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Nurturing partnerships to support data access for impact forecasts and warnings: Theoretical integration and synthesis

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ABSTRACT

This paper presents a synthesis and theoretical integration of findings from a research project that explored the data needs and sources for implementing impact forecasts and warnings for hydrometeorological hazards. Impact forecasts and warnings (IFW) have received global attention in recent years as they offer a novel way of improving the communication of hazards and risks. The fundamental idea behind IFWs is to enable warning services to meaningfully communicate the anticipated outcomes, consequences, or impacts of the hazard interacting with society or the environment by incorporating knowledge about the underlying and dynamic exposure and vulnerability of people and assets. One key question for IFW implementation is about data needs and sources to inform IFWs.Using the Grounded Theory Methodology, we address the question *"How can partnerships and collaboration better facilitate the collection, creation, and access to hazard, impact, vulnerability, and exposure data for IFWs?"* Our findings point to partnerships and collaboration as a necessary strategy for implementing IFWs. Implementation requires accessing various types and sources of hazard, impact, vulnerability, and exposure data to assess and communicate the potential impacts of hydrometeorological hazards. Partnerships and collaboration facilitate the sharing of and access to required data and knowledge. Based on our findings, we provide recommendations to increase interagency communication and partnerships for IFWs and disaster risk reduction, such as making cohabitation arrangements between agencies, running joint training scenarios, and encouraging meteorological services and emergency responders to co-define tailored warning thresholds.

Acronym/Abbreviation

ACC	Accident Compensation Corporation
CDEM	Civil Defence and Emergency Management
CRI	Crown Research Institute
DHB	District Health Board
DOC	Department of Conservation
DRR	Disaster Risk Reduction

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EM	Emergency Management
EQC	Earthquake Commission
ES-GTM	Evolved-Straussian Grounded Theory Methodology
EWS	Early Warning System
FENZ	Fire and Emergency New Zealand
GEMA	Geographic Emergency Management Aotearoa (formerly NZGIS4EM)
GIS	Geographical Information System
GIS4EM	Geographical Information System for Emergency Management (now GEMA)
GNS Science	Te Pū Ao Institute of Geological and Nuclear Sciences Limited
Gov.	Government
GTM	Grounded Theory Methodology
GWE	Global Weather Enterprise
HIVE	Hazard, Impact, Vulnerability, and Exposure
Hyd.	Hydrological
IFRC	International Federation of Red Cross and Red Crescent Societies
IFW	Impact Forecast and Warning
IFWS	Impact Forecasting and Warning System
LINZ	Toitū Te Whenua Land Information New Zealand
MBIE	Ministry of Business, Innovation, and Employment
Met.	Meteorological
MetOffice	United Kingdom Meteorological Office
MetService	Meteorological Service of New Zealand Limited – Te Ratonga Tirorangi
MCDEM	Ministry of Civil Defence and Emergency Management (now NEMA)
MfE	Ministry for the Environment
MPI	Ministry of Primary Industries
Nat.	National
NEMA	National Emergency Management Agency (formerly MCDEM)
NHP	Natural Hazards Partnership
NIWA	National Institute of Water and Atmospheric Research
NZ	Aotearoa New Zealand
NZTA	Waka Kotahi NZ Transport Agency
RC	Regional Council
Reg.	Regional
RNC	Resilience to Nature's Challenges Kia manawaroa – Ngā Ākina o Te Ao Tūroa
Stats NZ	Statistics New Zealand
SOE	State-Owned Enterprise
UK	United Kingdom
USA	United States of America
UN	United Nations
UNDRR	United Nations Office for Disaster Risk Reduction (formerly UNISDR)
UNISDR	United Nations International Strategy for Disaster Reduction (now UNDRR)
VGI	Volunteered Geographic Information
WMO	World Meteorological Organization

1. Introduction

Impact forecasts and warnings (IFW) have received global attention in recent years to improve the communication of hazards and associated risks. This is due in part to the World Meteorological Organization's (WMO) encouragement for member nations to implement them as a way of reducing losses and impacts from hydrometeorological events [1–3]. This is because notable historic events have exposed communication gaps between meteorologists, warning services, and target audiences, resulting in widespread losses [1,4–6]. This communication gap is a result of both technical failings and human behaviour [7]. Research has shown that meteorologists and warning services do not typically consider the warning audiences' current state of vulnerability and exposure at the time of the warning or at the expected time of impact, due to lack of knowledge and lack of easy access to this information [1,8]. For example, the ultramarathon tragedy on May 22, 2021 in Baiyin, Gansu Province, China where 21 race runners died due to exposure to high winds combined with low temperatures and precipitation highlighted the lack of consideration around the race runners' exposure to what normally would have been a low-impact weather event [6]. This and other notable examples show a need for warning systems to consider the current exposure and vulnerability of people at the time and location of the hazard, and to translate the hazard-based warning into an impact warning such that appropriate protective action decisions can be made [6].

The fundamental idea behind IFWs is to enable warning services to meaningfully communicate the anticipated impacts of the hazard by incorporating knowledge about the underlying and dynamic exposure and vulnerability of people and assets [6,8]. To date, much research has been conducted to understand the challenges and barriers for implementing IFWs (e.g., Refs. [9–13]); to explore the data needs and data sources for implementation and evaluation (e.g., Refs. [3,8,14–17]); to develop and evaluate hazard and impact models and risk-based approaches (e.g., Refs. [18–23]); and to understand public perceptions of IFWs (e.g., Refs. [24–31]).

These studies point to several outstanding questions that influence whether and how warning services can implement IFWs. For example, results around the efficacy of IFWs suggest that impact information alone is less effective at positively influencing intentions to take protective action than including action advice alongside the impact information [28]. This raises questions around whether the costs of implementing IFWs outweigh the perceived benefits of them [12]. A lack of useful data was also identified as a barrier to implementation [8,12,23]. Consequently, the WMO advises that the first step of IFW implementation is to explore possible data sources [3]. This led to investigations into existing and potential data sources to fill these data gaps [16,17,32].

Throughout 2018–2022 a multi-phased project was conducted to investigate the data needs and sources for IFWs for hydrometeorological hazards in Aotearoa New Zealand. The overarching project involved four central studies: exploring Volunteered Geographic Information (VGI; [14]); data uses and gaps [8]; sources of hazard, impact, vulnerability, and exposure (HIVE) data [32]; and exploring data governance issues [8,15]. The design and key findings of these studies are summarised in Table 1.

Central to the findings summarised in Table 1, is the important, and often missing, component of partnerships and collaboration required for implementing IFWs. Partnerships and collaboration are an established concept in DRR and EWS literature; they contribute to a resilient society by facilitating the sharing of knowledge and resources [33,34]. Garcia and Fearnley [35] argued that integrated partnerships that support constant communication are needed to achieve effective use of scientific information for EWS. Furthermore, partnerships are described as “the foundation for an effective” IFW system in the WMO Guidelines on Multi-hazard Impact-based Forecast and Warning Services Part II, where it is “essential” to understand partnerships, mandates, and governance structures for successful IFW systems ([3], pp. viii-ix). In support of this literature, the 2018–2022 research conducted by Harrison et al [3,8,14,15] found partnerships and collaboration to be critical for IFWs yet missing in some cases and contexts throughout Aotearoa New Zealand and abroad. Examples of the stakeholders likely to be involved in an IFW system and the required partnerships were consolidated from the literature and are summarised in Table 2, with New Zealand-specific examples provided for context.

In Aotearoa New Zealand, different agencies have the mandated responsibility for issuing warnings for specific hazards. The New Zealand Meteorological Service (i.e., the MetService) is the appointed National Meteorological Service for Aotearoa New Zealand and is thus responsible for providing basic public weather forecasts and issuing warnings of hazardous weather affecting land and marine areas [36]. Flood warnings, however, are the responsibility of Local and Regional Councils, with support from the MetService, the National Institute of Water and Atmospheric Research (NIWA), and Emergency Management agencies [37]. Reports have noted the need

Table 1
Summary of related papers previously published for this project, including the research questions and key findings of each paper.

Paper	Research Questions	Key Findings
Harrison et al. [14]	What are the current and potential uses of Volunteered Geographic Information (VGI) for severe weather warnings?	• Various forms of VGI, from geo-located social media, crowdsourcing platforms, participatory mapping/participatory Geographic Information Systems (GIS), and local knowledge, have roles to play in all components of a hydrometeorological early warning system (EWS). • Some forms of VGI are more useful for specific EWS components than are others. • VGI processes can bridge the gap between EWSs and audiences of warnings by incorporating local knowledge and personal experiences from stakeholders into the EWS components.
Harrison et al. [8]	What are the data uses and gaps for IFWs?	• There is a growing need for creating, gathering, and using impact, vulnerability, and exposure data for IFW systems. • Each data type (hazard, impact, vulnerability, and exposure) has relevant application in various components of the Warning Value Chain. • Different approaches can be used for impact forecasting and defining impact thresholds using objective models and subjective impact-oriented discussions depending on the data available. • There is a growing need to identify, model, and warn for social and health impacts.
Harrison et al. [32]	What are the sources of hazard, impact, vulnerability, and exposure (HIVE) data?	• Various sources for HIVE data are available for implementing hydrometeorological IFW systems, but are collected, stored, and managed by different agencies, introducing barriers to use of and access to the data. • GIS-based tools and mobile devices are examples of technological advancements for collecting and creating HIVE data to ensure the data are useful and useable for multiple purposes. • Priorities, motivation, and interest within organisations influence how data are collected and used. • There is a tension between the timeliness and trustworthiness of data needed for emergency response and warnings. For example, timely data collected from social media and other crowdsourcing platforms are perceived as less trustworthy than other more official and traditional sources of data, which may not be available as quickly. • Strategies for addressing challenges and barriers for collecting and using HIVE data include garnering support and buy-in and strong community leadership for overcoming conflicting management priorities or a lack of motivation and interest.
Harrison et al. [15]	How can HIVE data governance, access, and sharing be improved for hydrometeorological hazards in New Zealand?	• There is a need for improved data governance of hazard, impact, vulnerability, and exposure data. • There is a need for building and nurturing stronger partnerships to continue building trust between stakeholders for sharing data. • Systematic and standardised data collection approaches using GIS-based tools can address data integration challenges.

Table 2
Summary stakeholders likely to be involved in an IFW system.

	List of Stakeholders	Description and examples from Aotearoa New Zealand	Information and data sharing
Providers of hydro-meteorological forecasts, warnings, and advice	Meteorological Service	The meteorological service monitors meteorological conditions and produces forecasts based on their monitoring. When thresholds are met for hazardous meteorological conditions that are expected to impact society, a watch or warning might be issued. For example, the NZ MetService issues yellow watches, and orange and red warnings depending on the anticipated impacts.	Meteorological observations, forecasts and warnings.
	Local and Regional Councils	Local and regional councils in Aotearoa New Zealand monitor river levels and forecast and warn for river and surface flooding, and produce forecasts and warnings for floods. They might be in contact with the meteorological service to partake in the meteorological warning decision-making process.	Hydrogeological hazard observations, forecasts and warnings, knowledge of antecedent conditions contributing to vulnerability and exposure.
	Emergency Management Agencies	Emergency Management agencies are responsible for pushing out and acting on forecasts and warnings. They might also add action advice to the warning message and may also be involved in the warning decision-making process. These agencies also collect impact information in the form of intelligence for situational awareness.	Evaluate vulnerabilities, identify potential impacts and proper mitigation actions, share expertise, collect intelligence.
	Scientific Institutions	Scientists and scientific institutions like GNS Science, NIWA, and universities may aid in the development of hydrometeorological and hydrogeological models for forecasts as well as in the design of warning messages and advice. They might also produce impact forecasts such as the rainfall-induce landslide impact forecasts produced by RiskScape in response to the Auckland Anniversary heavy rainfall event and Cyclone Gabrielle in February 2023 [35].	Improve and develop technical processes/ equipment (e.g., modelling), share data sources/datasets, share expertise and advice.
Users of forecasts, warnings, and advice	The publics	Respond to the forecasts, warnings, and advice.	Identify thresholds, vulnerability, and exposure.
	Agricultural sector	Respond to the forecasts, warnings, and advice.	Identify thresholds, vulnerability, and exposure.
	Critical Infrastructure (e.g., roads, rail, aviation, power, water, telecommunications)	Respond to the forecasts, warnings, and advice.	Identify thresholds, vulnerability, and exposure.
	Public Health Sector	Respond to the forecasts, warnings, and advice. Provide tailored advice where appropriate.	Identify thresholds, vulnerability, and exposure.
	Businesses	Respond to the forecasts, warnings, and advice.	Identify thresholds, vulnerability, and exposure.
	Transportation	Respond to the forecasts, warnings, and advice. Provide tailored advice where appropriate.	Identify thresholds, vulnerability, and exposure.
	Public Transit	Respond to the forecasts, warnings, and advice.	Identify thresholds, vulnerability, and exposure.
	The media	Disseminate forecasts, warnings, and advice. Document and report on the impacts.	Impacts documented in news reports.
	Non-government organisations (NGOs)	Respond to the forecasts and warnings, plan and allocate response and recovery efforts and aid.	Vulnerability and exposure assessments, mitigation actions, impacts documented during recovery support.

for greater collaboration between organisations and increased data and information sharing for improving flood warnings and flood mitigation (e.g., [38–41]).

Furthermore, other agencies are responsible for issuing forecasts and warnings for other non-hydrometeorological hazards. The National Emergency Management Agency (NEMA) holds authority for issuing tsunami warnings, with support from GNS Science [42,43]. GNS Science is responsible for monitoring and delivering hazard information pertaining to earthquake, volcanic activity, and landslides).

Emergency Management agencies also play a key role in disseminating forecast and warning messages, initiating response plans including evacuations, and providing localised advice to their jurisdiction [42]. Strong partnerships, collaboration, and coordination across these multiple agencies are thus required for a fully integrated multi-hazard EWS where the impacts of cascading and concurrent hazards are considered, assessed, and communicated efficiently and consistently across agencies (e.g., Ref. [44]).

This current paper thus provides a theory grounded in qualitative data and results, previously presented by Harrison et al. [3,8,14,15], to answer the research question *"How can partnerships and collaboration facilitate better collection, creation, and access to HIVE data for IFWs?"* This theory (presented in Section 3) also provides strategies for building and nurturing such partnerships to support stakeholders both in and outside of Aotearoa New Zealand involved IFWs and DRR efforts.

2. Methodology

We used a qualitative Grounded Theory Methodology (GTM) to conduct this exploratory study [45,46]. More specifically, we employed the Evolved Straussian GTM (ES-GTM; [45,47,48]) visualised in Fig. 1. Under the ES-GTM we began with an initial literature

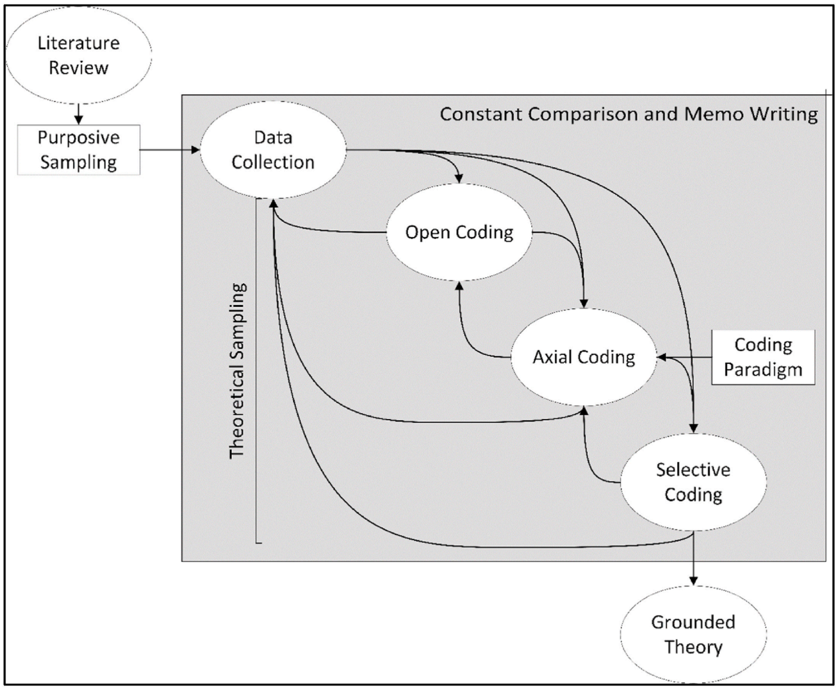

Fig. 1. Conceptual framework of the ES-GTM analytical process employed in this research. Figure created by the first author of this paper based on interpretations of Corbin and Strauss [45,47], Charmaz (2006), and Glaser and Strauss [46].

review to provide context and justification for the study and inform the research question [49]. Data collection and analysis commenced concurrently using purposive and theoretical sampling techniques to target future data collection by identifying clues, gaps, and uncertainties in need of further exploration [46,50].

2.1. Data collection methods

We used interviews and workshops to collect qualitative data for this study. We conducted interviews in the first phase to develop an understanding of the current perspectives on IFW systems and the associated data needs in New Zealand and abroad. In the second phase, we ran three workshops to triangulate the interview results. Data collection took place from November 2018 to May 2021.

2.1.1. Interviews

We initially used a purposive sampling method [50] to target and recruit interviewees based on their roles in hydrometeorological risk communication, response, and their use of impact, vulnerability, and exposure data. Recruitment was targeted towards individuals or organisations that issue hydrometeorological warnings, and/or collect, create, share, use, or manage HIVE data for hazard and risk management. We identified potential participants through our networks and contacted them directly via e-mail. After the initial interviews were conducted, theoretical sampling guided the rest of the data collection process whereby we recruited participants who were knowledgeable or experienced in themes that emerged from previous interviews [46].

We interviewed thirty-nine (39) individuals. The interviews ranged in length from 45 to 90 min. Interviews were audio-recorded and transcribed verbatim for analysis. Due to the COVID-19 pandemic recruitment was limited towards the final months of data collection as many of the target participants were responding to COVID-19. Interviews were conducted both in person and virtually. Details of the interview structure, questions, and participant profiles are reported in previous publications for this project [8,15,32].

2.1.2. Workshops

We conducted three 2-h long workshops to diversify the qualitative dataset and to triangulate the research findings [45,51]. Emergency Management officials and staff from the New Zealand Meteorological Service (herein referred to as the MetService) participated in one regional workshop each for Auckland and Southland, New Zealand. Researchers and scientists from GNS Science involved in hazard and risk management in Aotearoa New Zealand participated in the third workshop. GNS Science is a Crown Research Institute (CRI) of New Zealand and is heavily involved in the management of natural hazards and risks across the country by providing scientific evidence and advice for response, planning, and policy [52,53]. The workshops were held virtually due to COVID-19 concerns.

Twenty individuals participated in all three workshops. Four people participated in the Auckland workshop, representing Auckland Emergency Management, the MetService, and Auckland Council from the Planning Department and the Healthy Waters Department. Five people attended the Southland workshop, representing Southland Regional Council from the Geographical Information Systems (GIS) team, the Hydrology team, the Communications and Engagement team, and Emergency Management Southland.

Eleven people from GNS Science attended the third virtual workshop to represent a portion of the community of science in New Zealand.

We used the web-based whiteboarding platform, Mural,[1] to facilitate the workshops. We mapped out a virtual whiteboard as shown in Fig. 2 with specific questions and activities for the participants to navigate. We asked participants to provide feedback on an impact, vulnerability, and exposure data framework that we developed from the interviews. We then asked workshop participants to identify data requirements and sources for IFWs based their roles. In the third activity we asked the participants to identify one to two datasets or data sources that they think are important, to outline the life track of the data, and to describe how they understand what impacts are occurring or could occur from a hydrometeorological hazard. In the fourth activity participants identified alternative uses beyond IFWs for the datasets or data sources that they identified in activity three. In the last activity we investigated the application of the framework: whether the participants would use it, why or why not, and how. The workshops were audio recorded through Microsoft Teams, and data from the virtual sticky notes were entered into a spreadsheet for further analysis.

2.2. Analytical techniques

We utilised constant comparison, memo-writing, diagramming, and coding techniques to analyse the qualitative data as shown in Fig. 1 [45]. We used Nvivo 12, a qualitative data analysis software package that facilitates data management, idea management, data querying, graphical modelling of ideas and concepts, and data reporting [54].

2.2.1. Memo-writing and diagramming

Memos are "written records of analysis" ([45], p. 57). Memo-writing and diagramming were regularly used throughout the data collection and analysis for this study. When the lead author noticed common themes in the interviews, a memo was written to identify the theme and begin to understand the potential significance of the theme.

The lead author regularly diagrammed her mental map of key themes, concepts, and relationships that emerged during an interview and compared the resulting diagrams to each other. Through this process, the lead author developed a data collection and process flow for IFWs, presented in Harrison et al. [8], that was validated during the workshops. The theory presented in this paper (Fig. 5 in Section 3) was a further result of the diagramming and theoretical integration process presented herein.

2.2.2. Coding and constant comparison

Coding involves "denoting concepts to stand for meaning" in the qualitative data ([45], p. 57), and occurred in three stages in this study, following ES-GTM: open coding, axial coding, and selective coding. Interview transcripts were loaded into Nvivo for this analytical process.

In the *open coding* stage (see Fig. 1), open codes were developed directly from the data (i.e., in vivo), and with reference to the literature. We performed constant comparison by comparing the data pieces (e.g., sentences, paragraphs) for similarities and differences; similar parts were assigned the same code and different parts were assigned a different code [55]. The open coding process was documented with theoretical memos and in the code descriptions [45].

The resulting open codes were grouped into categories using constant comparison and memo writing. For example, interviewees identified data sources from the various social media platforms which the lead author coded according to the social media platform (e.g., Twitter, Facebook, Snap Chat), and grouped into a 'Social Media' category. The 'Social Media' and 'Crowdsourcing' categories were then grouped into 'Alternative or unofficial data sources', while another category was created for 'Official and Trusted Data Sources' to capture the data sources that interviewees deemed as such (e.g., Emergency Management-led damage surveys and impact assessments, emergency calls, and media reports). This relational process allowed for different dimensions of categories to be identified through the memo-writing process, such as trustworthiness of the data.

After the data were broken up into concepts and categories, we used *axial coding* (see Fig. 1) to piece the data back together to form categories [55] and to investigate the relationships between the categories [48]. For this stage, we found Strauss and Corbin's [48] 1990 coding paradigm to fit the data better than more recent variations of the coding paradigm as explained by Harrison et al. [15,32]. For example, the 1990 coding paradigm includes "Causal", "Intervening", and "Contextual Conditions" ([48], p. 99), while the most recent variation of the coding paradigm only provides "Conditions" ([45], p. 158). We found that Causal, Intervening, and Contextual Conditions better explain the data by identifying drivers (i.e., causal conditions) and challenges in the categories and phenomena, as visualised in Fig. 3. For example, past disaster events such as the 2010–2011 Canterbury earthquake sequence were identified in interviews as a driver (i.e., causal condition) for improving data collection and management within the Emergency Management sector in Aotearoa New Zealand. Contextual conditions were determined to be high-level influences of overall practice, particularly governance and cultural conditions in Aotearoa New Zealand. Results from the axial coding process were digitised into a spreadsheet for further aggregation and shifting of codes and categories. Significant themes were then highlighted for reporting.

Through this process we identified two phenomena as the subjects under study [48]. The first phenomenon was *IFW Systems*, and the second was *Hazard, Impact, Vulnerability, and Exposure (HIVE) Data*. These two phenomena were respectively analysed and reported by Harrison et al. [8,15,32]. The two phenomena and their associated categories and open codes are visualised in Fig. 4.

The *Impact Forecasting and Warning (IFW) Systems* phenomenon consists of two categories: IFW Implementation and IFW Data Needs. The codes for the IFW Implementation category relate to defining and understanding IFW systems and what is needed to implement them. The codes in the IFW Data Needs category relate to identifying the different types of data needs for IFWs (e.g., hazard, impact, vulnerability, and exposure data), and justification and uses for these different data types in the IFW systems context.

[1] https://www.mural.co/.

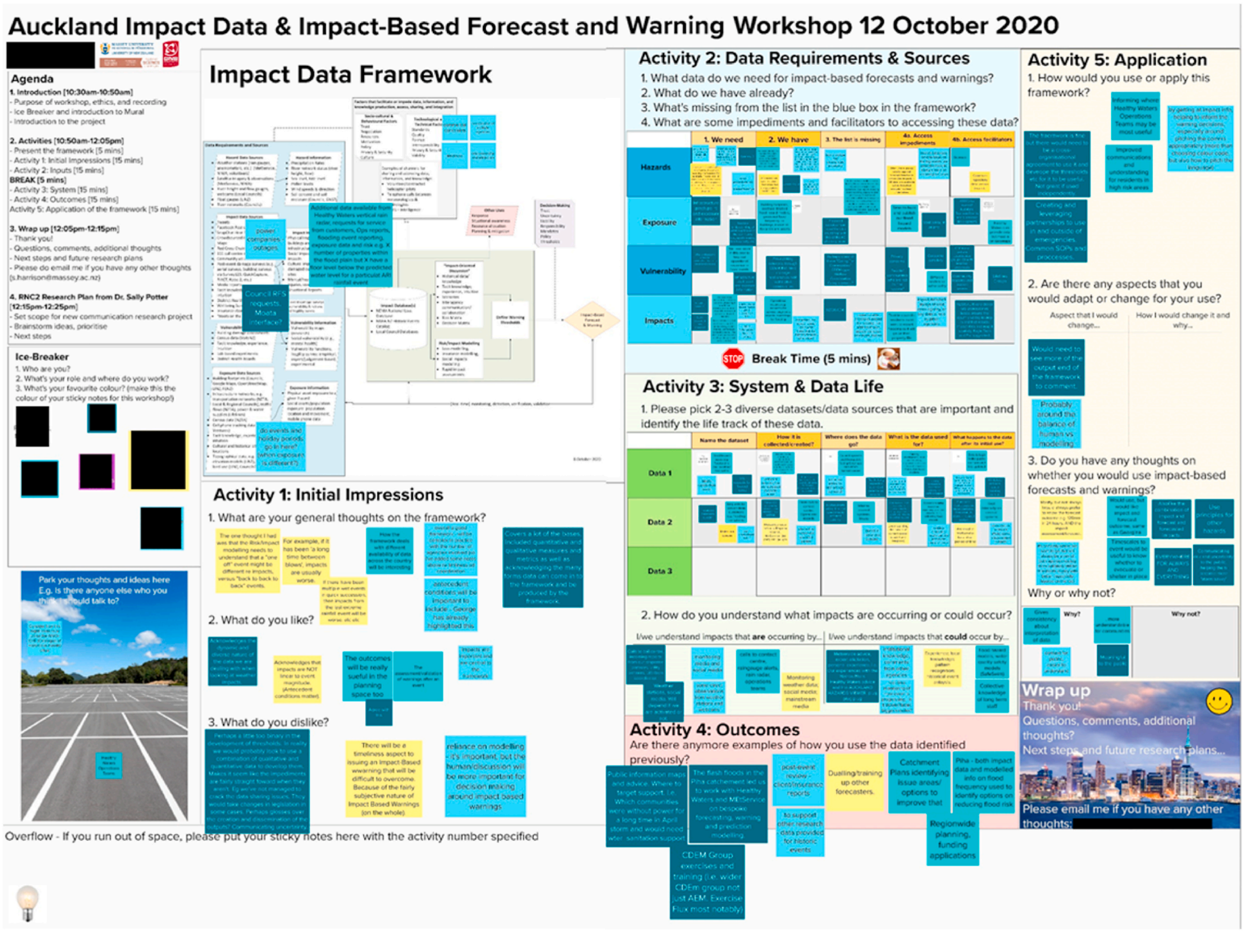

Fig. 2. Image of the virtual whiteboard the was populated using Mural during the workshop with participants from Auckland Council, Auckland Emergency Management, and the MetService on October 12, 2020.

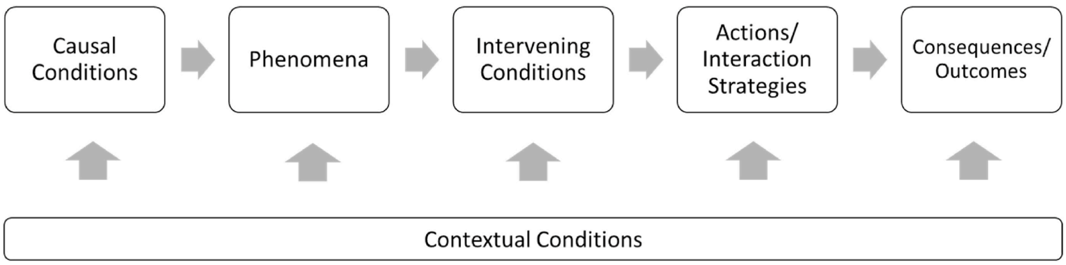

Fig. 3. The axial coding paradigm [48] used to relate the categories and identify the phenomena.

The *Hazard, Impact, Vulnerability, and Exposure (HIVE) Data* phenomenon consists of two categories: Data Sources and Collection, and Data Governance, Access and Sharing. During the axial coding process these categories were identified based on a common theme between the open codes. These three category topics arose organically by the participants and were discussed at length. Thus, they were deemed to be important enough to be their own categories. These three categories are inherently linked to each other. For example, in the Data Sources and Collection category, two codes emerged regarding the existence of many datasets and sources: 'More data is available or exists than we think' and 'Various stakeholders that create, manage, share, access, use data'. These two codes led to the idea that these datasets and sources exist and are collected by various sources, then there must be a way to share these data. As such, the lead author interrogated the qualitative interview data with questions around data sharing and access, resulting in codes identifying drivers for sharing data. Further questions arose around why these data are not being used very well, which led to identifying challenges with accessing these data (i.e., intervening conditions), as well as issues of Data Management and Governance, where the data are not managed or maintained very well, making it difficult to share and effectively use the data. Questions were asked around the potential causes of data management and governance issues that are inhibiting HIVE data collection and sharing practices in NZ.

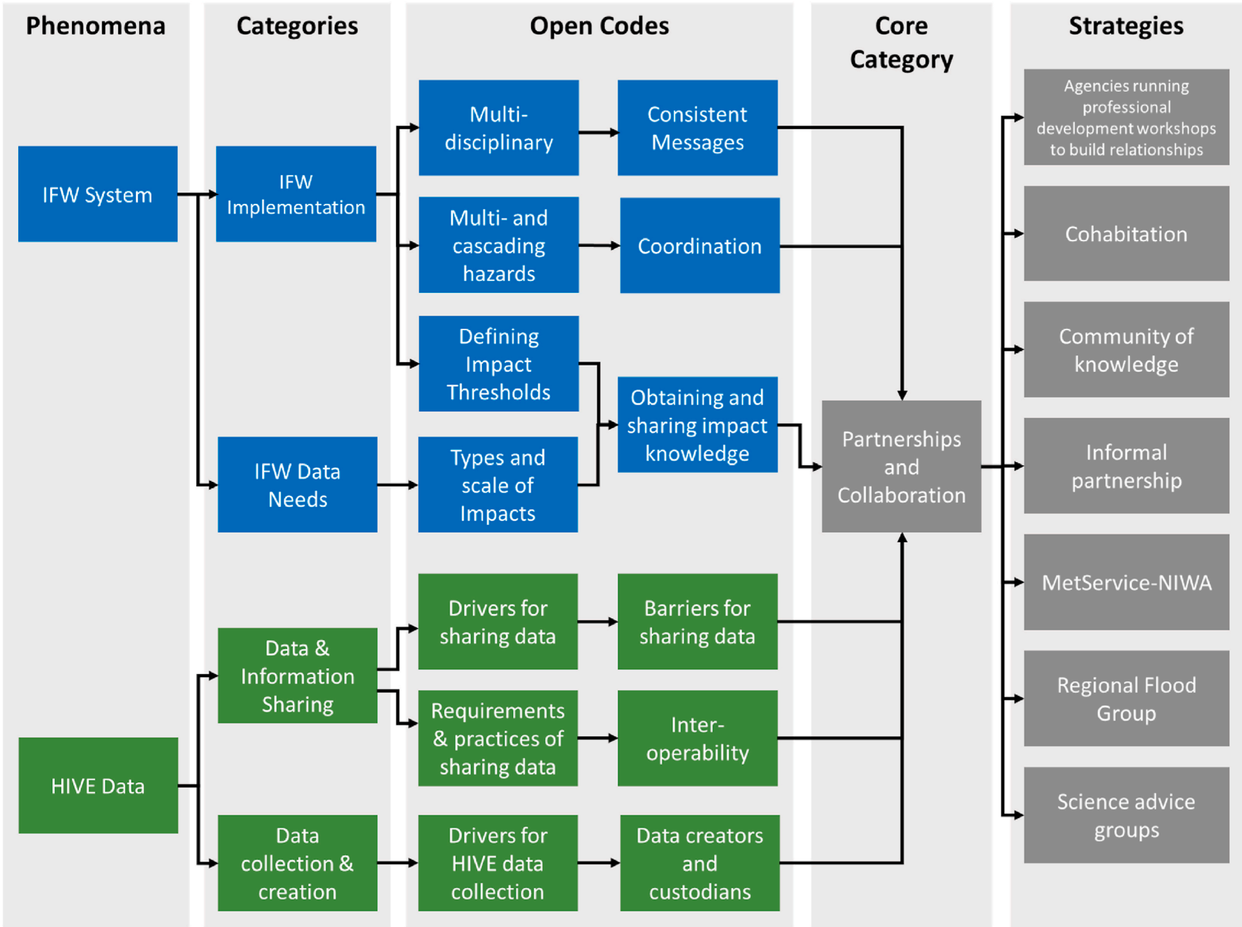

Fig. 4. Relationships between the two phenomena under study and the core category. The blue, green, and grey boxes represent codes and categories developed throughout the analysis. The blue boxes represent the IFW System phenomenon and associated categories and codes. The green boxes represent the HIVE Data phenomenon and associated categories and codes. The dark grey boxes represent the core category of Partnerships and Collaboration. The arrows portray the coding hierarchy and the relationship to the core category of Partnerships and Collaboration. The light grey boxes indicate the ES-GTM methodological component.

Through *selective coding* (see Fig. 1) we related all categories to the core category to develop the grounded theory. The core category "incorporates or supersedes other categories in explanatory importance and hence is 'elevated' to the status of an important concept" ([56], p. 7). Here, we validated relationships and refined categories [55]. Through continuous reflection, constant comparison, re-assignment of codes and categories, memo-writing, and diagramming, we established the core category and integrated all categories into one cohesive theory [55], described in Section 3.

We identified *Partnerships and Collaboration* as the core category in this study, as we found it weaves through all resulting themes and categories. Partnerships and Collaboration appear to be essential for both IFW Systems and HIVE Data, as shown by the open codes visualised in Fig. 4. For the IFW System Phenomenon, discussions with participants showed that the process of defining impact thresholds requires partnering with agencies and sectors (e.g., transportation, flood management, health, insurance, agriculture) that possess the knowledge needed to define these impact thresholds.

For the HIVE Data phenomenon, the concept of Partnerships and Collaboration cut across two categories: (1) Data and Information Sharing, and (2) Data Collection and Creation. In the first category, *'Data and Information Sharing'*, cooperation and collaboration were identified as strategies for facilitating data sharing between the various agencies that possess the data. In the second category, *'Data Collection and Creation'*, cooperation and collaboration were identified as strategies for establishing data collection standards across agencies. The need for this arose from the idea of agencies collaborating with each other after an event to co-design data collection forms such that the resulting data suit various users' needs (Met. Research NZ. J; Risk Modelling NZ. C).

Other codes relating to partnerships and collaboration were created outside of the direct relation to these two phenomena that were grouped together and elevated to the core category of Partnerships and Collaboration, as shown in the dark grey boxes in Fig. 4.

The integration of the findings described in Section 3 are structured around these two phenomena and how they relate back to the core category of Partnerships and Collaboration.

2.3. Ethical considerations

A ‘low risk’ ethics clearance was obtained prior to data collection in 2018. All participants remain anonymous and are assigned an alphabetic code (A, B, C, etc.), identified only by area of expertise and/or practice (e.g., Meteorology, Emergency Management, Data Management), sector (e.g., Private, Governance), location (e.g., NZ or International), or governance level (e.g., National, Regional, Local) as shown in Table 3. The acronyms and abbreviations in Table 3 are as follows: Meteorology (Met.), Emergency Management (EM), New Zealand (NZ), Geographic Information Systems (GIS), Regional (Reg), Government (Gov.), Early Warning System (EWS), International (Int.).

3. Integration of findings

Results regarding the two phenomena in this study have been previously published by Harrison et al. [8,15,32]. This paper aims to integrate the findings from the previous papers with the core category of *Partnerships and Collaboration* and situate these results in the context of the literature [57]. This integration is the final stage of ES-GTM where the interrelationships between the phenomena, categories, and core category are elaborated and related back to the literature [58]. The intent is to extend the literature and demonstrate the scholarly contribution of the Grounded Theory [59]. Next, we define the core category with its properties and dimensions and relate it back to the two phenomena and the wider body of literature on partnerships in DRR. We conclude the study and outline the limitations in Section 4.

3.1. Partnerships and collaboration core category defined

Based on the two phenomena under study in this research we define the core category of Partnerships and Collaboration as formal and informal, bottom-up or top-down approaches to establishing, building, and/or nurturing working relationships with stakeholders involved in the communication of and response to hydrometeorological hazards, to allow for defining warning thresholds; creating

Table 3
Interviewee codes.

Interviewee Code	Position	Classification	Location
Agriculture/Rural NZ. A	Agriculture policy coordinator	Agriculture/Rural	NZ
Data Management Gov. NZ. Nat. A	Senior Resilience Advisor	Data Management	NZ
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
EM. NZ. Reg. A	Director	Emergency Management	NZ
EM. NZ. Reg. B	Controller	Emergency Management	NZ
EM. NZ. Reg. C	Controller	Emergency Management	NZ
EM. NZ. Reg. D	Principal Science Advisor	Emergency Management	NZ
EM. NZ. Reg. E	Principal Advisor Strategy and Partnerships	Emergency Management	NZ
EM. NZ. Reg. F	GIS Lead	Emergency Management; Data Management	NZ
EM. Gov. NZ. Nat. G	Senior Hazard Risk Management Advisor	Emergency Management; Governance	NZ
EM. NZ. Reg. H	Emergency Management Advisor	Emergency Management	NZ
EM. NZ. Nat. I	First Responder	Emergency Management	NZ
EM. Gov. NZ. Nat. J	National Operations Manager	Emergency Management; Governance	NZ
EM. NZ. Reg. K	Regional Manager	Emergency Management	NZ
EM. NZ. Reg. L	Emergency Management Advisor	Emergency Management	NZ
EM. NZ. Reg. M	Group Controller	Emergency Management	NZ
Health NZ. Reg. A	Respiratory Doctor	Public Health	NZ
Hyd. Gov. NZ. Reg. A	Flood EWS Programme Manager	Hydrology; Governance	NZ
Lifelines NZ. Reg. A	Civil Engineer	Lifelines	NZ
Loss Modelling Research NZ. A	Economist	Loss Modelling; Research	NZ
Met. Int. A	Science Manager	Meteorology	Inter-national
Met. Int. B	National Manager Disaster Mitigation Policy	Meteorology	Inter-national
Met. Int. C	Senior Policy Officer	Meteorology	Inter-national
Met. Int. D	Senior Social Scientist	Meteorology	Inter-national
Met. Int. E	Consultant Meteorologist	Meteorology	Inter-national
Met. NZ. F	Senior Meteorologist	Meteorology	NZ
Met. NZ. G	Communications	Meteorology	NZ
Met. NZ. H	Public Relations	Meteorology	NZ
Met. Int. I	Division Chief/Meteorologist	Meteorology	Inter-national
Met. Research NZ. J	Meteorologist	Meteorology; Research	NZ
Met. NZ. K	Senior Meteorologist	Meteorology	NZ
Met. Private NZ. L	Head Weather Analyst	Meteorology	NZ
Risk Modelling NZ. A	Risk Modeller	Risk Modelling	NZ
Risk Modelling NZ. B	Risk Modeller	Risk Modelling	NZ
Risk Modelling NZ. C	Risk Modeller	Risk Modelling	NZ
Risk Modelling NZ. D	Risk Modeller	Risk Modelling	NZ

consistent warning messages; sharing knowledge and data of hazards, impacts, vulnerability, and exposure; collecting appropriate and useful data; and managing said data towards the implementation of an impact forecasting and warning system.

The concepts and the theory on which the above definition is based are represented visually in Fig. 5, which places Partnerships and Collaboration in the middle, supported by its properties and dimensions (discussed next, in Section 3.2). Partnerships and Collaboration were found to play a key role in both the IFW System phenomenon and the HIVE data phenomenon. This will be discussed in Sections 3.3 and 3.4, citing examples from the previous papers and additional evidence in the interview and workshop data. Evidence from interviews is referenced using the interviewee codes presented in Table 3, for example ‘Met. Research NZ. J’ for participant J in the meteorological research field in New Zealand. References to the workshops are formatted as either ‘Auckland Workshop’, ‘Southland Workshop’, or ‘Research Community Workshop’. Examples of how Partnerships and Collaboration threads throughout this study are listed in Table 4. This aligns with the literature, which demonstrates that partnerships and collaboration are critical in both research and practice for disaster preparedness, planning, and response [60–63].

3.2. Properties and dimensions of the core category: partnerships and collaboration

The *Partnerships and Collaboration* core category consists of several properties and dimensions shown in Table 5. Properties are “characteristics that define and describe concepts” ([45], p. 220), and dimensions are variations within those properties [45]. Three properties were identified to frame the core category: types of partnerships, the directional approach, and strategies for building partnerships. Dimensions were identified for each of these properties. For example, formal and informal partnerships are the dimensions of the ‘types of partnerships’ property. These properties and their respective dimensions are summarised in Table 5 and will be discussed next, with direct references to the findings reported in previous related papers and to additional interview and workshop data.

3.2.1. Types of partnerships

The first property of *Partnerships and Collaboration* is types of partnerships and collaboration, incorporating the dimensions of formal and informal partnerships.

In the context of this research, a **formal partnership** is defined as one that has been formally established (e.g., mandated, and/or formally outlined and agreed upon in writing) with clear roles and responsibilities between partners and distinct objectives for the partnership. Alternatively, an **informal partnership** is one that has formed rather spontaneously, typically in response to an event to

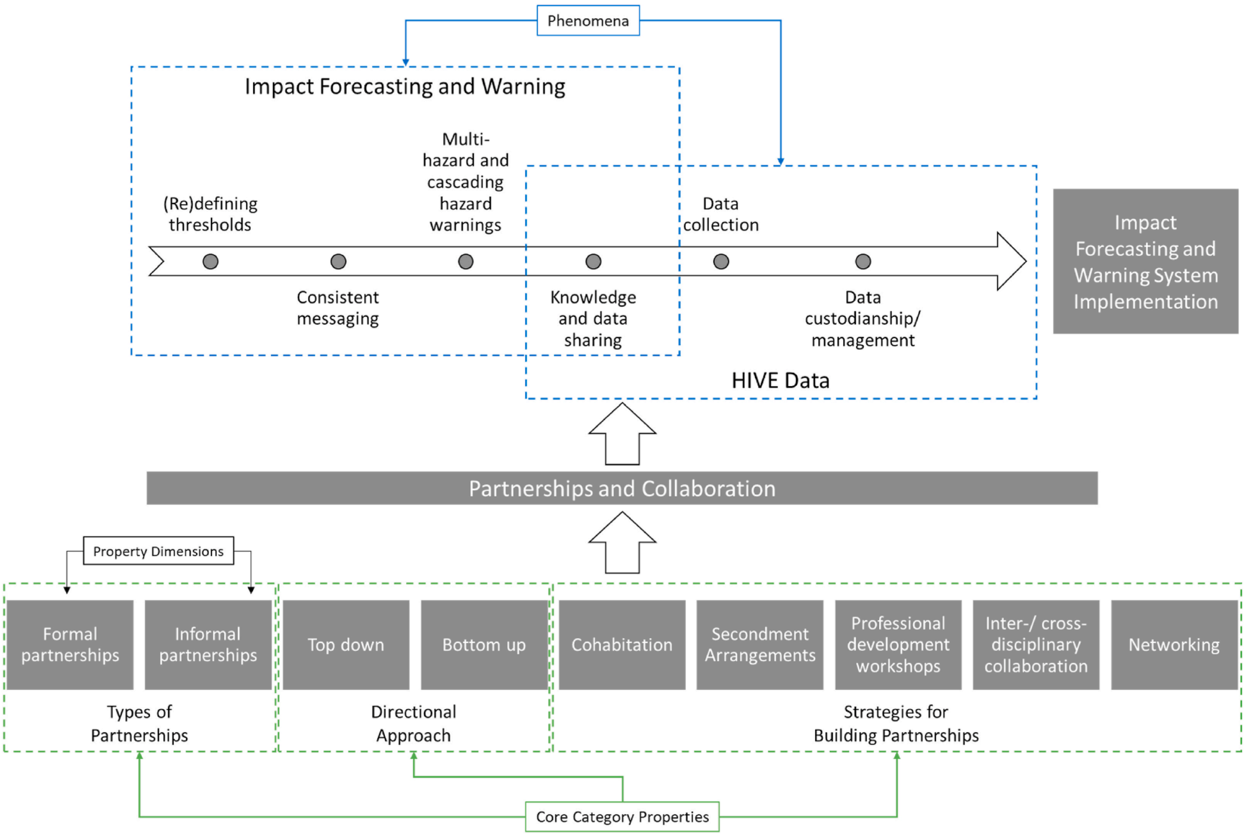

Fig. 5. Integrative diagram of the theory resulting from this study. The figure centres around the *Partnerships and Collaboration* core category for implementing an Impact Forecasting and Warning System. The two phenomena studied in this research (Impact Forecasting and Warnings, and HIVE Data) are outlined in blue. The properties and their dimensions of the core category are outlined in green. The core category is presented in the middle, with arrows linking the properties and dimensions to the two phenomena.

Table 4
Examples of themes relating to the Partnerships and Collaboration core category from the main results of each paper published to date.

Paper Reference	Key findings relating to Partnerships and Collaboration
Harrison et al. [8]	Partnerships and collaboration used throughout the EWS: • Hazard forecasting (e.g., initial discussions with MetService and hydrologists). • Impact forecasting (e.g., sharing data between agencies to support impact modelling in the UK Natural Hazards Partnership (NHP), and conducting impact-oriented discussions across stakeholders such as when the Southland Red Warning was issued, and for forecasting the impacts of ex-tropical cyclone Debbie and ex- Tropical Cyclone Cook). • Impact warning (e.g., defining impact thresholds like the UK MetOffice co-producing an impact matrix with stakeholders and updating warnings based on feedback form the stakeholders). • Co-design of an EWS with the target audiences. • Need for coordinated multi-disciplinary collection of human/social impact data. • Cross-sector collaboration for integrating dynamic exposure and vulnerability data.
Harrison et al. [32]	Partnerships and collaboration are needed to: • Reduce unwillingness to share data, which may be due to a lack of trust between agencies. • Garner support and buy-in across regional stakeholders to allocate resources for better data collection. • Support community leadership to drive innovation.
Harrison et al. [15]	Partnerships and collaboration help to: • Clarify roles and responsibilities, guidance in fulfilling tasks (e.g., Stats NZ helping NEMA manage their loss database). • Facilitate data sharing practices. • Develop integration strategies for seamless data sharing (e.g., developing the Common Operating Picture collaboratively to identify common needs and build trust and partnerships between agencies).

Table 5
Summary of the properties and dimensions of the partnerships and collaboration core category.

Property	Dimensions	Description
Types of Partnerships	• Formal • Informal	Formal and informal partnerships exist for IFW implementation and for collecting, using, and managing HIVE data. A formal partnership is one that has been established with clear roles and responsibilities between partners and defined objectives for the partnership. An informal partnership is one that has formed rather spontaneously, typically in response to an event, to fill an immediate gap, and the roles and responsibilities are not mandated by an authoritative body or document.
Directional Approach	• Top-down • Bottom-up	The directional approach to form partnerships and collaborations refers to the motivation or drivers for the partnerships and collaboration. The top-down direction involves political guidance and a mandate to form the partnership and collaboration, while a bottom-up approach results in self-organised partnerships and collaboration.
Strategies for Building Partnerships	• Networking • Professional Development •Cohabitation • Secondment arrangements • Multi-disciplinary collaboration	Five strategies were identified for strengthening and building relationships that can result in informal and formal partnerships and collaboration and can facilitate either a top-down or bottom-up approach.

fill an immediate gap, and where the roles and responsibilities are not stipulated by an authoritative body or document. The Natural Hazards Partnership (NHP) in the United Kingdom (UK) is an example of a formal partnership developed for providing authoritative and consistent hazard, impact, and risk information to responders and governments [64]. This partnership consists of 17 UK public service agencies and was a result of a post-event review of the 2007 UK summer floods that identified the need for a national framework for reducing risks from natural hazards on the delivery of essential services [64,65].

In Aotearoa New Zealand, no formal partnership like the UK NHP was identified over the course of this study. Instead, formal partnerships were found to exist in the form of science advice groups for non-hydrometeorological hazards, such as the New Zealand Volcanic Science Advisory Panel (NZVSAP; [66]), and the New Zealand Tsunami Expert Panel, as described by Harrison et al. [15]. These partnerships formed in response to gaps in services and communication that were observed from disasters that occurred both within and outside of New Zealand [15]. The purpose of the NZVSAP and the roles and responsibilities of associated members have been clearly identified in the Terms of Reference (see Ref. [66]). The formation of NZVSAP builds on prior regional volcanic science advisory groups, the oldest of which was Egmont Volcanic Advisory Group (EVAG)/Taranaki Seismic and Volcanic Advisory Group (TSVAG) formed in the 1990's [67,68]. EVAG/TSVAG was set up primarily to develop relationships around the newly (at the time) formed seismic network and to bring those data streams and interpretation together [67]. While these groups consist primarily of scientists who provide science advice to Emergency Management agencies in Aotearoa, New Zealand, other groups must be included for response and operations planning. For example, during the 2012 Tongariro eruption crisis, several other sectors became involved in the response, even though they were not initially identified or included in practice scenarios prior to the event [69]. These were the health, agriculture, and veterinary sectors [69].

No such formal science advice group was found in the course of this research for hydrometeorological hazards in Aotearoa New Zealand. However, the Resilience to Nature's Challenges Kia manawaroa – Ngā Ākina o Te Ao Tūroa (herein referred to as RNC) research programme has offered an avenue for starting this conversation. RNC was launched in 2015 and is funded by the Ministry of Business, Innovation and Employment [70]. RNC is a successor to the former Natural Hazards Research Platform, which was a 10-year research programme that funded natural hazards research in Aotearoa, New Zealand and "helped researchers and end-users work more closely together" [71]. A key objective of RNC is to promote innovative and collaborative research to build resilience to the natural hazards in Aotearoa, New Zealand [72]. RNC is composed of eight themes: Rural, Urban, Mātauranga Māori, Built Environment, Earthquake and Tsunami, Coastal, Volcano, and Weather and Wildfire. One participant in this study "always thought the [Natural Hazards Research Platform] was a pretty good vehicle for encouraging collaboration" (Met. Research NZ. J). This participant hopes "[RNC] does the same", indicating that the leaders of the Weather and Wildfire theme "try to be as inclusive as possible in terms of people developing their plans" and act as a "coordination point" for researchers to align with them and with each other (Met. Research NZ. J). This is reflective of the identified need to build interdisciplinary research teams for rapid response disaster research [60,63]. The RNC Weather and Wildfire theme may offer a potential mechanism for building both formal and informal partnerships for hydrometeorological hazard research and mitigation. Still, this may be difficult to implement in practice with no authoritative agency involvement, funding, or mandate [63]. The RNC programme will be ending in June 2024, with no clear next steps for future long-term collaborative research funding.

While few formal partnerships were found to exist in Aotearoa New Zealand specifically for hydrometeorological hazards, informal partnerships exist. One example is between the MetService and regional hydrologists, as described by Harrison et al. [8,15]. This form of partnership relies on the quality of the relationships between the MetService forecasters and meteorologists and the regional hydrologists, which can be influenced by staff turnover, training, interpersonal characteristics. This is considered an informal partnership because it has not been mandated and no guidance has been written to define roles and responsibilities [73,74]. It is a practical strategy developed to meet the need, and to support decision-making for forming and issuing hydrometeorological warnings. An important aspect influencing the types of partnerships and collaboration identified here (formal and informal), is the directional approach adopted when forming those partnerships.

3.2.2. Directional approach

The directional approach to form partnerships and collaborations refers to the motivation or drivers behind it. Top-down and bottom-up are the two directions (i.e., property dimensions) that were identified in the analysis of the interviews and workshops. The **top-down approach** would involve political guidance and a mandate to form the partnership and collaboration, while a bottom-up approach results in self-organised partnerships and collaboration [75]. Thus, formal partnerships are usually created using a top-down approach where a governing body mandates the formation of a partnership, such as the NHP in the UK [64], and makes funding available [62]. Alternatively, informal partnerships usually arise from a **bottom-up approach** where potential partners might self-organise to meet a common need [75]. The Geographic Emergency Management Aotearoa (GEMA) group, formerly named NZGIS4EM and described by Harrison et al. [15], is an informal partnership that was formed from the bottom-up to facilitate effective collaboration and coordination during disaster response efforts, and to build a large community of practice for the GIS and emergency management sector in New Zealand. GEMA played a fundamental role in the coordination of staff and geospatial data in the response to Cyclone Gabrielle in 2023 [76].

Establishing mandates and funding structures by authoritative bodies would further support the establishment of partnerships that enable various groups to effectively collaborate with minimal barriers [60,63]. Both top-down and bottom-up approaches might use some strategies, described next, to build new or strengthen existing partnerships, and build up evidence to obtain funding to sustain the partnerships.

3.2.3. Strategies for building and strengthening partnerships and collaboration

Five strategies were identified for building and strengthening partnerships and collaboration for IFW implementation and HIVE data collection, creation, and use. These strategies (i.e., property dimensions) are **networking, professional development, cohabitation, secondment arrangements, and multi-disciplinary collaboration**.

Networking was identified in the interviews as a strategy for building and strengthening partnerships and collaboration (EM. Gov. NZ. Nat. J). A technical or science advisory group like the NZVSAP and the New Zealand Tsunami Expert Panel may be useful for hydrometeorological hazards in Aotearoa, New Zealand to enable further understanding and consistent communication of the risks and impacts of these hazards (EM. Gov. NZ. Nat. J). This may also facilitate more efficient data access and sharing practices [60]. According to the participants in this study, forming such a group in Aotearoa, New Zealand for hydrometeorological hazards requires building and nurturing relationships by attending national conferences such as the National Emergency Management Agency (NEMA) Conference, NZ Meteorological Society Conference, NZ Hydrological Society Conference, etc., where attendees may test ideas together, garner support, and seek buy-in from higher-level decision- and policymakers (EM. Gov. NZ. Nat. J). For example, MetService staff might attend the NEMA conference, and Emergency Management agencies and council staff might attend the NZ Meteorological Society and the NZ Hydrological Society conferences. This kind of networking may act as a 'catalyst' for sparking connections to bring concepts forward into policy [77,78].

Agencies that often work together, such as the MetService, councils (e.g., hydrologists), and Emergency Management agencies, can also nurture their working relationships by running **professional development** workshops together and hosting these workshops at their own agencies, thereby creating a boundary organisation where agencies can build an understanding of each other's operational processes and create an interactive channel for transferring knowledge (EM. NZ. Reg. K; [79]). One regional Emergency Management agency indicated that the MetService used to host such visits with their group, which they found valuable for nurturing their relationship (EM. NZ. Reg. K). Past workshops held by researchers from CRIs were also seen as beneficial for keeping practitioners up to date on current research efforts and innovations (EM. NZ. Reg. K). These practices are akin to running scenario exercises to build relationships in advance of disaster events, for effective decision-making and communication [80]. Such exercises have proven highly beneficial for building and nurturing partnerships and collaboration for DRR [68,69,81,82].

Cohabitation is a strategy that has been employed overseas to improve flood forecasting and warnings [64,83]. Cohabitation occurs when experts from different disciplines operate from the same location. Co-location and cohabitation have been proposed to allow for the integration of broader expertise and to improve consistency and coordination in multi-hazard warning systems [84]. One such example is the co-location of the Environmental Agency Hydrologists in the UK MetOffice via the Flood Forecasting Centre formed in 2009 to allow for direct and rapid communication between hydrologists and meteorologists [85]. Another example, while not warnings-specific, is the Christchurch Justice & Emergency Services Precinct in Aotearoa New Zealand, where all justice and emergency services are located together in central Christchurch for better integration and coordination of these services [86]. When asked if cohabitation was an option to ease warning communication in Aotearoa New Zealand, our NEMA participant (EM. Gov. NZ. Nat. J) indicated that it could be done in a bottom-up fashion where the MetService and Emergency Management agency/ies and council(s) make their own cohabitation arrangements. This has been done between the NZ MetService and Auckland Council, where a MetService meteorologist sits in the Auckland Emergency Management office. Similarly, a co-author of this paper is co-located with a regional Emergency Management agency. However, the participant indicated that it might be more effective if some political direction was given from the top, for example, if a bill (i.e., a proposed law) were introduced or an existing bill was appended to say that this should be done (EM. Gov. NZ. Nat. J). Doing so would be difficult due to agencies' internal politics, funding sources, operational practices, and governance structures (EM. Gov. NZ. Nat. J). Thus, a starting point would be to look at the governance arrangements of each agency, for example the MetService, NEMA, CRIs, Emergency Management agencies, etc. and determine "how you would bring, and not bring the organisations together, [put] some of their functions together or instruct them" to achieve something together (EM. Gov. NZ. Nat. J).

Secondment arrangements are another approach to facilitating cohabitation (either in person or virtual due to shifts to working from home as a result of the COVID-19 pandemic) and growing partnerships in the science-policy interface (e.g., Refs. [87–89]). Secondment arrangements involve the temporary transfer of an employee from one agency to another. These arrangements between government agencies and research institutions have been uncommon in Aotearoa New Zealand until recently. For example, since late 2021, another co-author of this paper was seconded to a Crown Entity to support risk communication efforts, with other researchers in the DRR space in Aotearoa New Zealand taking up secondments with government agencies and crown entities such as NEMA and [90] to develop partnerships and strengthen relationships to enable more collaborative approaches to reducing risk in the country [90–92]. These arrangements indicate a growth of bridging science and central government. Such growth might be possible at the council level too.

Collaboration between scientists from **different disciplines** (e.g., risk modellers and social scientists) is a needed strategy for ensuring that data collection is comprehensive and accurate, and so that the risk and impact assessments of hydrometeorological hazards go beyond the built environment and extend into social human impacts [8]. This further reflects proposals for building interdisciplinary teams for disaster response research [60] and to support integrated transdisciplinary risk assessment and management processes [61]. Platforms like RNC can enable this kind of collaboration by providing a channel for researchers to engage with each other. Doing so enables knowledge co-production to support collaborative, adaptive, and robust policies [61].

The core category of Partnerships and Collaboration, consisting of the above properties and their respective dimensions, was found to thread through the two phenomena studied in this project (IFW Systems and HIVE Data). Examples of how Partnerships and Collaboration relates to IFW Systems and HIVE Data are discussed next.

3.3. Partnerships and collaboration in the impact forecasting and warning systems phenomenon

Partnerships and Collaboration thread throughout the IFW Systems phenomenon as an integral action/interaction strategy [48] for implementing IFWs. Partnerships and Collaboration enable the important practice of sharing data and knowledge between agencies [15]. Sharing data and knowledge through partnerships and collaboration can then facilitate (re-)defining impact thresholds for an IFW system and can ensure that messages are consistent across agencies. These actions of sharing data and knowledge, (re-)defining impact thresholds, and producing consistent warning messages emerged from codes relating to the IFW phenomenon. Examples of how Partnerships and Collaboration enable these actions in the IFW phenomenon are provided next.

3.3.1. Sharing data and knowledge

Various agencies possess the knowledge and data needed for IFWs, as reported by Harrison et al. [32] and visualised in Fig. 6. Fig. 6 displays the agencies that were identified by participants as those that possess HIVE data for hydrometeorological hazards and impacts in Aotearoa New Zealand, as reported by Harrison et al. [32]. Each leaf of the Venn diagram represents data partners for one of the four data types: hazard, impact, vulnerability, and exposure. The agencies identified by Harrison et al. [32] for collecting or possessing datasets from each data type are placed within each leaf. For example, the MetService was identified as possessing hazard, impact, and vulnerability knowledge and data in various forms: they continuously monitor and collect observational data on meteorological hazards, they monitor severe weather impacts reported in the media, and they possess tacit knowledge of regional vulnerabilities to certain meteorological hazards such as knowing that Auckland is particularly vulnerable to north-easterly winds [8]. They use this information to inform their decisions to issue a warning and how to emphasise and communicate the associated threats. In another example, Data Ventures, a commercial data brokerage branch of Statistics New Zealand (typically referred to as Stats NZ, New

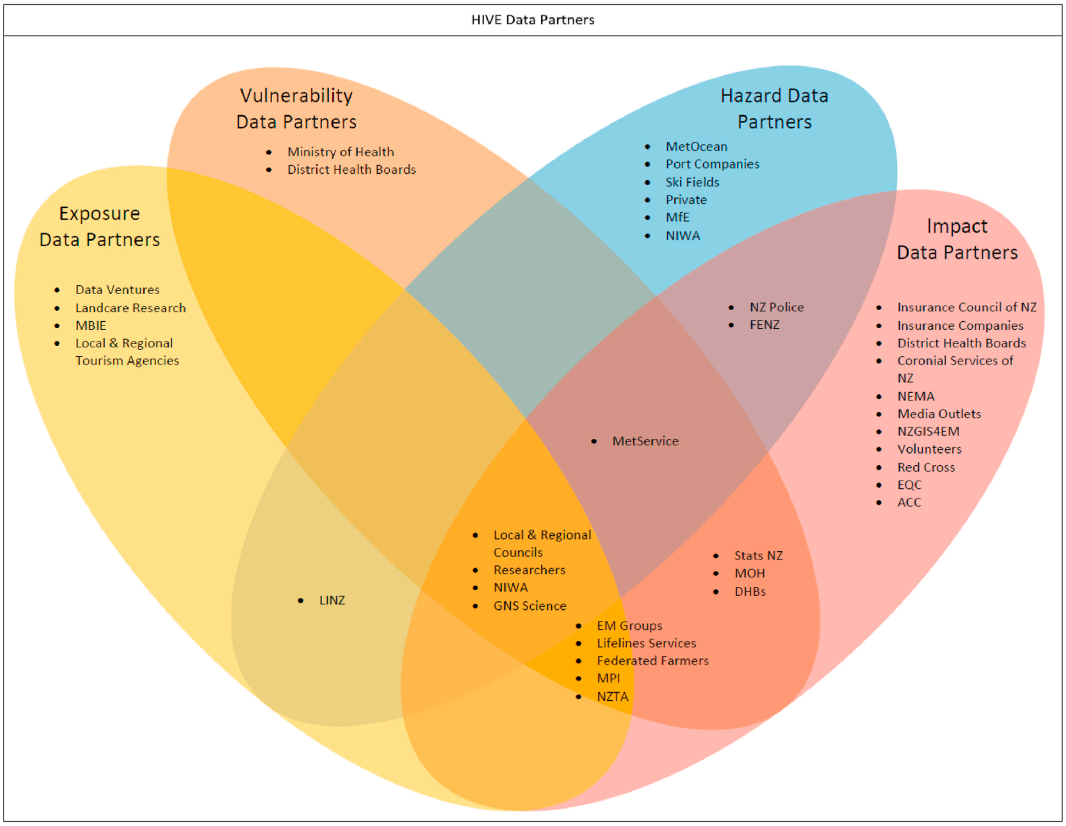

Fig. 6. A Venn diagram displaying agencies that possess HIVE data in Aotearoa New Zealand.

Zealand's national statistics agency), held exposure information in the form of cell phone location data. These data were used recently to inform decision-making around alert level changes in New Zealand in response to the COVID-19 pandemic [32]. There is potential for these data to be useful for risk and impact modelling for hydrometeorological hazards [32].

From the interviews, it appears that at least four groups in Aotearoa New Zealand possess all four types of data needed for IFWs. As shown in Fig. 6, based on the results presented by Harrison et al. [32], these are local and regional councils, university and independent researchers, and CRIs such as NIWA and GNS Science.

Local and regional councils possess data on flood hazards, such as river height and flow gauges, sea level data, river network, overland flow paths floodplain data, coastal inundation maps, slope data, and live camera feeds of river heights. In terms of impact data, some councils were found to use social media, crowdsourcing, and community volunteers to collect reports [32]. Councils also have their staff and contractors conduct damage assessments, and often write post-event reports after a significant event for post-event analysis. Councils possess data or information needed for vulnerability assessments, such as asset information (i.e., characteristics) and building damage assessments. Likewise, for exposure, councils have data on asset location and land-use zoning. Council staff possess tacit knowledge of hazard, impacts, vulnerability, and exposure, much of which is undocumented [32].

Researchers were also found to have various forms of HIVE data based on the interviews and workshops. Researchers often use social media and crowdsourcing to collect hazard and impact data for their own purposes [32]. Researchers indirectly collect data from media reports, and directly from damage surveys and post-event interviews/surveys [32]. Researchers also produce outputs from risk and impact models (e.g., Refs. [93–95]).

From the interviews and workshops, NIWA and GNS Science were the third and fourth agencies found to possess HIVE data in various forms for hydrometeorological hazards. Like the MetService, NIWA collects observational data for hydrometeorological hazards in addition to possessing data on river networks and sea levels in Aotearoa New Zealand. NIWA and GNS Science also conduct risk modelling for hydrometeorological and hydrogeological hazards using RiskScape, and thus collect and possess HIVE data for these assessments. For example, NIWA and GNS Science officials conduct damage surveys following heavy rainfall events to collect flood and landslide damage data respectively for buildings and produce exposure layers based on overlaying spatial asset and hazard layers [95,96]. At GNS Science, efforts are underway to build a Pacific region exposure dataset of buildings for use in risk models [93,94].

While one organisation might contain specific types of HIVE data (as shown in Fig. 6), they may not be useable for IFWs in isolation. For example, GNS Science has landslide hazard data but does not collect rainfall data, instead they obtain rainfall data from the MetService and NIWA. Thus, the distribution of HIVE data across the various agencies represented in Fig. 6 demonstrates the need to share data and knowledge between agencies for IFWs. This argument is supported in related IFW reports (e.g., Refs. [1,97]). The UK NHP is an example of how agencies share HIVE data to support IFWs. Findings from Harrison et al. [8] and Hemingway and Gunawan

[64] highlight how this formal partnership enables the UK MetOffice to obtain key information for their IFWs, such as transportation data from the UK transport authority, to inform their Vehicle OverTurning Model, or population movement (i.e., exposure data) from the UK Health and Safety Executive. Furthermore, as found by Harrison et al. [8], if an agency were to possess all of the required data for IFWs, the agency still cannot issue IFWs if that falls outside of its remit. Partnerships and collaboration thus are important for IFWs, to allow agencies with the required data for IFWs (such as NIWA, GNS Science, emergency management agencies) to work with the mandated warning services (such as the MetService and councils). Still, dynamic exposure and vulnerability, which have been identified as important for IFWs [8,98], were not found to be readily available in Aotearoa New Zealand.

3.3.2. Re-defining warning thresholds

The informal partnerships that were found to exist between the MetService and Emergency Management agencies and hydrologists in Aotearoa New Zealand allow the MetService to (a) include Emergency Management agencies and hydrologists in their decision to issue a hazardous weather forecast, and (b) alert them to the fact that they have issued a hazardous forecast or warning so that they can prepare. They do this by ‘phoning up’ the hydrologists or Emergency Management agency to start the conversation, as shown in Fig. 7, and as reported by Harrison et al. [8].

Fig. 7 provides a conceptual example of a severe weather warning chain in Aotearoa New Zealand and the partners involved in this chain. This figure is the result of diagramming and memo-writing following interviews with the NZ MetService staff, Emergency Management agency officials, and hydrological experts within councils. Starting with monitoring hydrometeorological hazards by the MetService and council hydrologists, when a potentially hazardous hydrometeorological phenomenon is identified (such as heavy rainfall), the MetService reaches out to their hydrological and Emergency Management agency contacts in the region of interest to conduct a risk or impact assessment. This assessment can be discussion-based, model-based, or both [8].

Together the MetService and council may choose to issue a watch or warning and assign the appropriate warning colour (e.g., red or orange). For example, the MetService could issue an Orange or Red Warning based on feedback from the Emergency Management agency and hydrologist(s), considering antecedent conditions and long-term forecasted conditions [8]. The council would also be responsible for issuing a flood warning if needed [12]. The MetService also works with regions to adjust warning thresholds. For example, the MetService has worked with Auckland to adjust thresholds for damaging winds [8]. They also lower thresholds if they know the antecedent conditions might exacerbate the impacts by talking with the hydrologists and Emergency Management agencies to be aware of their current exposure, vulnerability, and response capacities [8]. This shows the importance of communicating and collaborating with stakeholders to define or redefine thresholds based on impacts for more effective warnings.

3.3.3. Consistent warning messages

The consistency of warning messages is critical for effective risk communication [99]. Partnerships and Collaboration are important for ensuring that the warning messages and information are consistent across agencies and reaches target audiences. For this reason, Auckland Emergency Management works with the MetService to ensure the messages they release align with the forecasts and warnings from the MetService (Auckland Workshop). The MetService and a private weather forecasting company in Aotearoa Zealand have worked together over the years to strengthen their relationship to ensure that the messages they are releasing are productive for the public to act appropriately (Met. Private NZ. L). Alternatively, instances of conflicting weather forecasts have also occurred between hydrometeorological agencies in Aotearoa New Zealand where conflicting forecasts were posted on social media channels [100]. Having multiple providers of (sometimes conflicting) weather forecasts and warnings in the media (and social media) may cause public confusion, and lead to potential mistrust of the MetService and their role as the weather warning authority. As demonstrated by Smithson [101], receiving conflicting messages from multiple sources can raise suspicions about the trustworthiness or credibility of those sources. Further research should explore the impact of these multiple weather service providers on public judgement and warning related decision-making in Aotearoa New Zealand.

3.3.4. Multi-hazard and cascading hazard warning messages

It is important to work towards multi-hazard EWSs that encapsulate cascading, coincident, and compounding hazards, as outlined in the Sendai Framework Priorities [102] and in the WMO IFW guidelines [1–3]. As summarised in Section 1, different agencies handle the monitoring, detection, forecasting, and warning of meteorological, hydrological volcanic, and tsunami hazards that present threats to society and the environment in Aotearoa New Zealand. While there is currently no established framework for a landslide EWS or earthquake EWS in Aotearoa New Zealand (although GNS Science is responsible for monitoring, identifying, and analysing both landslide and earthquake hazards [43]), researchers continue to investigate the feasibility of implementing landslide and earthquake EWSs in Aotearoa New Zealand [103–107].

Participants in this study emphasised the importance of taking an all hazards or multi-hazard approach for designing and implementing IFWs (Risk Modelling NZ. A; EM. NZ. Reg. D; EM. Gov. NZ. Nat. G; EM. Gov. NZ. Nat. J). This is because hazards rarely occur or produce impacts in isolation and it is important to consider how cascading, coincident, or compounding hazards produce impacts.

The warning chain shown in Fig. 7 provides one example where a meteorological phenomenon (rainfall) can produce a secondary hazard (flood), which can together produce various societal and environmental impacts. Similarly, heavy rainfall and floods can result in landslides, as demonstrated by recent large-scale heavy rainfall events and Cyclone Gabrielle that produced floods, hundreds to thousands of landslides, and fatalities in various parts of Aotearoa New Zealand 2023 [108,109]. Unrelated hazards can also occur at the same time and exacerbate impacts. For example, while ex-Tropical Cyclone Cody passed northeast of Aotearoa New Zealand and caused rough sea conditions from January 12-16, 2022 [110], the Hunga Tonga-Hunga Ha'apai volcanic eruption occurred on January 15, 2022 and produced a tsunami that hit parts of the Aotearoa New Zealand coastline [111,112]. These two concurrent events produced intense wave activity and subsequent impacts such as flooded campgrounds and damage to a marina and several boats

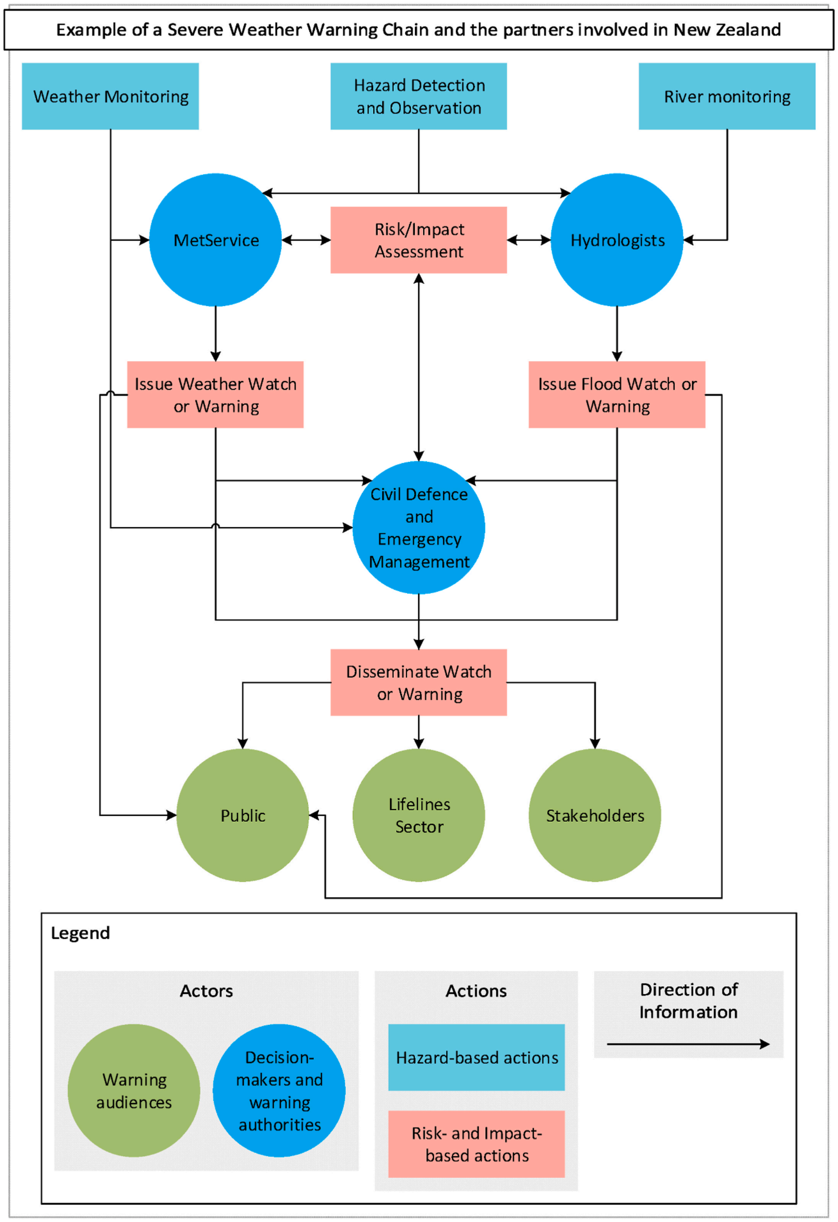

Fig. 7. A conceptual example of a severe weather warning chain in Aotearoa New Zealand and the partners involved. The figure identifies the actors (warning audiences and decision-makers and warning authorities) involved in the warning chain and their actions. The actions are either hazard-based (such as monitoring and collecting observational data of hazards) or risk- and impact-based (where risk and impacts are considered in addition to the hazard information). The direction of information and communication is represented by arrows. Multi-directional arrows indicate that the actors such as the MetService, hydrologists, and Emergency Management agencies both contribute to the risk assessments and are informed by the risk assessment outputs for their warning messages.

[113]. The need to consider these two hazards occurring simultaneously became evident when the authorities had to consider the most appropriate action advice for their warnings and advisories [114]. Given that responsibilities for warning of various hazards fall on different agencies in Aotearoa New Zealand, these agencies must continue to build and nurture strong relationships and communication networks to facilitate rapid data and knowledge exchange such that warnings contain accurate information about the impacts that may be produced from the multiple hazards interacting with, occurring alongside, or cascading after each other.

One regional emergency management official indicated that "[IFW] can be used for multi-hazards" (EM. NZ. Reg. D). One national emergency management participant described how

> "we've recently started some conversations … around … the options to bring together agencies from the emergency services … not around meteorological or natural hazard monitoring but more responding to hazards and risks in their spaces … There's an example of it in Christchurch with … the Christchurch Justice and Emergency Services Precinct, …it's police, fire and ambulance, the courts, NEMA. And it was created as a consequence of the [2011 Canterbury] earthquakes … so they had to rebuild

> and they said ‘everybody's going to be in the same place, we'll have a common operations room and all the agencies will have their own separate things that they need, but when we come together for a thing that's a cross-agency response, we use this common space.’ And I could imagine something [like that] with those natural hazard agencies. But it would need some … direction to be given by basically politically for that to happen because they're all managed in slightly different ways, as you know - boards and CRIs and funding and sources are all different” (EM. Gov. NZ. Nat. J).

This participant points to cohabitation, previously described, as a strategy for improving communication and enabling a more coordinated natural hazards response, including formulating multi-hazard early warnings and the need for top-down approaches to support this.

3.4. Partnerships and collaboration in the HIVE data phenomenon

Due to the distribution of HIVE data sources across these agencies and stakeholders, as previously shown in Fig. 6, partnerships and collaboration are needed to increase accessibility to these datasets and data sources for IFWs and reduce instances of repetition for data collection and creation. Within the HIVE Data phenomenon of this study, partnerships and collaboration were found to affect data collection, data custodianship and management, and data access and sharing, as reported by Harrison et al. [15,32].

3.4.1. Data collection

Many agencies collect and create various forms of HIVE data for various uses [32]. Interdisciplinary or cross-disciplinary collaboration has become increasingly important for disaster-related data collection [60]. For example, Harrison et al. [8] found that to capture the social impacts of hydrometeorological hazards, risk modellers who typically conduct post-damage assessments to calibrate their models should coordinate and collaborate with social scientists to ensure that the templates capture appropriate characteristics to inform social impact models as well, and to ensure that the data collection method itself is ethically sound. Such interdisciplinary collaboration has the potential to incorporate new and shared perspectives to a problem [60]. Collaborators can thus jointly define and scope problems and identify the data types that are of interest to these problems [60]. The overall outcomes of this kind of ‘data-driven’ collaboration can be the production of “more holistic solutions that grow and evolve from the shared space” ([60], p. 1146). Successful collaborations typically have institutional support and a foundation of long-term collaborations [60].

3.4.2. Data governance, access, and sharing

Governance, access, and sharing of HIVE data also involve aspects of partnerships and collaboration. Data governance protocols help to establish authority and control over data by assigning clear roles and responsibilities [115]. Data governance also involves examining practices for data collection, management, accessibility, and use [116]. As reported by Harrison et al. [15], data governance became an important theme in discussions with participants about managing HIVE data. Furthermore, partnerships and collaboration were found to be important for agencies to learn from each other for best practices, particularly for agencies who have not traditionally collected such data in the past. For example, NEMA worked with Stats NZ to receive guidance on best practices for managing the national loss database currently in development for reporting under the Sendai Framework (see Ref. [15]). This example supports the notion that data governance depends on collaboration between the organisations and people of which the system comprises [116]. This includes establishing trusted frameworks for reliable and secure data sharing between organisations [116].

Partnerships and collaboration were found to enable access to and sharing of hydrometeorological HIVE data. The partnerships between the NZ MetService and Emergency Management agencies and hydrologists were outlined in the previous section to inform hydrometeorological warnings, as reported by Harrison et al. [32]. In addition to that, interviews indicated that the MetService shares their data files with hydrologists to integrate with their flood models [15]. Furthermore, the partnerships and collaboration formed in the GEMA community facilitates data sharing across agencies [15].

The MetService and a private weather forecasting company in Aotearoa New Zealand are co-developing amicable data access and sharing arrangements (Met. Private NZ. L). This is not necessarily the case with other agencies due to data sharing restrictions (Met. Private NZ. L). This has introduced a debate around which data should be made ‘open’ (Met. NZ. K). Global calls have been made to make hydrometeorological data openly accessible in a timely manner (e.g., in real time or near real time), citing various economic benefits (e.g., Ref. [117]). However, a review of open access to weather data in Aotearoa New Zealand conducted by MBIE [118] found that most data reuse principles are being met by the involved agencies, but access to observational weather data in Aotearoa New Zealand is more restricted than in other countries [118]. This is due to the State-Owned Enterprise and CRI models under which the agencies operate, which are based on earning commercial revenue to support data collection and cover operating costs [118]. MBIE [118] concluded that the costs to the taxpayers of increasing open access to raw observation data would outweigh the benefits.

While the MBIE [118] review determined that the current accessibility of weather-related data is acceptable when considering the cost-benefit to taxpayers, this issue highlights the importance of forming functional partnerships such that data sharing agreements can be made between agencies [119]. The Weather Enterprise in the USA is an example of a public-private-academic partnership formed across the various sectors involved in collecting, creating, using, and communicating weather information (e.g., Government agencies, emergency management agencies, academia, private agencies, broadcast media, social science) ([120].). The Global Weather Enterprise (GWE) is another example of efforts towards increasing the accessibility of weather information [121]. The GWE comprises all the EWS components, products, processes, and actors that must come together to provide accurate and reliable weather information [121]. As the GWE is collaborative in nature, partnerships across culturally different sectors are essential to its success [121].

4. Discussion and conclusion

There are global efforts to design and implement IFWs to better communicate the anticipated outcomes, consequences, or impacts of the hazard with more context around vulnerability and exposure. This paper is part of a larger project that investigated the data needs and data sources for implementing an IFW system in Aotearoa New Zealand (e.g., Refs. [3,8,14,15]). Partnerships and collaboration emerged as a critical component to facilitating data access for implementing IFWs, and in this paper we drew lessons from across this work to demonstrate the importance of partnerships for IFW systems.

The relationship of Partnerships and Collaboration with the two phenomena in this study (IFWs and HIVE Data) is represented in Fig. 5. Sharing knowledge and data is the crucial interface between IFWs and HIVE Data because it helps to fill the knowledge and data gap identified by meteorologists in practice and that identified from the literature for implementing IFWs (e.g., Ref. [12]). Findings from Harrison et al. [8] showed the needs for HIVE data throughout the warning process for IFWs, such as the need for dynamic exposure and vulnerability information to set thresholds for impact warnings and account for changes in population movement. Additional findings from Harrison et al. [32] identified existing and potential sources for HIVE data that can support IFWs, such as tacit knowledge, damage surveys, social media, crowdsourcing, wellbeing surveys, and insurance claims. However, because the data sources are numerous with many actors involved in their collection and use, the need for effectively managing, sharing, and accessing the data was identified and further explored by Harrison et al. [15]. Thus, it was found that Partnerships and Collaboration are essential for facilitating effective data sharing practices for IFW implementation.

The findings of this study that point to Partnerships and Collaboration as a necessary strategy for implementing IFWs align with recommendations in the WMO Guidelines [1,3] and a guide on impact-based forecasting published by the International Federation of Red Cross and Red Crescent Societies (IFRC; [97]). Partnerships enable organisations to understand hazards, identify impacts, and assess user requirements [97]. The UK's NHP was lauded for "leading the way in moving from hazard-based to impact-based natural hazard research to better understand and forecast potential impacts" ([64], p. 508). Such a partnership allows for including diverse scientific expertise that promotes efficient, robust, and "practically relevant" forecasting tools ([64], p. 508). This current study provides further empirical evidence from the Aotearoa New Zealand context of the need for building and nurturing partnerships and collaboration both for implementing IFWs and for better management of, and access to, HIVE data for IFWs and DRR in general. This contributes to the need identified by Kox and Lüder [11] for international cross-analysis of the meanings of impact weather-related challenges and communication procedures.

Multi-organisational collaboration has many challenges [122]. The process of building partnerships requires extensive time, coordination, communication, and interaction between agencies [64]. Barriers to these factors include resourcing, such as available funding for billable hours, workloads, and establishing roles. Building trust and increasing the willingness of individuals and organisations to participate are additional hurdles [122,123], particularly in organisations or roles where staff turnover may be high (a particular challenge in organisations where staff frequently move between teams or experience burnout and leave the sector). Further challenges include mutually identifying goals and objectives and agreeing on timelines, the use of differing terminology and epistemologies, legal issues around intellectual property and data access, developing workflows and communication standards, and sustaining the collaboration [122,123].

Additionally, individual psychological and behavioural factors can also impede or enable the formation and sustainability of relationships and collaboration. Such factors include, and are not limited to, needs, biases, mood, motivation, preferences, personality, culture, ambitions, attention and memory, and working style as summarised by Patel, Pettitt and Wilson [124]. These factors, combined with other factors such as organisational structure, can shape the organisational culture and its openness and capacity to enter into partnerships and collaborations [124].

Finally, developing partnerships to share data between agencies for an IFW system is based on the initial assumption that agencies that possess the desired data are both willing and able to share these data. Legal and ethical policies and frameworks may prevent the ability to openly share certain datasets (e.g., Ref. [125–127]). Indeed, data privacy laws have impeded the sharing of data between public service and public safety agencies [125]. Lips et al. [125] noted that agencies in Aotearoa New Zealand operating under a public safety mandate are less restricted to information sharing than those operating under the public service mandate. Co-location and information sharing protocols were further identified as enablers to inter-agency information sharing, whereby co-location was observed to facilitate trust-building and information co-creation and sharing, and information sharing protocols allowed staff from other agencies to be treated as "honorary employees" with unrestricted access to the information and data ([125], p. 263). Most recently, the Data Privacy Act prevented the sharing and use of sensitive data for responding to and mitigating the spread of COVID-19 in Aotearoa New Zealand [126]. Consequently, there is a call for debate about the use of data in disaster events in Aotearoa New Zealand [126]. The discussions and legislation would provide a regulatory framework about the appropriate and ethical collection and sharing of data for disaster response and collective public safety, and the deletion of data after an event [126].

When considering sharing of non-sensitive data (e.g., data that are not collected from or about individuals), open access data policies exist to facilitate open and free access to other datasets, such as weather and other hazard monitoring data. However, the current restricted access to weather data in Aotearoa New Zealand prevents the voluntary provision of open weather data.

Similar to the influencing factors of collaboration and partnerships, as summarised by Patel, Pettitt and Wilson [124], an agency's values are likely to influence their approach to open access data in the absence of a more 'open' data access policy. For example, in Aotearoa New Zealand, GeoNet (a partnership between GNS Science, EQC, LINZ, NEMA, and MBIE) collects and distributes geohazard data which they make freely available to the public to support hazard and risk management and research [128]. It is likely that, in addition to the funding structure of the GeoNet partnership, the values of these agencies involved in the GeoNet partnership towards open data access align and thus directly support the open and free access to these datasets.

The findings of this study build on existing recommendations from the international literature to increase interagency communication and partnerships for IFWs and DRR (e.g., Refs. [3,11,97]) by providing more tangible and direct strategies. For example:

- Meteorologists can **directly communicate with the emergency services** in question, as is done in Aotearoa New Zealand using telephone and email. A mailing list or stream of meteorological forecasts and warnings can be made available for emergency responders to loop into and choose to escalate according to their own situation. Simple and direct communication systems can help with the rapid exchange of information and knowledge in high pressure times, as was proven during the 2012 Tongariro eruption crisis in Aotearoa New Zealand where email and telephone communication lines were rapidly established to facilitate communication between key response agencies [69].
- The meteorological service and emergency responders can **work together to define tailored warning thresholds.** For example, the meteorological service can adjust thresholds for a particular area, hazard, or event based on feedback from emergency management agencies who are knowledgeable about their communities' exposure and vulnerability and have experienced or observed the impacts directly. For example, the Aotearoa New Zealand MetService adjusted the severe wind threshold for Auckland due to its vulnerability to northeasterly winds [8]. In the USA, the National Weather Service changed the criterion for severe hail based on empirical research and feedback from emergency management agencies [129].
- The meteorological service, emergency responders, and other stakeholders can **make cohabitation arrangements and run joint training scenarios** together to facilitate visits, and identify needs, or fill gaps in communication. This builds trust between agencies, and helps with mutually identifying goals, clarifying terminologies and epistemologies, and sustaining the collaboration [130]. However, in a combined digital and post-pandemic era following Covid-19, remote working arrangements have increased in practice. Therefore, co-location arrangements should allow for flexibility and the leveraging of new technology to allow for remote collaboration and coordination. One example is to create multi-agency channels on Microsoft Teams, Slack, or similar software tools.
- Attending conferences across sectors **facilitates networking** and scoping initial interest and capabilities in building partnerships and collaboration. The results of the networking exercise may then be brought to policymakers and decisionmakers to implement a more top-down approach for mandating formal partnerships which may then open funding opportunities to support these efforts and provide guidance on legal issues with data sharing.

While the qualitative nature of data collection and analysis herein limits the generalisability of results beyond the participants, this approach offers in-depth understanding of a problem not readily available from quantitative approaches, appropriate for an exploratory study such as this [131–133]. Furthermore, the purpose of theory-building in GTM is not to generalise, but to generate a theory with the most explanatory power for a particular set of data [134]. The results of this study are grounded in the experience and knowledge of the participants of this study in a specific time and place [58]. To increase the generalisability of these results beyond the participants and beyond the context of Aotearoa New Zealand, future research can be conducted to test the concepts developed in this research to a study in another area and/or amongst a different set of participants [135].

The response to the COVID-19 pandemic interfered with the data collection efforts for this study. As such, several key informants were unable to participate in this study due to their involvement in the COVID-19 response, such as Emergency Management practitioners well-versed in the collection and management of Wellbeing and Welfare data. Interview and workshop methods had to be adaptable to the dynamic conditions posed by the COVID-19 risks and response. While in-person interviews and workshops were preferred to facilitate high quality data collection this was not always possible. This created an opportunity to experiment with novel workshop data collection methods, such as the online whiteboard platform Mural. The results of these workshops revealed both strengths and weaknesses of running virtual workshops. Some notable strengths to using a virtual whiteboard to facilitate virtual workshops and to capture data are the lack of additional administrative work required to document and store the resulting data (e.g., there was no need to take photos of sticky notes before packing up the sticky notes, sheets of paper, pens and other workshop materials), the flexibility to design and customise the virtual whiteboard as desired and unrestricted by paper size, and the ability for all participants to remotely interact and participate individually during breakout sessions. However, some of these benefits were only observed when each participant joined remotely from their own computers. In one workshop, we did not anticipate that the participants would coordinate with each other and join online from the same meeting room such that the facilitator/researcher was the only person joining virtually. This made it difficult to record each participants' responses onto virtual sticky notes as the participants had to share the keyboard until one person was anointed scribe to record the responses. While this resulted in less detailed response on the virtual whiteboard, the discussion was found to be richer than that from the other workshops where each participant joined on their own computer. This experience points to further opportunities for learning from and planning future virtual data collection methods, such as to investigate impact forecasting and warning collaborations across distributed global teams.

CRediT authorship contribution statement

Sara E. Harrison: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Sally H. Potter:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing. **Raj Prasanna:** Methodology, Project administration, Supervision, Writing – review & editing. **Emma E.H. Doyle:** Supervision, Writing – review & editing. **David Johnston:** Funding acquisition, Supervision.

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.

Data availability

The authors do not have permission to share data.

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