberman, Qualitative Data Analysis: an Expanded Sourcebook, second ed., Sage Publications, Inc, 1994.

[78] M.Q. Patton, Qualitative Research and Evaluation Methods, third ed., Sage Publications, Inc, 2002.