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Where does scientific uncertainty come from, and from whom? Mapping perspectives of natural hazards science advice

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ABSTRACT

The science associated with assessing natural hazard phenomena and the risks they pose contains many layers of complex and interacting elements, resulting in diverse sources of uncertainty. This creates a challenge for effective communication, which must consider how people perceive that uncertainty. Thus, we conducted twenty-five mental model interviews in Aotearoa New Zealand with participants ranging from scientists to policy writers and emergency managers, and through to the public. The interviews included three phases: an initial elicitation of free thoughts about uncertainty, a mental model mapping activity, and a semi-structured interview protocol to explore further questions about scientific processes and their personal philosophy of science. Qualitative analysis led to the construction of key themes, including: (a) understanding that, in addition to data sources, the 'actors' involved can also be sources of uncertainty; (b) acknowledging that factors such as governance and funding decisions partly determine uncertainty; (c) the influence of assumptions about expected human behaviours contributing to "known unknowns'; and (d) the difficulty of defining what uncertainty actually is. Participants additionally highlighted the positive role of uncertainty for promoting debate and as a catalyst for further inquiry. They also demonstrated a level of comfort with uncertainty and advocated for 'sitting with uncertainty' for transparent reporting in advice. Additional influences included: an individual's understanding of societal factors; the role of emotions; using outcomes as a scaffold for interpretation; and the complex and noisy communications landscape. Each of these require further investigation to enhance the communication of scientific uncertainty.

1. Introduction

The effective provision of science advice before, during, and after emergencies is vital for facilitating a timely, appropriate, and effective response. However, the information and response contexts in which communication occurs are complex, particularly because of the diversity of hazard processes and stakeholder needs (that are driven by demographic, geographic, and circumstantial differ-

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ences) and because circumstances vary over time such that the communication network (representing information flow between individuals and within and across organisations) itself evolves. This adds a dynamic source of uncertainty for all concerned. In addition, there can be considerable individual differences in how people react to information, particularly in novel, uncertain, and threatening circumstances. This variability can arise due to functional needs, biases [1,2], numeracy and literacy [3–5], cognitive and social influences [6–9], framing [10–12], outcome severity [13–16], assumptions about a natural phenomena's base rate or behaviour [17–19], worldviews and mental models [4,20–25], and past experience and perceived relevance [26–29].

Communication must address not only the decision and information needs of a range of audiences [30], but it must also be formatted to accommodate these influences on message interpretations, a particular challenge in uncertain rapidly evolving circumstances. This issue has been highlighted as a global issue for disaster research [31–33]. Additionally, underlying the uncertainty arising from the evolving event and the shifting communication network, is the uncertainty in the hazard science itself and the challenge of communicating it in a way that is understood and actionable by various groups [30,34–36].

Current global events, from climate change and its impacts through to the COVID-19 pandemic demonstrate the clear need to identify effective methods to communicate uncertainty in science advice [37–39], to enable robust decision-making by the public, policy-makers, government, and emergency managers [16,30,40]. However, an important element in facilitating this is to communicate scientific information in a manner that still encourages public and professional confidence and trust, even if the message contradicts their prior expectations [37]. With the high uncertainty and fluctuating conditions inherent to hazards, the latter can often occur. Thus, we must understand how individuals perceive scientific uncertainty *itself*, such that the range of perspectives can be understood and to inform guidelines for more effective and tailored communication.

To develop this understanding, we used a qualitative interviewing technique to explore mental models of science and scientific uncertainty held by various individuals involved in natural hazard risk management [see review in [41]]. Such mental models describe how individuals think the world works [24,42–45], encompassing an individual's understanding of physical systems, how we produce knowledge, as well as cultural, philosophical, socio-political, educational, and organisational influences on understanding [see also [24,42,45]]. They thus provide an invaluable tool to understand different perspectives of natural hazards science and have been successfully used previously to inform hazard and risk communication (e.g., Morss et al. [46]; Bostrom et al. [47]).

We present here the first phase of this study, the collective identification of sources and definitions of uncertainty across a cohort of 25 participants. We next briefly review literature regarding the challenges of communicating risk and uncertainty, before introducing our method.

1.1. Science informing risk communication

Historically the study of effective risk communication has been conducted independently from the study of effective science communication [see review in [23]]. However, for natural hazards, the communication of the associated science is inherently interwoven with, and crucial for, the effective communication of associated risk and risk assessments. As highlighted by Aitsi-Selmi et al. [48] such scientific knowledge is vital for the achievement of the Sendai Framework (especially Priority 1: Understanding disaster risk), and therefore there is an urgent need to integrate science and technology more effectively when informing decision making about risk. Most disaster risk communication focuses on managing the flow of information, building awareness, generating warnings, and governing responses. This is generated through both top-down approaches as well as through partnership and community-led 'ground-up' approaches [23,49,50]. However this communication is not just limited to providing information about hazards and risks; it also includes actionable information, such as how to prepare for, protect against, respond to, and recover from risk [51]. This communication is critical to the management of hazards, as it allows people to make informed decisions about risk, and how they might respond to it [23,32,36,52,53]. If there were perfect knowledge about a user's risk, communication would be simple: effectively convey this knowledge to the user [54]. However, usually knowledge is imperfect and incomplete, with uncertainty arising from numerous sources within, and associated with, the scientific process, including those directly associated with unknowns and conflicting information in technical data and model assessments [29,30,55], as well as broader uncertainties arising from problem formation, value judgments, and societal, cultural, and epistemic differences [30,56,57] This creates significant science and risk communication challenges [58,59], in turn resulting in additional communication uncertainties [23].

1.2. The challenge of scientific uncertainty

Managing uncertainty is a key issue in risk communication [54,60–64]. When identifying how and what uncertainty to communicate, a considerable challenge arises from the many types of uncertainty that exist in science information and advice [30,65–68]. A systematic thematic review by Doyle et al. [30] identified that key uncertainties include those related to stochastic uncertainty (the variability of the system), to epistemic uncertainty (lack of knowledge and differences in theoretical orientation), and to disagreements amongst scientists due to incomplete information, inadequate understanding, and 'undifferentiated alternatives' which describes equally attractive or conflicting choice options [16,69]. In a disasters context, uncertainty affects scientific advisors' communication decisions, as well as the decisions of emergency managers who depend upon that advice [34], and has multiple sources that can contribute to communication challenges prior to disaster. For example, reflecting on the L'Aquila earthquake, Benessia and De Marchi [70] identify a range of uncertainties that may have contributed to communication issues beyond just the scientific, including legal, moral, societal, institutional, and proprietary, appraised collectively as an overall "situational uncertainty" (p. 39).

Because of this complexity, defining what uncertainty represents and where it comes from has thus been a pressing challenge across multiple domains, including disaster risk reduction, climate change, public health, economics, and psychology (see reviews in Refs. [30,65]). Research has focused on how to identify it, communicate it, manage it, and make decisions in its presence, and in particular how to *define* it, resulting in a range of definitions. For example, working groups I, II, and III of the IPCC Sixth Assessment Report define uncertainty as "*a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable*" [71,72], building upon approaches used in previous IPCC reports and recommended by Moss & Schneider [73] and Mastrandrea et al. [74] to represent that uncertainty quantitatively and qualitatively. Meanwhile, they also define deep uncertainty as a situation that exists when experts or stakeholders do not know or cannot agree on conceptual models, uncertainty probability distributions, and how to weigh and value desirable alternative outcomes. In comparison, more technical definitions of specific uncertainties, such as those associated with modelling and simulation, focus more on the sources of uncertainty (see review in Ref. [30]), including those associated with the problem definition, the structure of a model, initial conditions, parameters, scenarios, data, outcomes, validation, and software decisions (see e.g., Refs. [75–77]).

Stirling [78] extends the definitions further and proposes an uncertainty definition should focus not only on risk, but on ambiguity and ignorance in order to assess and convey incomplete knowledge for policy-makers (see also [79]). As outlined by Scoones [57] these varying definitions of uncertainty differ depending on how societal, political, cultural, practice, and individual perspectives are incorporated. Thus, how uncertainty is then managed and communicated also varies, from structured quantified approaches with guidance around use of language [71,73,74,80], to recommendations for the classifications of levels and natures of uncertainty via typologies (see review in Ref. [30]), and through to approaches that communicate via scenarios, event trees, adaptive pathways planning, or narrative storytelling (e.g., Refs. [81–86]).

An important consideration for the management of natural hazards is how to effectively communicate scientific advice and associated uncertainties to non-scientific audiences, which can include emergency managers who must make time-sensitive and challenging decisions. The intended audience may not understand technical terminology or the process of science itself, particularly how science handles uncertainty, or that scientific conclusions are always uncertain [35,87–89]. Another consideration is a disconnect between what non-scientists and publics expect of science and what science actually does [62,90,91]. For example, some individuals may understand science as a search for 'truth', while others may understand it as a process of exploration or debate [35,90,92]. Further, scientists and non-scientists may have fundamentally different understandings of how confident we can be in scientific findings and have different notions as to what constitutes evidence for or against a theory or hypothesis, and how that relates to the presence of uncertainty [30,78,93,94].

Despite some difficulty with deciding which uncertainties, and how much uncertainty, to communicate, it is generally accepted (and encouraged) that uncertainty in science should be acknowledged and communicated [61,95]. If uncertainty is not communicated effectively, decision makers (either those in disaster management who make decisions for communities, or the public who make decisions about themselves) may put too much or too little faith in the science advice [54,61]. For example, if faced with too much uncertainty, people may be prompted to inaction. In contrast, uncertainty that is communicated well has the potential to promote motivation rather than demotivational anxiety [19,96], encouraging risk management actions such as the purchasing of home insurance [62].

Providing information about uncertainty has been shown to both increase and decrease the perceived credibility and trustworthiness of the communicator, and the legitimacy of the information [53,54,87,91,97,98]. These different outcomes have been shown to relate to the quality of the relationship between the communicator and receiver, the prior credibility of the communicator, the interpretation of messages, past experiences, and personal attitudes [35,88,91,99]. As concluded by Balog-Way et al. [53] these positive or negative effects "are strongly influenced by how well uncertain risk information is communicated in the first place" (p. 2249).

Trust between scientists, officials, and the public can also be damaged by perceptions of the messages communicated, such as accusations that officials or scientists are 'crying wolf' (Kilburn [95]). However, as discussed by Fischhoff and Davis [61], if a call to action proved to be unnecessary, it could be that the science was highly uncertain or the threshold was overly cautious (see also Rabinovich & Morton [35]). Thus, increasing people's understanding of this uncertainty is crucial to improve tolerance of any overwarning situations. Different perceptions and tolerance levels of uncertainty may require adapted and tailored risk communication for this to be effective [30,35,93]. Similarly, the communication of uncertainty in isolation from ethical, political, and societal concerns can cause ongoing challenges, and has been attributed by Benessia & de Marchi [70] as contributing to the controversies surrounding the communication prior to the L'Aquila 2009 earthquake and the subsequent legal proceedings.

While historically there has been debate as to whether one should acknowledge uncertainty or not, due to its potential for negative outcomes discussed above (see also reviews in van der Bles et al., [100]; Hudson-Doyle et al., [34]; Doyle et al. [30]), current research and practice has identified that it is vital to communicate it [40,76,80,101–103] to assist effective decision-making. The World Meteorological Office recommends uncertainties be communicated as it reflects the state of science, promotes user confidence, improves decision-making, and helps manage user expectations [80]. Similarly, other international bodies (e.g., the International Panel for Climate Change, the National Research Council of the U.S. National Academies, and the International Commission on Earthquake Forecasting for Civil Protection) [74,80,104,105] and academic literature reviews outline how this can be done (e.g., Spiegelhalter [103]; Doyle et al. [30]; van der Bles et al. [100]). These consider both the technical aspects of communication as well as the social and organizational context and influences on the communication landscape. However, several challenges still exist. In particular, while recommendations highlight that effective communication requires that consideration must be given to the audience's beliefs, expectations, and worldviews [23,30,35,97,106], to achieve this recommendation there is still a need to understand how to identify those perspectives, what they are, and how they influence the communication and receipt of uncertain science information and advice.

1.3. Rationale

Key challenges across all domains and perils include understanding how individuals understand and define uncertainty themselves, and what they consider the sources of that uncertainty to be. Miscommunication can arise between scientists and policymakers, decision-makers, other scientists, and the public if assumptions are made about a shared mutual understanding of uncertainty. However, often what an individual understands uncertainty to be, and what it constitutes, is not the same as what a scientist or communicator understands, and we have poor understanding of this diversity in understanding. While explicit definitions of uncertainty may exist (see section 1.2), these may not be intuitively used; and so effective communication requires understanding how receivers of information conceptualise and define uncertainty *themselves*, such that we can successfully design and apply guidelines for communicating uncertainty [23].

Rabinovich and Morton [35] identified epistemic divides at both individual and public response levels as one of the reasons people may not act upon a risk message in the manner expected by a communicator. People are not just influenced by how the message is framed, but also by their prior expectation of the content of the message, which depends upon their personal framing and expectations of science. Their prior expectations are dependent upon their mental models: how they understand the phenomena and issue, and its dependencies and causes [24,36,41]. Similarly, Maxim and Mansier [91] also identified that an individual interprets information based upon their model of the science. As defined above, this mental model includes many related aspects and influences, and may help explain why scientists, non-scientists, and decision-makers interpret information differently, including, for example, probability statements (e.g., Doyle et al. [65]).

Most existing research exploring the influence of different perceptions of science, or of scientific information, is usually focused on science advice for long term policy or risk management decisions or considers quite context-specific situations (such as the IPCC communications; [107]). Other research, including that on effective aftershock communication following the Christchurch earthquakes [29], highlights the need to adapt the provision of science information to the perspectives, needs, roles, and experiences of different audiences. This is particularly important for effective multi-team coordination [108], where building shared awareness that accommodates different understanding is vital for response [109].

The above demonstrates how the communication of scientific uncertainty can impact trust in, and use of, scientific information and advice. However, while several studies have explored how individuals react to the communication of uncertainty in different contexts, there is still little understanding of how the different communication audiences involved in natural hazard management conceptualise scientific uncertainty themselves, and where they think it comes from, and thus how those perceptions influence interpretations of communication and subsequent decisions to act. It is crucial to understand these views if we are to effectively enhance communication that addresses the differing perspectives of uncertainty and engenders and maintains trust across audiences [30]. In this research we thus seek to develop this understanding by exploring individuals' mental models of scientific uncertainty, driven by the research questions:

1. What key factors characterise the mental models of scientific uncertainty amongst the diverse individuals involved in the management of natural hazards (including scientists, emergency managers, local and regional councils, policy-makers and planners, and broader community members)?
2. Where do these individuals consider uncertainty comes from, and from whom? And
3. How do these individuals define uncertainty?

Findings from these questions and an improved understanding of the perceptions of uncertainty will enable communication guidelines to be improved, as well as signalling areas that require further work.

For the purposes of this study, and when recruiting participants, we used a broad initial definition of uncertainty as "unknowns associated with, or within, science and science advice" from which our participants conversations then developed. Explicit definitions, such as those in section 1.2, were not provided such that participants were not biased or influenced by them and were free to define uncertainty in ways and terms that met their own understanding, explained further in Section 2, next.

2. Method

A three-phase interview was developed to understand individuals' perceptions of uncertainty associated with natural hazard science. This was developed based upon a systematic review of mental model interview approaches by Doyle et al. [41], and based upon the Conceptual Cognitive Concept Mapping (3CM) approach of Kearney and Kaplan [110] and Romolini et al. [111], which is a less constrained form of mental model mapping interview (compared to for example [47,112]). **Part 1** of the interview contained three initial direct elicitation questions around uncertainty in science, including asking participants to define what uncertainty means.

In **Part 2,** the mental model mapping activity, participants brainstormed where uncertainty came from with post-it notes, which they then arranged into clusters to represent their perception of sources of uncertainty in natural hazards science. **Part 3** involved a semi-structured interview protocol of indirect elicitation questions, to explore their broader understandings of the philosophy of science, as well as their epistemological and ontological understanding, and views on effective communication. The full interview protocol is provided in Appendix 1.

This structure and ordering were chosen to reduce the influence of the researcher by enabling initial free thought responses with few prompts in part 1 and 2 [113], as well as enabling participants to structure and organise their own thoughts systematically through the clustering of post-its [41,114]. The use of a creative, tangible, and visual post-it brainstorming and clustering process such as this has been identified as also promoting higher-level thinking [115]. The tactile nature enables access to more implicit knowledge [116] by enabling participants to explore their understanding of the topic through a media beyond spoken language (see review in Doyle et al., [41]). The latter semi-structured protocol in part 3 then explores participant perspectives of specific topics of interest that may not have been raised by the participants in part 1 and 2 of the interview.

Interviews were conducted by the lead author (EHD) either in person, or virtually via Zoom. For part 2, the in-person participants were provided with a large sheet of paper, markers and post-it notes, while the virtual participants were directed towards a virtual online whiteboard (Mural[2]). At times, the interviewer acted as scribe for the participants, noting their ideas onto post-it notes, either in-person or virtually. At the end of the full interview, participants were invited to reflect on and revise the post-its and maps produced in Part 2. Images (photos or screenshots) of the brainstorming and post-it mapping activity were captured periodically throughout the interview and at the end of the interview. The total interview took between 60 and 90 min, depending how much the participant chose to share. Interviews were audio recorded and transcribed verbatim for later analysis. Interviewees were each offered a NZ$40 supermarket voucher as a thank you. The Massey University Code of Ethical of Conduct was followed, and this research received a Low-Risk Ethics Notification Number of 4000023593. Pseudonyms are used when referring to each participant.

2.1. Study location and participants

This research was conducted in Aotearoa New Zealand (AoNZ) which is exposed to a wide variety of natural hazards including earthquakes, volcanoes, severe weather and its impacts (flooding, landslides), near-coast and far-field tsunami sources, and seasonal drought. In the last decade, AoNZ has experienced a series of such shocks, including the 2010–2012 Canterbury earthquake sequence (including Mw7.1 & Mw6.2 events), the Mw6.6 2013 Cook Strait Earthquakes, the Mw7.8 2016 Kaikōura earthquake, the 2012 Te Maari volcanic eruption, the 2019 Whakaari volcanic eruption, and most recently the 2023 Auckland Floods and Cyclone Gabrielle impacts to the east coast. Across these events lives have been lost, and the socio-economic impacts have been significant. For example, in 2013 Treasury estimated the capital costs of the Canterbury earthquake to be over $40 billion, equivalent to 20% of the gross domestic product, while the recent Auckland floods and Cyclone Gabrielle impacts are estimated by Treasury to cost between $9–14.5 billion due to the broad damage to land, homes, and infrastructure.[3, 4] Unfortunately, this latter hazard and impacts will only increase under future climate change, with future impacts subject to many evolving uncertainties. Thus, research both internationally and nationally is working to identify how to understand the influence of climate change on natural hazard uncertainties and risk (e.g., Refs. [117–119]), and to address the challenge of planning natural hazard mitigations under uncertain climate change futures (e.g., Refs. [120,121]). The growth of this integration of climate change and disaster risk reduction is also evidenced in practice in AoNZ, with climate change now a core thread to both the National Emergency Management Agency's Disaster Resilience Strategy[2] and Toka Tū Ake Earthquake Commission's (the Natural Hazard Insurance Agency) research investment priorities.[5]

Due to AoNZ's small population, many scientific experts operate in multiple fields in ways that are less common in other countries. For example, members of the NZ Volcanic Science Advisory Group overlap with members of the Aotearoa Earthquake Science Advisory Panel. Similarly, planners, policymakers, and decision-makers work across these hazards, while the public often have indirect and direct exposure across this hazard spectrum due to the high levels of social connections across geographical regions in AoNZ. Thus, AoNZ offers an ideal location within which to study individuals' mental models of uncertainty *across* the natural hazard spectrum, as well as being preferable due to the important need for this study to be locally grounded and relevant, with a direct pathway to implement communication lessons [122]. Accordingly, we sought a range of participants involved in the management of AoNZ's spectrum of hazard events, who were recruited using a snowball approach via email contact with individuals in organisations from across the natural hazards and disaster management sector. For this study the scope included the science and research community (including universities, consultancies, and crown research institutes), emergency management and civil defence authorities, local and regional councils, the policy and planning communities, and broader community members who may act upon associated information. We also advertised in different community or organisational newsletters, such as those of Aotearoa NZ's Resilience to Natures Challenge Science Challenge[6] and the QuakeCoRE project.[7] As we were interested in exploring and identifying how people conceptualise scientific uncertainty *across* multiple natural hazards, recruitment was not focused on any one hazard. In addition, as many scientists and decision-makers often work across multiple hazards, isolating their mental models of uncertainty per hazard could be unreliable. Thus, participants generally came from contexts where they planned for impacts using an 'all-hazards' approach (as is often adopted in AoNZ), or included scientists who studied multiple related or cascading meteorological or geophysical hazards. Throughout our conversations, participants were encouraged to constrain their scope of conversations to natural hazards, however some did make references to climate change and to the COVID-19 pandemic situation at the time of the study.

Participants needed to be 18 years or older to participate in this project. In total, 25 participants were recruited to the study and were assigned a pseudonym prior to interview. All were residing in Aotearoa New Zealand at the time of the interview. Given the exploratory nature of this study described above, a wide range of participants were selected for interview. Professions included 4 physical scientists, 2 boundary or other knowledge transfer scientists, 2 social scientists, 6 policy writers/analysts and planners, 2 engineers, 4 emergency management practitioners, 2 with a legal background, and 3 others that included a journalism student, an anthropologist, and a geography teacher. All had undergraduate education, with many having completed or working towards postgraduate

[2] https://www.mural.co/(last accessed 27/02/2023).

[3] See the National Emergency Management Agency's National Disaster Resilience Strategy, https://www.civildefence.govt.nz/cdem-sector/plans-and-strategies/national-disaster-resilience-strategy/(last accessed 3/8/2023) and AoNZ Government's Budget 2023 https://www.beehive.govt.nz/sites/default/files/2023-05/Summary%20of%20Initiatives%202023-NIWE-14%20May.pdf (last accessed 3/8/2023).

[4] "Repair bill from cyclone and Auckland floods at least $9bn, Treasury estimates"; https://www.stuff.co.nz/business/131883544/repair-bill-from-cyclone-and-auckland-floods-at-least-9b-treasury-estimates (last accessed 3/8/2023).

[5] Toka Tū Ake EQC's Research Investment Priorities Statement 2021–2023, https://www.eqc.govt.nz/assets/Publications-Resources/Resilience-and-Research-Publications-/Research-Investment-Priorities-Statement_2021_2023.pdf (last accessed 3/8/2023).

[6] Resilience to Nature's Challenge is one of Aotearoa New Zealand's National Science Challenges. Kia manawaroa – Ngā Ākina o Te Ao Tūroa. They are collaborative research projects funded by the Ministry of Business, Innovation and Employment to tackle the biggest science-based issues and opportunities facing Aotearoa New Zealand https://resiliencechallenge.nz/.

[7] QuakeCoRE is the NZ Centre of Research Excellence for Earthquake Resilience, Te Hiranga Rū, funded by the AoNZ Tertiary Education Commission, and bringing together inter-disciplinary researchers across programmes focused on advancing earthquake science and resilience. http://www.quakecore.nz/.

education in their professional field (post graduate diploma, masters, or PhD). All except the student had a minimum of 3 years' experience in their field.

Ages ranged from 25 to 75 years old, with nine participants identifying as male and 15 participants identifying as female. Ethnicities included 16 who identified as NZ European, five as Pākehā,[8] 5 identified as European (including Italian, English, and British), and the remaining identified as Māori/NZ European, Latino, Iranian/Middle Eastern. One participant chose not to disclose demographic details.

2.2. Analysis

A reflexive thematic analysis approach (as described by Braun and Clarke [123]) was used to code the transcribed interviews alongside the photographed mental model maps. This was conducted using NVIVO software by the research assistant (JT), in a reflexive consultation with the lead author (EHD). JT has a background primarily in critical health psychology with emerging experience in the disaster research space. EHD has a combined background in both physical and social science of natural hazards and disasters, with education in geophysics, volcanology, and meteorology, and over 12 years subsequent research in disaster social science, risk communication, and decision-making.

The thematic analysis approach produced 86 unique codes. These were condensed into three clusters that represented the three main concepts underlying the full interview guide: 'uncertainty', 'knowledge', and 'science'. The current manuscript uses the first cluster of codes 'uncertainty' to answer the core research questions (Section 1.3). Underlying patterns of shared meaning across the 'uncertainty' codes led to the construction of three key themes, which are presented next (Section 3).

To support the interpretation of the thematic analysis findings, the post-it mental model maps were also considered collectively to develop a cohort interpretative mental model map containing key constructs as a visual aid to consider alongside the themes presented here and facilitate deeper understanding of the linking and dependent issues between themes (similar to Cassidy and Maule [114]). This was inferred by the research assistant (JT) via a summative content analysis of the maps' brief text statements, by looking for exact or similar key words from the maps and grouping them into overarching clusters with links describing any dependent relationships.

Finally, it also became clear from the interviews that there is an issue of confused language and descriptive terminology when it comes to 'uncertainty', representing a form of *linguistic uncertainty* [124,125]. Thus, to further inform research question 3, an additional summative content analysis [126] was conducted on their responses to defining uncertainty. This provided a more direct approach than reflexive thematic analysis for this issue, and involved comparing keywords, content, and statements, allowing us to understand the range of definitions, terminology, and language being used to represent the term 'uncertainty' specifically. It also provides a foundational context and understanding of the range of these definitions across the cohort of participants which may then influence the broader reflexive thematic analysis and interpretation, which is alternatively focused on understanding the underlying patterns of meaning from across the dataset.

3. Results

Through the thematic analysis of the transcripts and maps generated by participants, we interpreted three leading themes that describe *sources of uncertainty* to address research questions 1 and 2. These themes include: 'the data', 'the actors', and 'known unknowns'. Additionally, a smaller standalone fourth theme was recognised: 'sit with uncertainty', which relates to how participants discussed dealing with the overall uncertainty rather than focusing on a source of uncertainty.

When presenting the themes, we present relevant quotations from participants and also summarise perspectives collectively across participants to represent the deeper patterns of meaning across the data set (Braun & Clarke [123]). Development of the collective 'concept' map described in Section 2.2 was supported by the interview analysis, and is illustrated in Fig. 1. This visual aid enabled further reflection with the purpose of identifying factors that influence key themes, connections between them, and associated dependencies. It also helps prioritise those factors individuals found to be the most influential sources of uncertainty from the range identified through the interview discussions and analysis themes.

Before presenting the themes, which are summarised in Table 1 (with example quotes in Appendix 2), a brief definition of uncertainty as described by the participants is offered next to provide context and to address research question 3. It demonstrates the difficulty people have understanding and defining exactly 'what uncertainty is'.

3.1. The challenge of defining uncertainty

During the interviews, many participants seemed to struggle to 'grasp' the words to describe the concept of 'uncertainty'. While some participants described it in terms of 'not knowing', the 'unknown', or being 'not sure' of something, others found it amusing that they could not describe uncertainty without simply saying they were 'uncertain' about something or without using the term 'uncertainty' itself. Across the participants' initial definitions of scientific uncertainty, it becomes clear that there are a variety of perspectives ranging from uncertainty in the scientific process, uncertainty related to the outcomes and impacts for decisions, and uncertainty as an intrinsic state of knowledge and part of science itself. These descriptions embody the difficulty the participants experienced in attempting to define this nebulous and complex concept, resulting in the variety of definitions provided. It was also noted

[8] Pākehā is common parlance in Aotearoa New Zealand and means "New Zealander of European descent" in the Māori language, the indigenous language (Te Aka Māori dictionary, https://maoridictionary.co.nz/, last accessed 02/03/2023). Individuals may define Pākehā as representing people with European ancestry and who are of multiple generations in Aotearoa New Zealand, and thus being distinct from more recent European immigrants ("tauiwi").

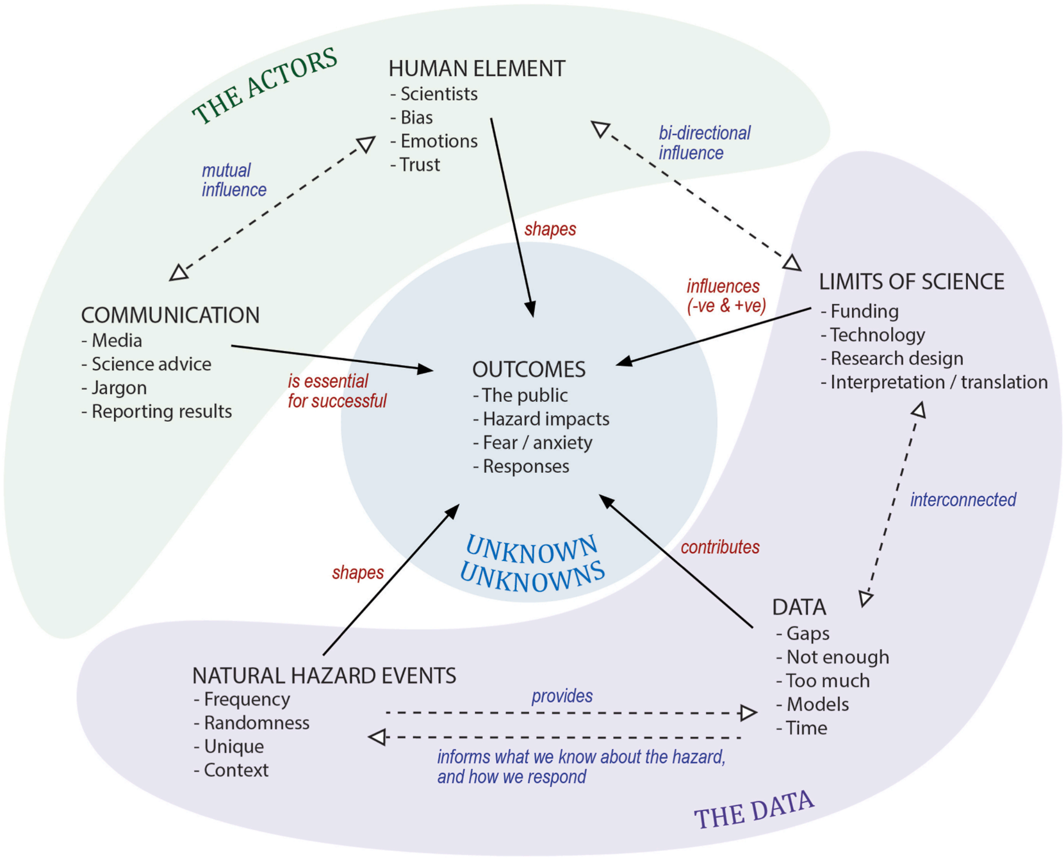

Fig. 1. The collective concept map inferred from individual participant mental maps and thematic analysis of interview transcripts (Section 2.2). Concepts illustrated include a central node "Outcomes" which is influenced both positively and negatively by the "Limits of Science" (a Source of Uncertainty: The Data, Section 3.2), is shaped by "the Human Element" (The Actors, Section 3.3), and the "Natural Hazard Event" characteristics themselves (Section 3.2.2). In turn "Data" quality and characteristics (Section 3.2.1) contribute to these Outcomes, and "Communication" (Section 3.3.3) is essential for successful outcomes. Relationships and dependencies between these elements also exist. For example, "Human Element" has a bi-directional influence on "Limits of Science", describing how scientists who may prefer specific research designs may be limiting the available results and thus creating uncertainty. Similarly, the scientific project design or issue prioritised for research may attract scientists with particular biases in the design of their work, creating uncertainty in the developing scientific knowledge for that issue. It is likely that this map, and the locations of uncertainty, may change through the time frames of natural hazard risk management, through the steps of risk analysis, and dependent upon different responsibilities. This should be explored in future research.

that the process of identifying the different sources of uncertainty helped participants develop a clearer sense of, and articulate, what is meant by the term scientific uncertainty, leading to the themes 'the data', 'the actors', and 'known unknowns' (see sections 3.2-3.4).

Participants seemed to find it easier to use tangible examples to help expand their definitions, referring and relating it to natural hazard events (NHE) in the context of the interviews:

> *So uncertainty - just not knowing, being unsure. If we talk about natural hazards, I think most people that aren't science people have uncertainty because we don't understand what's happening, or the causes behind it. People sort of know how an earthquake works for example but we don't understand what impacts different levels are going to make on us. I think uncertainty too around we don't know when a natural hazards going to occur* – Alif (Local Government/Civil Defence & Emergency Management (CDEM))

Alif represents a view expressed by many of the participants who would not describe themselves as scientists and whose definitions differ distinctly from many of the more technical descriptions scientists gave. Alif notes people who do not understand science may have more uncertainty because they do not understand '*what's happening*', particularly around '*impacts … on us*'. Views similar to this were expressed by a number of participants, where their understanding of uncertainty expands beyond the science itself to encompass the uncertainty around outcomes, what it means for them, whether it can be made meaningful, and its impact on dependent decisions (building on Doyle et al. [65]).

In comparison, more science-focused descriptions of uncertainty included describing uncertainty as 'lack of information or data', having 'more than one outcome', being unable to 'land on an absolute answer', and an answer being 'not exact or definitive'. These participants often used the context of being able to 'predict' when a future NHE may occur, for example an earthquake, or being able to predict the outcomes of the event, such as where the next earthquake would hit (i.e., urban or rural setting).

Table 1
Themes constructed from the interview data and maps regarding participants perspectives of sources of uncertainty in natural hazards science and advice. For each theme, the codes and sub-codes are shown, including code descriptions.

Theme	Master Code	Sub Code	Code Description
The Data	Not enough data or gaps in data	Uncertainty comes from data	Is there uncertainty in the data, what data available, gaps in knowledge, how do we understand data
		We don't have all the information we need	Volume, quality, source, gaps, unique information
		We don't know everything	What we know now, don't have a definitive answer, need more info, is this helpful
		Reaching thresholds of information	Reaching a threshold of information
	Models/Technology	Depends on what you feed into a model	Are models effective, missing data means less effective, how they're used to inform decisions
		Model types and parameters create uncertainty	How accurate are models, what they can produce
		What role does technology play?	How it can help us, will it help us, do we have the tech we need
		Not enough time to get information	Increases uncertainty, not enough time to get information
	Interpretation of data	How data is interpreted/ evaluated in science	Drawing conclusions
		Can we have confidence in this?	In data, in outputs from models, in advice given, in understanding data
		Translating or interpreting science creates uncertainty	How it's used
	Uniqueness of Events	You can't predict an earthquake	Can they be predicted, difficulty predicting
		Can past events inform the future	Learn from, inform future
		Uniqueness of disaster events themselves	No two earthquakes are the same
		Uniqueness of the context disasters occur	e.g., Auckland vs Wellington, multiple contexts or factors
		Uniqueness of events creates uncertainty	Context, natural hazards not replicable
		Hazards themselves create uncertainty	How they create uncertainty
		Uniqueness of Aotearoa New Zealand setting	Communities
		Uncertainties over many instances build up	Uncertainties over many instances build up, or various uncertainty in an event, multiple uncertainties
		Change creates uncertainty	Environment, information, data, over time, rapid change
The Actors	The Scientists	Science is elite	Privileging science, authoritative opinion, expertise
		People create uncertainty	People creating uncertainty, disagreeing, egos
		When do you need to be ethical?	Ethical compass
		Is there one correct answer?	Is there one, consensus of data
		The risk of doing science	Of litigation, getting it wrong, managing risk, accountability
		Rigour of scientific publication is really important	Publishing, peer review, journals, debate, disagreeing, evaluate research
		What scientists are passionate about	What influences them, different viewpoints, their interests, passion
		I have to be able to trust that opinion	Who's giving advice or who's doing the research, expertise
		Are we starting to see a trend?	Contradictions, consensus, is uncertainty consistent with other sources
		Translating or interpreting science information	How it's used
		I have a lot of trust in science	Believe science or not, trust people, credibility
	The Media	The media	It's influence, the role it plays, how it works
		You can get information from so many different sources	The internet, media
	Communication	You need to be an effective communicator	Communicating about disasters to the public, what's communicated, the media
		I didn't understand what you were saying	What science is communicated, it is effective communication, can people understand it?
		Also, clear advice, to be able to understand them	Giving advice to the public or government so they can understand it and follow it
		Uncertainty into advice	Giving advice about how to respond to event, and communicating that to public, to govt, to leaders to make decisions

(*continued on next page*)

Table 1 (*continued*)

Theme	Master Code	Sub Code	Code Description
		Communicating uncertainty so people can understand	To public or other people, how communicated, language
		Decision makers wanting something	How decisions are made, getting answers, those who make decisions
		Meaningless statistics	Using probabilities or percentages as a way of explaining uncertainty or risk, giving predictions based on stats
		As a leader, you've got to be able to take people with you	People who make decisions e.g., planners or govt - what makes good leaders, when leadership is poor does uncertainty increase
Human Behaviours	Keeping the public safe	Keeping communities safe	Of communities, the public
		Aware of the risks	Need to be aware of them for safety
	Ethics	Ethical responsibility to people's lives	Ethical responsibility
		Mitigating the hazards	Reducing or preventing, role of technology, decisions made
		Trying to mitigate with uncertainty	How uncertainty affects decisions, mitigating risks, procedures to mitigate
		Uncertainty of risk	What are the risks, levels of risk, how to respond
	Joe Public	How people respond to hazards	What they do/don't do
		The public create uncertainty	Individual factors, groupthink
		Emotions are fueld by uncertainty	Emotions involved
		The unknown	Afraid of the unknown, what is unknown, wanting an answer
		Becoming desensitised to risk	Ignoring advice, justifying risk
		Social media	It's influence, the role it plays
		Influential lay people	Knowledge that's not coming from scientists, influential people
Sit with uncertainty	Uncertainty as a positive thing	Uncertainty can be positive	Push for more data, create debate
	Part of the process, build it into models/advice, manage it/reduce it	Reducing uncertainty	How this can be done
		Degree of uncertainty	Aware of it, its built into the model, manage it
		Sit with uncertainty	As a part of the process, from lack of information

Interestingly, several participants discussed uncertainty as an intrinsic and immovable part of science: "where you have scientific knowledge, you always have uncertainty" (Zeta, Boundary Scientist). This links to the core theme 'sit with uncertainty' discussed below, where participants indicated uncertainty should always be expected in science as it is not possible to know everything. One participant, a policy writer, described uncertainty and the lack of knowledge through a hypothetical visual analogue, a 'crevasse', where previous experience, knowledge, prior events, and 'solid evidence' forms an even foundation for decisions to be made. However, eventually, one comes upon a crevasse which represents the 'uncertainty'. This too is an 'unknown', as a crevasse is deep, unknowable, and unpredictable. They discussed the fear people have of "fall[ing] into that crevasse" which they need to "leap" across. We note that this crevasse analogue is similar to the more commonly used 'gap in knowledge' to describe uncertainty.

3.2. Sources of uncertainty: the data

This theme focused on how data were a source of uncertainty for participants when it came to NHE advice. Three sub-themes describe this theme: not enough data, the uniqueness of events, and interpretation of data.

3.2.1. Not enough data

This sub-theme was mentioned extensively by participants, where uncertainty in NHE advice was fundamentally due to not having enough data. This was also discussed alongside having 'gaps' in data (also represented by the 'data' node on the collective map; Fig. 1), with both creating an incomplete picture of the NHE (represented by the relationship between the nodes 'natural hazard events' and 'data' on Fig. 1), and therefore the difficulty in giving advice in that space that was entirely uncertain. Several reasons for having gaps in data were described by participants, such as areas of research not being funded, failures of technology, and having time constraints on gathering data (represented by the 'limits of science' node on Fig. 1, and the relationship between 'limits of science' and 'data'; Fig. 1).

Funding, in terms of distribution and pressures, was identified as a significant source of uncertainty. The majority of participants (16[9]) from across all interviewed professions discussed funding as contributing to uncertainty and in particular as contributing to 'not having enough data', due to it resulting in some topics or phenomena having less knowledge than others. In turn the greater amount of research on those other topics was also noted to create uncertainty as it may potentially result in an increase in conflicting results. Funding is a complex issue, which can impact globally as well as locally. Participants noted that what was funded relied on who was interested in the data (this relationship is demonstrated on Fig. 1 between the nodes 'human element' and 'limits of science', Fig. 1). For example, the government generally funded areas of research in line with their priorities, usually linked to promoting well-being such as disaster risk reduction. However, a funder's interests may not entirely align with significant gaps in data or what other parties consider to be salient. Lambda surmises some of these issues in the following quote:

[9] Lamda –Public/Legal professional; Upsilon – Data Scientist; Chi – Policy writer; Omega – Geography teacher; Eta– Social Scientist; Iota - Planner; Mu - Planner; Omi – Emergency Manager; Pi – GIS Analyst; Alpha - Emergency Manager; Beta - Engineer; Delta – Non-scientist/Journalism student; Rho – Food Scientist; Tau– Policy writer; Xi – Emergency Manager; Zeta – boundary scientist.

(Uncertainty comes) From not having all the information or not having the ability to get the information. I think from a funding perspective, not all areas are funded the same and so you have these global projects that go on and you might have some funding to do that, but that's great because you can only take it so far, so it might leave more questions than answers or it means "oh yes we've done this feasibility study to here but now we need to know more" - Lambda (Public/Legal)

Importantly, Lambda notes that there is not always the ability to get information. This can result from what is funded but also from an inability to record data. Participants explained that, in some circumstances, not having enough data could result from failures of technology. That is, certain technology was not in the right place to record a NHE (e.g., not in an optimal location to record earthquake ground shaking) or was not sophisticated enough to record a particular NHE. For example, larger earthquakes may "go beyond our ability to understand them with the tools we have" (Zeta, boundary scientist) such that the uncertainty "becomes massive". Through this, participants demonstrated that their understanding of uncertainty included what *cannot* be measured and thus the influence of both known and unknown unknowns (see also Section 3.4). Additionally, participants discussed how computer models that were used for prediction of NHE, and the potential impact of the event, were only as good as the data that was fed into them, as Iota describes below:

We have to make assumptions in terms of whatever we, say for modelling for example, if we're feeding into the modelling, we do our very best, or the scientists do their very best based on what has happened before to make correct assumptions or hypothesis, but at the end of the day they don't know what exactly is going to happen. And so it's kind of that error margin in any kind of prediction – Iota (Planner)

Here, Iota discusses how assumptions are made around what data is fed into a model (based on prior NHE), the output data that is then produced by a model, and that these assumptions ultimately mean they do not know exactly what is going to happen regarding a NHE. This leads to a level of uncertainty around the model's output data that then needs to be taken into consideration when communicated to others, such as emergency managers, community stakeholders, and the public (this is demonstrated on Fig. 1 between the nodes 'data' and 'outcomes').

Participants were also aware of time constraints in being able to gather data from a NHE, and that this too created a gap in the data. That is, there was a window of time to be able to gather data on an event and once this passed then what could be learned from the NHE was more constrained. For example, the first wave of a tsunami, the initial eruption of a volcano, or the rupture of a seismic fault. Although it was still possible to gather data as the event unfolded, this too was constrained by time, as a NHE is usually a finite event. This meant that researchers were limited to what data they could gather on an event, which would lead to uncertainty around what could be advised about for those and future events. Similarly, if data was not acted upon in a timely manner, it could become obsolete and no longer relevant to the evolving situation.

3.2.2. Uniqueness of events

Participants readily noted that NHEs are unique events and that, in a way, this limited the amount of data available about them (this relationship is represented on Fig. 1 between the nodes 'natural hazard event' and 'data'; Fig. 1). For instance, no two earthquakes are the same, thus data on one earthquake may not be able to inform our understanding of another. Similarly, the contexts are unique affecting "the supporting information, and what's right for Wellington is not going to be necessarily right for Auckland" (Lamda, Public/Legal professional). Thus, an earthquake occurring in Tāmaki Makaurau (Auckland) would differ from an earthquake occurring in Te Whanganui-a-Tara (Wellington) because of the geography of the area, the density of the population and other factors. The uniqueness of events thus contributed to participants' sources of uncertainty, as clearly stated by Mu and Rho:

A fault may behave slightly differently. There may be a deflection because of an undersea topographical feature. It may arrive on low tide and not high tide. It could decide to arrive on a giant storm event. There will always be a variable that you have not allowed for, and that is okay – Mu (Planner)

There's a lot of scales of things or greyer areas or different outcomes each time. Like if you think about natural hazards, the different impacts depending on a whole lot of things that feed in – Rho (Food scientist)

Here Mu and Rho also demonstrate how individual uncertainties can compound to create higher levels of overall uncertainty and can thus also compound the impact of the NHE. Uncertainty may also change over time.

The uncertainty that results from the uniqueness of events links back to the previous sub-theme on gaps in data. That is, because events (and the contexts within which they occur) are unique it is not always possible to get replicable data, which can create a gap, as Beta describes below:

Sometimes science needs to be replicated, but in some cases, you cannot replicate an event, like, yes, I study earthquakes in 2018, but it's 2020 and there's no more of that kind of similar conditions, so it's not replicated. So, there is not an accurate method to apply to all of them – Beta (Engineer)

Interestingly, many participants also focused on replicable data and repeatable experimental methodologies as being the 'gold standard' for understanding a phenomenon. Their comments demonstrate a view that this replicability is, and should be, a crucial scientific priority. We note this conflicts with the challenge of replicability associated with unique events discussed above.

3.2.3. Interpretation of data

While a level of uncertainty must be interpreted based on the available data, participants discussed how uncertainty can also result because of *how* data are interpreted, *when* (noting the relevance of data through time discussed in 3.2.1), and by *whom.* Uncertainty was also identified to come from which conclusions can reasonably be drawn from the data, particularly if there are gaps in it (this was represented by the node 'limitations of science' and its connection to the 'data' node on Fig. 1).

Several participants discussed how there was no one 'right' answer in science and thus what might be 'true' for one person may not be 'true' for another. This demonstrates a relativist position and considers there to be no objectively true knowledge that can be interpreted from data [127]. Phi and Alif describe this well here.

> *The old adage that there's no right answer to things is so often very true, it's how you interpret what you're measuring and seeing in as much as what you've measured and seen* – Phi (Public/Legal professional)

Participants also acknowledged that people can view the world in different ways, which would therefore result in different interpretations of the same phenomena or data.

> *I think it comes from like interpretation of data sometimes, people can … Because science is science, but it's still studied by people, we all sort of see things slightly differently and so I think can interpret things in slightly different ways. Where some person might look at the data and see one thing, someone might see something slightly different. So I think there can be more than one answer.* – Alif (Local Government/CDEM)

Phi and Alif thus both identify the difficulty in producing a singular 'right' answer in science and acknowledge the significant role played by worldviews in the interpretation of data. Participants also discussed how the interpretation of data could influence the prediction of NHEs. They discussed how questions can arise due to their confidence in how the data were interpreted, as well as how understandings are drawn from data interpretation (discussed further in Section 4.1). Xi recognised that this interpretation is reliant on 'who is in the room' when data are being handled.

> *So there's uncertainty in terms of having the right people in the room introduces some uncertainty, or what we've called 'confidence' - how confident you are in your decision* – Xi (Emergency Manager)

As well as introducing the notion of a 'lack of confidence' as a type of uncertainty, here Xi starts to consider the role *people* themselves play in the generation of uncertainty around NHE science and advice, discussed next.

3.3. Sources of uncertainty: the actors

This theme focused on how the participants viewed 'people' as a source of uncertainty related to NHE advice (this is represented by the nodes 'communication' and 'human element' on Fig. 1). Three sub-themes describe this theme: the scientists, the media, and the communicators.

3.3.1. The scientists

Scientists were mentioned extensively by participants as a source of uncertainty in NHE advice, also represented in the node 'human element' on the collective concept map (Fig. 1). The main discussions focused on the expertise and reputation of the scientists and therefore whether they were trustworthy, and how scientists work within the scientific community.

The individual scientist giving advice about NHE was considered a source of uncertainty by participants. They discussed how their ability to trust the scientists giving advice created uncertainty as it impacted their trust in the advice being given. On an individual level, the generation of this trust involved the reputation, expertise, and qualifications of the scientist. Tau explains this well.

> *To a certain extent I have to have a certain trust that they're, because they're the ones that are qualified in the space. So, if a tsunami expert is coming in with an opinion, to a certain extent I have to be able to trust that opinion* – Tau (Policy writer)

Here, Tau ties the ability to trust a scientist's advice to being able to trust the individual scientist. However, this ability to trust was further complicated by the offering of differing opinions by several 'experts' in their fields (and sometimes, as noted by participants, when a scientist was offering advice on a topic they were not an expert in). An inability to know who to trust and whose expert advice to follow was considered a significant source of uncertainty for several participants, particularly when it created conflicting evidence and advice, as Iota describes here:

> *It's basically the underlying assumptions that tend to be where competing experts disagree. So that can be confusing for councils and for public, unfortunately, to try and … Well, who's right? Who's actually … Who do I believe, and who's right and who's wrong* – Iota (Planner)

When participants were asked what made them trust a scientist, as well as the individual aspects of the scientist they also discussed their trust of science more generally. Most participants mentioned the 'scientific method' and how it created a level of rigor that was universally accepted, and therefore trusted. Additionally, they mentioned the peer review process and the reputation of scientific journals. Participants also discussed how the source of the science advice made it more credible, such as the reputation of an individual, a research institute, or the government. The participants in this study generally trusted in science, and that scientists were working in a moral or ethical way, as Kappa describes here.

I personally have a lot of trust in science, so I believe that they're always doing the best for what they're passionate about, so I always feel like they're looking for enough information and then doing the right thing in order to get the right conclusions. So, yeah, if something is proven and peer reviewed in a journal then I kind of feel as though it's trusted advice – Kappa (Policy analyst)

Kappa's trust of science reflects how trust may exist, but what is being trusted can vary between the scientific system and the individual scientists. Interestingly, Kappa's use of the word 'proven' implies they hold more certainty and trust in scientific conclusions than may exist, given a conclusion is only proven if it follows with absolute certainty from the premises [128]. This is an unattainable standard for most applied empirical research. Like Kappa, several participants indicated they had more trust in science than the individuals. The participants in this study recognised that at times, personal risk may be at play for individual scientists, which may influence their motivations and advice. This can result in those scientists acting more conservatively to protect themselves, rather than 'going out on a limb' and risk being 'wrong', thus impacting the trust participants have in what they say. Mu discusses this below:

When we get into that situation and we have risks of litigation and we have risks of being dragged through the media […], it is resulting in what I suspect is, we're starting in a conservative baseline, and most scientists' starting point at the moment is in a conservative view, but that's because we are in a world that you get rewarded for being conservative, but you get smashed or you get taken to task if you're slightly less conservative or slightly wrong and a consequence results from that – Mu (Planner)

Here Mu touches on the motivations scientists might have when giving advice to other parties. In their example the 'conservative', or precautionary risk avoidance, influences on the advice creates uncertainty. As well as protecting themselves from litigation, participants speculated that protecting reputation may also be a motivation for scientists to give conservative advice. That is, a reputation for being overly conservative, or for having made past mistakes, meant a scientist was considered a source of uncertainty, because conservativism and past mistakes impacted the trustworthiness and reliability of the scientist and their work. Mu also mentioned being 'dragged through the media' as a form of damage to reputation, and the next sub-theme explores further the role the media plays in creating uncertainty in scientific advice.

3.3.2. The media

Participants mentioned the media as a source of uncertainty, and this included the variety of media available, particularly from the growth of non-mainstream online news sources (this is represented in the 'communication' node on Fig. 1). Participants noted that two factors are at work here. The first is that conflicting advice is readily available online – it is possible to find 'experts' who support and 'experts' who disagree with scientific advice given (this is represented in the relationship between the 'human element' and 'communication' on Fig. 1). The second is that the Internet is a free and open resource, meaning anyone with access can write anything and post it online, without the need for expertise or 'evidence' to inform their opinions. Kappa describes these issues below.

I guess the freedom that people have to write whatever they want on the Internet can also have an impact on that sort of thing. So, you can kind of get information from so many different sources that it can create more variation than there actually is, and what's actually being studied – Kappa (Policy Analyst)

Although participants mentioned the availability of online sources as sources of uncertainty, it was interesting that most participants did not discuss social media, and the few that did only mentioned it very briefly. This is surprising as the influence of social media, particularly around misinformation, is under increasing public scrutiny as well as formal research [129–131]. In addition, the role social media might play in NHE communication is often being explored by emergency managers and local councils [132,133].

Participants noted that both mainstream and non-mainstream media were influential when it came to affecting people's receptiveness to receiving scientific advice about NHEs. Specifically, participants discussed how uncertainty was created when the media presented conflicting experts, opinions, or stories with conflicting information and advice. Lambda explains this below:

For conflicting stories, so you'll have one piece saying "this is bad" and then the other saying "oh it's not that bad", there'll be a scientist in both camps, and so, who's quoted. So you're like "well they're both scientists, who do I listen to?" – Lambda (Public / Legal)

Sometimes a legitimate disagreement may be represented realistically by these media portrayals, however at other times the media may present a 'false balance' in scientific views causing uncertainty about who to trust (discussed further in section 4.5).

3.3.3. The communicators

The information that communicators purvey, and the ability of the actors to communicate that information, was extensively identified as a source of uncertainty by most participants (this is represented by the 'communication' node on Fig. 1). Effective and clear communication was considered more reliable. Without clarity in communication, uncertainty was considered implicitly present even if not explicitly stated. For example, participants discussed the difficulty in, at times, understanding what a scientist (or other communicator) was advising when they used language that was unable to be understood by the participant. This led to uncertainty about what was being advised, and therefore how to then respond on that advice during a NHE (represented by the relationship between the nodes 'communication' and 'outcomes' on Fig. 1). Instead, participants suggested communicators use everyday language to communicate risk and advice around NHEs, as Alpha and Alif discuss here.

There can be a disconnect between, there's some very smart people out there but they're piss-poor communicators and therefore the science might be extremely valid but if you can't apply it to a people component, then it's of limited value – Alpha (Emergency Manager)

Easy language, not top-level science language but common, everyday language that anybody can understand, is going to give me the ability to trust them more, just 'cos *I then know what they're talking about. If they're going to talk at me in science stuff, I'm going to be like "well I don't know if that's true or not, I didn't even understand what you were saying to me"* – Alif (Local Government/CDEM)

Alpha demonstrates how advice can have only a small impact on decisions if it is not understood, and Alif notes that if the language and information being communicated is understandable it can increase their trust in the person communicating advice. As discussed by participants (section 3.3.1) this is important as low levels of trust can create further uncertainty in the advice and information being conveyed. As well as using clear language, clear advice was also considered an important factor in reducing uncertainty, and therefore, unclear advice can be considered a source of uncertainty. Below, Epsilon suggests that clear advice might come from having a unified voice giving the NHE advice.

And the importance of having, together with good communication, also clear advice, so just one unique voice and not different ones, and guidelines for the public to be able to understand them, even if it's not that specific thing, they would understand it – Epsilon (Geologist)

Here Epsilon touches on the issue of having conflicting advice communicated to the public, making it difficult for them to understand, and potentially respond. The difficulty in communicating NHE advice effectively was noted by participants, with some suggesting ways to improve on communication, particularly to the public. Specifically, they noted that meaningless statistics should be abandoned, such as describing NHE's as a 'one in ten year' event. Tau explains this below:

I'm thinking this actually has become a meaningless statistic because we're just getting these events after events after events and you're going "what is this 1/50? Is it in terms of timing? Is it in terms of size?" And I'm just at the point now where I'm going "I'd like some other indication that tells me this could be quite nasty" – Tau (Policy Writer)

Tau and other participants noted that presenting risk or advice using statistics that the public do not understand will thus result in a failure of communication and may reduce public compliance during a NHE. The public's potential responses to NHE advice thus represents an unknown that can feedback into the natural hazards science being conducted. This source of uncertainty sits within the theme *known unknowns*, discussed next.

3.4. Known unknowns

This theme focused on how the participants described 'known unknowns' as a source of uncertainty related to NHE advice (this is not represented as a singular node on Fig. 1, as it was discussed widely across all the nodes). Three sub-themes describe this theme: the range of possible outcomes, the human responses, and the unknown unknowns. For this theme we consider that these known unknowns represent uncertainties that are known to exist but can't be constrained, and unknown unknowns are those uncertainties that are relevant but we do not know. We note these have been previously defined respectively as 'conscious ignorance' and 'meta-ignorance' [66,134–137].

3.4.1. The range of possible outcomes

This sub-theme describes how the conceptualisation of the range of possible outcomes was regarded as a source of uncertainty by participants when thinking about NHEs (this is represented by the 'outcomes' node on Fig. 1). Participants described this a) in terms of the risks and consequences of the NHEs themselves (which NHE, when it will occur, where, who it will impact), and b) in terms of the risks or consequences of the *advice* provided around NHEs (what advice is given, when, and to whom). Importantly, throughout their discussion of outcomes, participants identified that people working in natural hazards fields needed to be aware of the diverse range of NHEs Aotearoa NZ potentially faces:

You know, we have a lot of natural disasters or natural hazards in this country, because of our terrain and where we are. So yeah, it's essential that we are aware of the risks of everything from debris flows to volcanic eruption to flooding – Phi (Public/Legal professional)

Safety and the risk to humans was raised as a priority for emergency managers when considering these outcomes, guiding the advice they want and they themselves give around potential NHEs. As outlined by Alif below, this requires future-thinking to understand how the situation (and thus the potential) risks and outcomes could evolve, creating additional uncertainty for themselves and the scientists:

I would imagine they're always future-thinking about how do we use this data to make things safer in the future – Alif (Local Government/CDEM)

Many of the sources of uncertainty associated with understanding possible risks and outcomes can be considered as *known unknowns*. Participants outlined how uncertainty arises in terms of *what* risks potentially exist, *when* and *where* they might occur, and *who* will be affected by the NHE and to what degree. In turn this creates uncertainty for emergency managers and other stakeholders, in terms of identifying *what* to say about outcomes in advice that will be most salient for the public, as well as when considering *which* of the potential risks and outcomes should be prioritised for study and management. As outlined by Sigma below, further uncertainty arises because different disciplines approach the process of identifying and managing these potential risks differently:

I have worked in risk frameworks where you just scope as widely as you possibly can. And I actually found that was a bit of an adjustment for me because I realised that I'd limited my own concept of risk on the basis of knowing what the mitigation was. So because *you're dealing with it, it's not a risk. Whereas sit down with a bunch of engineers and they want every risk written down and identified, and even if you [cross] it off because you can mitigate it, you still identify those* – Sigma (Planner)

Therefore, even if the range of risks are known, how they are managed by different groups creates further known unknowns due to differences in training and disciplinary epistemologies. We also note here that this discussion by Sigma relates to identification and removal of risk, however mitigation has limits and risk evolves, so there will still always be a residual risk due to the uncertainty associated with any mitigation action.

The presence of these known unknowns, and how scientists and advisors then communicate those uncertainties was identified by several participants as raising ethical challenges and ethical obligations (see also Section 3.3.1):

It kind of comes with a big responsibility I suppose if you're doing things like communicating the risk of [a] hurricane making landfall at a certain time, a certain place. That's people's lives on the line …. Yeah, it's kind of like an ethical responsibility I suppose – Nu (Anthropologist)

However, participants were less clear about how this ethical challenge could be addressed (i.e., through the application of informal ethical guidelines or formal ethical codes), creating an ambiguity around what to say and how "… *and it's like when do you need to be ethical? When do you need to just think about how this is coming across?"* – Tau (Policy writer). Therefore, while these ethical uncertainties are known, how these ethical challenges are managed and how each stakeholder handles their ethical obligations becomes further known unknowns (see also [30,89,138]).

In addition, participants identified that these ethical challenges are further influenced by consideration of the potential to desensitise the public to NHE advice through overreporting of risks:

People expect to see the big devastation of Indonesia or of Japan. That's their view of a tsunami. Now, scientific community knows a 10cm high tsunami is still a tsunami. Okay it might not have been up to a metre that arrived, but it still arrived. Now when the community gets desensitised to it, because they hear "tsunami warning! Don't go to the beach!", inevitably a portion of the population goes to the beach and starts filming, and nothing turns up. Then you start getting this narrative playing out in the community of "oh my God, you didn't get this right, you stuffed this up, tsunamis is not a thing, we don't have them, they never occurred in my lifetime, you've given me twenty warnings." That drives the uncertainty in the community side of things. And therefore, it starts getting real hard to get traction with community because it doesn't happen – Mu (Planner)

Mu's comment here also touches on the ethics of reporting risks, particularly to the public, where the known unknowns are both how to effectively communicate the NHE advice and how the public will *respond* to that advice, discussed further next.

3.4.2. Human responses

This sub-theme describes how the public respond to NHEs and NHE advice. Participants identified that a source of uncertainty arises from the lack of knowledge about how the public will respond to a NHE, or to specific events or moments within the duration of a NHE, as described by Phi:

I guess maybe the variability in responses to hazards. Um, I'm not quite sure what I mean by that. Sort of the variability in how people respond to hazards makes it uncertain, like some people will react differently to others in the same situation – Phi (Public/legal)

While a range of responses may be anticipated, the response of an individual is an unknown. A variety of influences on those individual's responses were also identified by participants, such as how individuals responded compared to how groups responded (familial groups or neighbourhood groups), the influence of other people (such as family, friends, and knowledgeable people), and the role of social media.

And they learn more from social media than they do, they're more willing to accept someone from social media than their teacher at school. That's a pain in my life. And that mode of communication is huge – Omega (Geography teacher)

I think one other one would go kind of along with the conflicting advice from the media/social media is like friends and family. You have friends who you perceive to have a lot of knowledge that may pass on their advice but that's not necessarily the best advice. Like, if you perceive someone to be very knowledgeable, you tend to listen to what they have to say, but just because they're knowledgeable about some things doesn't mean they know what they're talking about in this instance – Alif (Local Government/CDEM)

As discussed in Section 3.3.2, social media was mentioned by only a few participants, which was surprising given its prevalence, however Alif and Omega do identify above some of the issues related to treating social media as a reliable source of information. The participants also highlighted the many unknowns associated with how the public will assess information on social media alongside more official scientific advice, particularly in an environment of rapidly circulating, and often conflicting, misinformation and disinformation. How this assessment then relates to their actions and associated behaviours prior to, during, or after a NHE creates further uncertainty. Importantly, Omega describes the inability to control or predict where the public gets NHE advice from which creates uncertainties in how science information or advice is received. Therefore, the use of social media is known, but what information will be accessed on social media is unknown, as well as how it will be interpreted and acted upon.

Alif also applies similar reasoning to family, friends, and other known sources of information. However, the specific information those family and friends relay will be unknown. This complex, and sometimes contested, conflicting communication landscape was discussed by participants as creating an additional source of uncertainty in natural hazards science for those who give NHE advice. They may not know which sources the public will access, which could have a significant impact on how the public respond to the NHE itself. Participants explained that this then influences which potential impacts are considered for the NHE, depending upon which human behaviours and (potential) actions are considered. In turn this influences the appropriate related scientific advice developed and communicated.

Some participants in the current study were aware that keeping the public safe was a priority for emergency managers and indicated that this priority could then create additional uncertainty associated with the NHE scientific advice. They outlined how conflict between decision-makers can arise around what is the best public safety decision to make during a particular NHE, due to the uncertainties that arise in the range of interpretations and applications of the science advice. This can be compounded in situations where multiple hazards are present but require different advice (e.g., for coincident tornado and flash flood warnings). Thus, participants viewed 'People' again becoming a source of uncertainty due to disagreements amongst decision makers as to which is the best course of action, as well as disagreements about which science should be conducted to assess the risk and generate the advice (similar to uncertainties associated with 'The Data' and research funding decisions, Section 3.2).

Through these participant discussions, actions required for public safety can be recognised as 'knowns' however the range of uncertainties regarding how the public and decision-makers will interpret and act upon advice creates 'known unknowns' such that public safety cannot be assured.

3.4.3. The unknown unknowns

This sub-theme describes how there are some aspects of NHEs that are just 'unknown', and what role the 'unknown' plays in NHEs and responses to NHEs. When discussing 'the unknown', some participants did not offer a definition but discussed the concept as if it was known that there were other unknowns, but not known what those unknowns may be. One participant did articulate this specifically as 'known unknowns' and 'unknown unknowns', however, most participants talked about 'unknowns' more generally, such that they knew there were unknowns in science, in models, and in NHEs, but could not articulate what they were, nor knew how to categorise them. Most participants shared that, we, collectively, do not know everything, and thus these unknowns will always exist. Essentially that we do not know what we don't know (see also [66,134–137]). Participants highlighted such unknowns also increase when we consider knowledge may only have currency in specific times and places.

> *Within the environment of the time. Or … I think about science is, what we know from science is the most likely knowledge given the data, given what we understand of the constraints and the context at the time* – Zeta (Boundary scientist)

Here Zeta outlines the known (i.e., the constraints based on data availability) and also the unknown (i.e., what we don't know about the constraints in time). Some participants noted that the concept of these 'unknowns' often generated fear and a desire to get an answer, and what those unknowns are may depend on individual knowledge and experience:

> *Just that uncertainty can cause fear because you're just … I think people tend to be quite fearful of just unknown. We fear what we're unsure of, and I think most people, unless you're a scientist, don't probably have a high understanding of natural disasters apart from what they're told from the media, and so just kind of that fear I think …* – Alif (Local Government/CDEM)

Alif further suggests that to cope with these uncertainties and unknowns, the public may base their decisions more on emotion than information:

> *It's a lot of emotion that comes up with these sorts of things. People immediately get that fight or flight response, don't they, when something happens. Even when it's a smaller earthquake you kind of freeze and be like "is this big or not?"* - Alif (Local Government/CDEM)

These emotions may lead to more complicated responses to NHEs and compound the uncertainties associated with human responses discussed above (Section 3.4.2). Other participants also discussed how uncertainty created anxiety, however they did not fully discuss what role emotions played in creating uncertainty or responses to NHEs, discussed further in Section 4.4.

The above themes describe sources of uncertainty in NHE advice. Another smaller theme was also identified that focused more on how uncertainty could be considered a positive factor in science and scientific advice, discussed next.

3.5. Sit with uncertainty

This theme describes uncertainty with a more positive lens, reframing uncertainty as something that could be embraced and mitigated, rather than feared, ignored, and avoided. Participants considered uncertainty as something that can lead to better research or something that pushed for more data to reduce uncertainty:

> *I think if a scientist came up and said "I'm uncertain about this data" and it encourages other scientists to then say "oh well let's have a look at it" and like take it forward, then that actually improves the science, surely* - Omega (Geography Teacher)

Omega also notes that a more positive response to uncertainty could create opportunities for collaboration amongst colleagues, move science forward more generally and potentially reduce uncertainty through more work with the data, such as additional analysis or re-examination (discussed in Section 4.4, see also [66,134–137]). Participants considered uncertainty as being part of the process of science and working with data. Zeta describes this well.

> *Uncertainty is kind of like where you have scientific knowledge, you always have uncertainty. Even the best science is always uncertain. We never know anything absolutely, and all of science is kind of just a big stack of work that all has uncertainty, yet together it works in that final polished form* – Zeta (Boundary Scientist)

Zeta's narrative here demonstrates an understanding that uncertainty is inherent in science because science cannot have 'all the answers all the time'. This acknowledgment of the inherent existence of uncertainty was also expressed when participants discussed how uncertainty could be communicated in a way that allowed it to be understandable, rather than not communicating it at all. This would give the public more agency to make decisions relating to NHE. Nu and Mu explain this here:

> *I think it's always helpful when a piece of information or a paper has like "we have this degree of certainty about this information", and they kind of make their disclosure right at the beginning, and they're open and honest about it, rather than saying "we 100% know that this is going to happen or this has happened or this is the way that something works". It always helps if they're open and honest, just share that they don't quite know* – Nu (Anthropologist)

> *I would rather have someone get up and say "look, there are uncertainties in the model, but in my professional opinion this is fit for purpose. Based on the science we know, this is the risk that we're dealing with, this is the likelihood, this is what I expect, I'm comfortable with that" rather than someone (saying) "and yes it may change in time, but that'll be picked up in the next plan review in 10, 20 years' time". 'Cos our science is understood, and it is an evolving knowledge, it's not perfect now, but we are okay with that, based on what we know now, which is (a) damn sight better than what knew 10 years ago* – Mu (Planner)

The comments by Nu and Mu also reiterate that trust can be built with the communicator if they are transparent about what they do not know or are uncertain about. It also relates to the discussion above (Section 3.3.1) outlining how lack of trust can contribute to further uncertainties. Through this desire for these uncertainties and unknowns to be communicated, participants were also accepting and comfortable with the notion that not everything in science can be known (as discussed in Section 3.4.3).

Similarly, when directly asked what they would like to know if a scientist was uncertain, several participants also responded with approaches that reflect 'sitting' with uncertainty, as well as advocating for transparent communications. They reiterated that it was "okay to be uncertain" as there would always be uncertainty in science. This also relates to the theme 'uniqueness of events' (Section 3.2.2) which outlines the difficulty in describing and investigating the uncertainties associated with irreplicable events. Participants noted it was important to be up front about uncertainty, and indicated they would want scientists to state that they were uncertain, how uncertain they were (for example with use of percentage ratings or degrees of uncertainty), what the sources of uncertainty were, what it's characteristics or 'particular aspects' are, what it's impacts could be, whether other scientists had similar uncertainties, what assumptions were made, where uncertainty may have been 'introduced', and how the uncertainty might be reduced (e.g., through future research or what information they needed to be more certain). These responses demonstrate a comfort with uncertainty, an expectation *for* uncertainty, and a desire to know that uncertainty to inform more robust decision making and planning:

> *Whether the uncertainty impacts only certain aspects, for example, it could influence the likelihood of the size, i.e. breaking through the gate, but not the likelihood of the recurrence.* 'Cos *just reading that research I would think that the recurrence is more certain.* – Xi (Emergency Manager)

Crucially, through this, while participants demonstrated a comfort with uncertainty and the need to sit with it, they strongly indicated the need to communicate this uncertainty not only transparently and with explaining the nuances of uncertainty, but also in a *meaningful* way: "*(they) need to find a way to convey that uncertainty in a way that's meaningful to people*" (Eta – Social Scientist).

4. Discussion

Understanding where people think scientific uncertainty comes from, and what it is, is crucial for improving effective science communication in a crisis. Using this knowledge, information and messages can be more appropriately framed to meet expectations and to enhance trust when the most likely outcomes do not occur (see e.g., Refs. [34,139–143]). Qualitative analysis of these mental model interviews led to the construction of key themes representing participants' perspectives on sources of uncertainty, ranging from The Data sources through to more social aspects including The Actors involved, and the Known Unknowns, which includes how people may or may not behave.

While several communication researchers have highlighted the importance of communicating social influences on scientific uncertainty (sometimes described as the social history of uncertainty [144,145]), it is still not common practice to communicate this additional nuanced information to decision-makers and the public during natural hazards risk management [30]. The findings herein demonstrate that individuals expect these social influences to exist, and thus make assumptions about their existence and meaning. This raises questions regarding the influence these assumptions may have on their interpretation of uncertainty communication when this additional information is *not* conveyed. Those assumptions may be incorrect, influencing their trust in the message. Alternatively, if those additional factors *are* conveyed, questions arise as to whether their presence enhances understanding of, and trust, in the message, or whether this additional information could cloud the message and cause confusion or information overload [146,147]. Thus, should the communication of uncertainty about these social aspects be undertaken in conjunction with the communication of more traditional scientific uncertainty? Or, should we simply acknowledge these social aspects exist? Future research is needed to explore the potential influence of this additional information on people's understanding and use of natural hazards science. This should be grounded in the understanding we have developed here of what people expect and perceive scientific uncertainty to be.

Reflecting on the themes presented herein in the context of the wider literature, and explored through Fig. 1, leads to the recognition of several additional *key influences* upon the degree of uncertainty, and on people's perception of science advice or uncertainty. These cut across the key themes presented here, can increase or decrease uncertainty, and should also be explored in future research. These include the perceived influence of: (a) governance and funding, (b) societal factors, (c) outcomes, (d) emotions, and (e) the communication landscape. If communicators do not consider these additional influences, they may not shape their scientific messages appropriately, nor consider all appropriate audiences. These influences point towards specific areas for future communication research into how they should, or should not, be recognised in uncertain science advice communication processes, discussed next.

4.1. Governance and funding

A key lesson from this research included how several participants identified governance and funding decisions as specific key sources of uncertainty, due to their influence on what science is conducted. This can result in data gaps or incomplete knowledge, or even poorly designed parallel studies creating conflicting information. In addition, it can be driven by our need to understand different regional impacts (e.g., earthquake research directed more towards Te Whanganui-a-Tara | Wellington rather than Tāmaki Makaurau | Auckland). While our participants identified governance and funding as a *source* (section 3.2.1), we note they could also be seen as *enablers* of uncertainty because they can act as *influencing or moderating factors* that can also increase or decrease any existing uncertainties. For example, the degree of funding can result in data gaps, can decrease data gaps and inconsistencies, and can increase the amount of conflicting information. Similarly, as discussed in Section (3.4.2) this governance and funding influence is reflected in our 'keeping the public safe' theme, and in the 'outcomes' node of the mental model map (Fig. 1), where what is researched is driven by which populations and impacts we care about.

Often, in the natural hazards domain, what is *not* researched is rarely communicated or transparently available [30]. In a review of existing guidelines for communicating scientific (model) uncertainty, Doyle et al. [30] highlighted that there is a need to communicate more than just scientific and technical uncertainty, but also the 'social history of uncertainty' (p. 19; see also [68,144,145]), which would encompass the governance and funding decisions identified herein and the related value judgements inherent to those decisions. Winsberg [148] states that value judgements occur in methodological choices, problem solving, evaluations, and beyond, such that they are woven throughout all complex science. To address this, authors such as Janssen et al. [77] and van der Sluijs et al. [149] have included metrics to distinguish the "value-ladenness of choices" when communicating model and assessment information. Thus, we propose governance and funding decisions represent value judgments and sources of uncertainty (see also [30,57,76,77]). Effectively capturing and conveying these is important given research has demonstrated significant variation in conclusions due to different analytic decisions (Silberzahn et al. [150]). Tools such as Kloprogge et al.'s [68] pedigree matrix can help scientists assess the value-ladenness of such assumptions and decisions, and include criteria for: practical aspects, epistemic, disciplinary-bound epistemic, and socio-political issues, the latter of which could encompass these governance and funding decisions. These values arguably should be communicated at a level appropriate for each audience, so they can understand the limitations and biases of the science and make an informed decision.

These recommended practices have been developed for the communication pathway between scientists or risk assessors and informed decision-makers, where quite detailed and nuanced information can be queried and evaluated by them with few time constraints. Future research is needed to explore whether such nuanced information is useful for broader audiences, and if so, how such factors can be communicated effectively when time and resource constraints might also exist. Our participants expected uncertainty to exist because of what is and isn't funded, but did not expect that heterogeneity of funding (and thus limitations of knowledge) to be well communicated. This is important as governance, policy, political, and economic imperatives, as well as political ignorance of key issues, are all manifest in funding decisions. In some contexts, these funding decisions may reflect political priorities that impose limits and may not be in line with prevailing research, thus leading to poorly informed decision-making. It is unclear how and to what degree these influences on scientific uncertainty should or could be communicated. However, our participants expect them to exist, and thus assumptions about them will factor into their interpretation of the science itself. Similarly, there is a potential that if this 'reason' for uncertainty is not transparently communicated, it may be used against science communicators, particularly in polarised debates (see Corner et al. [151] in the context of climate change).

4.2. Understanding influence of societal factors

Closely related to the above is the question of how, or whether, we should communicate the influence of societal factors on science advice, when conveying its uncertainty (such as the *reasons* why something is or is not funded). Our participants clearly identified that scientific uncertainty is not just about the science, or the influences on science, but also about the broader landscape on which science is conducted and communicated. For example, this includes the scientific outcomes and objectives and resulting impacts upon decisions. However, it also includes how people might react to the science or behave upon receipt of that information (Section 3.4.2). This is particularly important if future or ongoing decisions and science or risk assessments depend upon an understanding of those response behaviours. Thus, uncertainty cascades and feedback loops can be created: 1) public response, or lack thereof, to NHEs can compound the effect a NHE will have on communities, 2) scientific risk assessments and advice may thus not fully consider this range of human responses, creating 3) further uncertainty. For example, if people do not evacuate from their homes before a predicted flood event, the impact of the NHE becomes compounded, as public safety is now at risk. This situation is further complicated when the risk and potential outcomes are also uncertain (Section 3.4.1), as it can be difficult to communicate clear advice to the public. Thus, effective actions can be compromised, and there may be a greater variety in, and understanding of, the potential human behaviours in response to that uncertain advice. Further, that advice may not have considered the diversity of the affected population and their likely actions, particularly as marginalised or underrepresented groups may be excluded from the impact or risk assessment informing that advice.

This feedback loop can also be described as 'human reflexive uncertainty' [152], such as that described by the influences of the unknowns associated with future socioeconomic systems [102]. Such uncertainty limits scientists' abilities to constrain forecasts for phenomena where humans play a critical role in the future pathways, such as for climate change or sea level rise projections [102,152]. As discussed by Dessai et al. [153], a range of different approaches have been proposed for representing such [deep] uncertainties in the complex context of climate change, ranging from 'tales of future weather' through to storylines of atmospheric circulation or of climate sensitivities. Similarly, adaptation pathways and dynamic adaptive decision-making utilise scenarios to provide descriptions of plausible futures reflecting different perspectives (see e.g., Ref. [154]). Meanwhile, approaches such as climate narratives can address decision-making under deep uncertainties in a way that existing approaches from psychology and economics cannot [155]. Dessai et al. [153] thus propose a methodology that uses narratives to help *characterise* uncertainties by qualitatively describing physically plausible evolutions of future regional climate through expert elicitation. As discussed by Constantino & Weber [155], such narratives are "stories about how the world works, what the future will look like, and our own role in this process" (p. 152), creating an external representation of a model that is not that dissimilar to our definition of a mental model (see section 1, [24,42–45]).

Such climate narratives, sometimes referred to as 'literary narratives' [156](p. 398) thus offer a scenario planning approach to capturing uncertainties as they can convey mutually exclusive possible futures [157]. They can include the influence of social and economic factors on decisions and impacts over time, and when these narrative descriptions include multiple alternative future scenarios they attempt to capture the different potential influences of societal factors amongst other uncertainties, and offer creative approaches to grappling with the 'uncertainty shrouding the long-term future' [156](p. 398). Similarly, event-based storylines can be used to explore uncertainty [82] by focusing on plausibility, salience, and relevance of multiple, mutually exclusive outcomes.

However, in many domains, the assumptions about the socio-political and economic factors, and associated decisions, are often not conveyed via these various communication tools, future scenarios, or forecasts. Yet our participants expect them to exist, although they do not know what they are and cannot use them to evaluate the scientific information and forecasts or scenarios conveyed. Given decisions upon natural hazards science may include assumptions and perceptions about future human behaviours based upon that very science advice (Section 3.4.2), how and to what degree should those behavioural assumptions associated with a scientific risk assessment also be conveyed? Such assumptions relate to cultural factors, the social construction of risk [158], as well as scientists' understanding of the role of different knowledges upon individual decisions, the diverse needs and capabilities of different communities, and how uncertainty arises, evolves and is managed differently by people and processes (including their management of residual risk, or strategic planning) [23,109,159]. It also draws upon social science of how people behave based upon informational and social cues [32,160–162].

4.3. How outcomes are intrinsically linked into perceived sources of uncertainty

As discussed in Section 3.4, our participants had a complex understanding of uncertainty, including sources related to the world and phenomena, through to those related to forecasts and social influences on science, and finally to those related to event outcomes including uncertainties arising from assumptions about the human decisions being informed. The approach of rationalising uncertainty in terms of impact and consequences has similarities with approaches used to reduce uncertainty to a form of measurable 'risk' [78], within which uncertainty and risk are intrinsically related. For example, the International Organization for Standardisation [163] defines risk as the "effect of uncertainty on objectives". Similarly, the UK Government states "risk refers to uncertainty of outcome, whether positive opportunity or negative threat, of actions and events. It is the combination of likelihood and impact, including perceived importance" ([164] p. 7; see review in Ref. [23]). This is in contrast to the definition of uncertainty often found in science, and discussed in our introduction (Section 1), where it is classified as arising due to the natural stochastic uncertainty (variability of the system, aleatoric), or the epistemic uncertainty (unknowns, lack of knowledge, imperfect knowledge) (see reviews in Refs. [30,34]), or through its definition of 'unknowable knowledge' as found in climate change [152,165].

This diversity in understanding of how uncertainty, risk, and outcomes relate, creates a challenge when communicating scientific information and its associated uncertainty in the context of natural hazards, where risk and people's understanding of risk is central to the scientific endeavour. In the definitions of uncertainty discussed by participants in Section 3.1, the strong focus on outcomes demonstrates how participants needed to contextualise and think about impacts to rationalise what uncertainty is, and what it means. Are individuals conflating uncertainty and risk, and focusing more on the *outcomes* of the science rather than the *content* of the science when recognising and defining sources of uncertainty? This may also explain why some participants focused on perceived personal as well as societal impacts (such as legal consequences, [166]) in their identification of sources and consequences of uncertainty and its communication (Section 3.3.1), whether those are accurate perceptions of impacts or not. Participants thus described risks in terms of *consequences of the event* itself, as well as the *consequence of the advice* associated with the event (Section 3.4.1). As discussed by Sword-Daniels et al. [165], uncertainty can prevail even when substantial information is available, due to the different interpretations of this knowledge, and what this knowledge means. In risk domains, uncertainty is however often primarily studied as it relates to 'absent and/or conflicting knowledge' and how that uncertainty relates to the difficulties assessing probabilities and consequences, and the values of those consequences (see also [32,167]). Less focus is on the sense-making, or meaning-making process applied to these uncertainties, and what that means for effective communication.

Considering our findings herein, it appears the perceived outcomes or impacts of the science can also act as a *scaffold* through which people make sense of the uncertainty itself. The structure of the different outcomes may act as an initial system to construct a mental model to understand and reconcile the uncertainty, and to develop shared mental models with others built around the scientific process. This scaffold then takes a different form depending upon the worldview and priorities of the reader, being different for those focused on natural hazard events and emergency management, compared to public or political decision makers (see also Doyle et al. [65]). Future research must explore the different interpretation scaffolds that may be used across the different communities involved in natural hazard risk management, with a view to then informing the effective communication of uncertainty.

4.4. Emotions, fear, and drivers of and because of uncertainty

Meaning making within the realm of science and scientific uncertainty does not just relate to our prior experience, knowledge, epistemological and cultural worldviews [20,168,169]. Our participants highlighted how they also felt the presence, and interpretation, of uncertainty also relates to our internal affective state of not knowing, being influenced by emotions including fear and anxiety in particular, such that *"it's more of a feeling, like an emotional feeling I suppose, rather than an intellectual sort of a thing"* (Nu, Anthropologist). These emotional influences lie within the scientists when crafting their science and message, and in the audiences' interpretation and application of that science.

Emotions can affect decision making and rational thinking both positively and negatively. Mild 'stress' emotions can enhance reasoning [170,171], particularly for trained professionals responding in uncertain situations [172–174]. However, some emotional reactions (extreme fear and anxiety, etc.) can reduce rational thinking and impact effective decision making due to issues such as fatalistic thinking [2,175–178]. Similarly, uncertainty associated with a scientific message, or felt in response to the content of a message, could contribute to the enactment of various cognitive biases seen in response to messages, such as the ostrich effect, optimism bias, or confirmation bias (see review in Crawford et al. [179]), or as discussed by Mu (Planner) can cause a form of desensitisation to the science through overreporting of risk (Section 3.4.1). This may contribute to the perception of 'false alarms' [180]. How our participants conceptualised uncertainty thus related to both the emotional impact of uncertainty upon people, as well as emotion related behaviours that can create sources of uncertainty when giving or receiving NHE science advice. Several participants highlighted the relationship between fear and uncertainty, and how fear can arise due to not knowing what the future will be, or because people have a poor understanding of the situation and science, such that the fear of the unknown future can "breed" more uncertainty (Alif, Local Government/CDEM).

The role of emotions in decision making has become increasingly researched in the last twenty-five years and has produced a paradigm shift in decision theories [170]. In a review of emotion and decision-making literature, Lerner et al. [170] found that, for example, a person who feels anxious about the potential outcome of a risky choice may choose a safer option rather than a potentially more lucrative option. Therefore, in the case of responding to a NHE, a person may choose to act in a way that they perceive as 'safer' in that moment (such as choosing to shelter in place in a familiar known environment, such as their home, even if it may flood) rather than taking a 'risk' on an unknown action (such as evacuating through a storm to an unknown environment, like mass evacuation shelters). Lerner et al. [170] note that these integral emotions operate at conscious and nonconscious levels, which could be described as 'known' and 'unknown' levels, such that uncertainty exists as to which emotions will be present and how they will influence responses to NHEs.

Such emotions, like the anxiety associated with uncertainty, can be motivational and drive the science that is conducted. As highlighted by participants, this positive perspective on uncertainty can encourage scientists to improve science (Section 3.5). Smithson [181] also highlights the positive aspects of uncertainty describing how the nature of research *"presupposes conscious uncertainty … at the outset; otherwise there is nothing to research"* (p. 20). The absence of information overlaps with known unknowns and acts as a driver to stimulate us to gain further knowledge [66]. Bammer et al. [66] highlight known unknowns are often the focus of 'future studies' work to identify blind spots and challenge assumptions to mitigate future surprises or devastating consequences from their presence (see e.g., Aven [182]). Similarly, Espig et al. [135] discuss a middle ground between accepted knowledge and unknown unknowns, within which sits *"known or suspected unknowns, not-yet-knowns and desired unknowns"* (p. 5), stating this non-knowing is not negative or undesirable but rather can be a key impetus for scientific research and creativity (see also [57]), It can also drive the need for information amongst audiences who wish to reduce their anxiety and any uncertainty associated with a risk [19,96,183–185]. Unfortunately, this may also drive individuals to conspiracy theories and misinformation as a maladaptive coping strategy to manage the uncertainty of science and 'grasp for certainty' [186–190].

4.5. Trust and the communication landscape

Participants identified that the communication landscape and information networks (between individuals and within and across organisations) provide additional sources of uncertainty. For example, as discussed by participants in section 3.3.2, the conflicting science stories in the media creates uncertainty as to who to listen to, and who to trust. This relates also to the issue of 'false balance', as often seen in climate change contexts, where the media seeks to represent both views equally and, in this process, may imply considerably more support for one view than exists and also increase perceptions that experts are divided [191–193]. It's unclear how uncertainty feeds into, or drives, this media approach, however it is clear from our participants' views that it generates uncertainty in the communication landscape. Participants highlight how it becomes difficult to know who to listen to and therefore who to trust when scientific advice is presented in this way (section 3.3.2). The way scientific advice is portrayed in the media can thus have a significant impact on how the public responds to advice, as evidenced by empirical studies demonstrating the influence of media framing and media interpretations upon how people attribute the cause of risk, or the efficacy of mitigation actions [194,195]. This highlights the important need for scientists to become trusted communicators in the media and online, particularly during the time-critical stages after an event when these information sources may be prioritised for rapid communication [196]. In such circumstances, the role of local scientists becomes important for building trust, as they also share the disaster experience and impacts with the affected public [ibid].

Considering this role of *trust*, or lack thereof, participants discussed the presence of individual vs. multiple experts as either engendering or reducing trust, which was tightly related to their previous experience of those experts and of media portrayals of them (see Section 3.3.2). Several participants trusted the science more than they trusted individual scientists, demonstrating the different locations of trust that can exist [141,197,198]. Events and emergency management exercises have demonstrated the value people hold in there being ‘one trusted source’ of science advice in a crisis, as represented by science advisory groups [109,199–202], even when these SAGs present a range of interpretations or outcomes. These advisory groups were identified to enhance trust, preventing conflicting or confusing messages [203]. This approach is supported by studies that have shown that individuals prefer ambiguity over conflict when it comes to science advice (e.g., Ref. [197]), such that having mechanisms to encourage collaboration across science communicators through a unified voice is preferable to conflicting communicators, even if there is uncertainty of opinion within that unified voice (see also section 3.3.3).

Similarly, Johnson [204] found that participants felt disagreements amongst scientists were due to self-interest or incompetence, rather than the nature of evidence. However, several participants in our current study did not provide such negative comments about scientists who disagreed, noting that at times it created space for healthy debate, future research, and the advancement of science. In other instances, participants felt scientists disagreed for more self-serving reasons, such as not wanting to look ‘wrong’, having their work discredited, and protecting their reputation. Maxim and Mansier [91] found that conflicts of interest and the institutional affiliation of a scientist can also affect the perceived credibility of scientific messages (see also Keohane et al. [89]). Meanwhile, more recently, Johnson et al. [205] identified that laypeople respond to several influential cues when scientists disagree, these include the majority vote (how many scientists support a position), replication of the science, information quality, and experience; with several moderators, such as attitudes to science (when positivism is higher people place more weight on information quality and the majority vote).

To address these communication challenges, modern Civil Defence and Emergency Management (CDEM) practices incorporate science advisory groups (SAGs) such as the Aotearoa Earthquake Science Advisory Panel (AESAP) or the Tsunami Expert Panel (see Doyle et al. [199]) to provide coordinated advice across scientists and disciplines, to reduce conflict and enhance trust. However, further research is needed to understand whether the framing of advice that comes from SAGs should focus on the diversity of science evidence represented by the SAG, or whether it should focus on representing the diversity of the individual scientific opinions within the SAG. Future research should thus explore which factors influence the different locations of trust in a scientific message (e.g., trust in individual scientists, agencies, and disciplines of science). In addition, how does that relate to an individual's mental model of science, the location of uncertainty within that, and its evolution through time?

How the public receives information about natural hazard events, the role of media, and potential portrayals of false balance of evidence [191–193], as well as the issues of misinformation, disinformation, and social media due to the growth of increasingly diverse sources of information [129–131,133] were all thus seen as sources and drivers of uncertainty by our participants. Conversely, these factors also provide mechanisms that helped individuals develop *perceived certainty*, often driven by a motivational anxiety due to the presence of uncertainty (discussed above, Section 4.4). The rise of social media and its influence upon individuals is well recognised, with ongoing research in this area [106,132,206,207]. Khan et al. [106] note that an individual is not just informed by the government or media, but also by family, friends, and neighbours, who may not be adequately knowledgeable. They also note that emergency managers (EM) have lost the monopoly on risk communication as the public engages with television, social media, and the internet. Interestingly however, few participants in our current study mentioned social media in their discussion of sources of uncertainty. For those who did, they did not discuss it in depth. It may be that the participants in this study did not hold much value in social media as a source of information (and therefore a source of uncertainty) or were not aware of the potential disinformation movements on the various platforms to warrant it a threat [208,209]. Future research should explore how this broader understanding of where uncertainty comes from in this ‘noisy’ communication landscape influences how scientists choose to craft their messaging, and how people then respond to those crafted messages. In addition, previous events in AoNZ, such as the Canterbury earthquake sequence and the Kaikōura earthquake, have demonstrated the large public interest and desire for information from the scientific community through broader communication pathways such as formal and informal science websites (see Refs. [196,210]). Thus, further research is needed to understand how these websites are understood and used alongside social media and other sources, particularly when uncertainty is high or information is in conflict; as well as the ethical responsibilities of the scientists when using such websites to convey uncertain information.

4.6. Time and decision-making

Considering the influence of *time*, most participants indirectly or directly discussed the influence of time pressures, time constraints, and time availability on the presence of uncertainty, and upon its interpretation. Thus, time acted as an influencing factor on the level or amount of uncertainty present. Time pressures can also create sources of uncertainty, such as when decisions are made before adequate information is available, creating uncoordinated actions that adds complexity to the situation (see e.g., Khan et al. [106], and Doyle & Becker [23]). If advisors and decision makers choose to reduce uncertainty rather than acknowledge, suppress, or plan around the uncertainty [65,69], then additional time is also needed to solicit further information to reduce that uncertainty. This thus impacts the perceived timeliness of, and trust in, science advice in a crisis (see e.g., Refs. [196,211]).

Time was also present in participants' discussion of past events, in the relevance and currency of science information, in the ability to gather data, and in the evolution of individuals' understandings. In their discussion of the uniqueness of events (section 3.2.2) participants highlighted how in some cases, and particularly for NHEs, inferences need to be based upon nonreplicable unique case study events and research, which are often based on perishable field data (see also Devezer et al. [212] for more). Thus, *change over time* impacts what can be known about events, and what is then prioritised for research and funding after events (as well as what is not researched). This creates gaps in data and reiterates participants’ comments about needing to make assumptions about events to address associated data gaps (section 3.2.1), such that those assumptions and interpretations become additional sources of uncertainty.

Future decisions are often influenced by knowledge of past events, and these decisions may not take into account how social or physical contexts have changed, nor accurately factor in a lack of previous events from which to draw from (see also Fig. 1). Thus, time is integral to having enough relevant data (Section 3.2.1), and how uncertainty around model output data can change depending upon evolving input data and knowledge of past events. Research has shown that the evolving nature of model input data requires structured communication that acknowledges its influence on uncertainty (Doyle et al. al., [30]), particularly in legal contexts and when providing expert witness testimonies (e.g., for AoNZ's Resources Management Act [213]). However, our research highlights a need to understand how individuals' mental models evolve through time and what that means for communicating changing uncertainties. This should not just consider their mental models of the scientific phenomena, scientific processes, and risk assessment, but also their mental models of the communication landscape and influence of societal factors discussed previously (Section 4.1-4.3).

4.7. Emerging lessons for communication

Doyle and Becker's [23] review of the literature outlines several key principles that should be strived for to enhance risk and science communication as it relates to natural hazards. These include:

- understanding how the audiences structure the risk problem (individual and societal);
- identifying information that is relevant to people's actual concerns and meets decision needs;
- understanding and developing trust through relationship-building and shared approaches to communication; and
- being aware of the different goals, priorities, and concerns of diverse audiences, as well as between the communicator and these audiences.

The literature that considers the communication of uncertainty in natural hazards communication emphasises (see also review in Doyle et al. [30]):

- the need for decision-maker centredness for ethical uncertainty communication;
- the importance of understanding social and organizational contexts and how that influences interpretations of, and needs for, uncertainty information through time;
- the need to communicate the social history of uncertainty and potential value-ladenness of assumptions;
- and the need to support communication with exercises, simulations, training, and education to facilitate greater mutual understanding.

Across these lessons and guidelines for effective communication, there is a requirement to understand each scientist's and diverse audience's perspectives on the science, the uncertainty, and the risk being conveyed. In the current study we have increased our understanding of the *perceptions* of uncertainty associated with natural hazards science advice. Effective communication that is decision-maker led, and considers audiences' perspectives and values [23,36,41,214,215] depends on understanding what those different perspectives are. We have thus demonstrated the wide range of uncertainty sources that are recognised by individuals involved in the management of natural hazards, extending beyond the traditional sources related to data, and including more nuanced sources related to the communicators, scientists, and public themselves.

Across our interviews, the participants highlighted the need to communicate not just transparently, but in a *meaningful way* (see section 3.5) that was relevant to their needs, concerns, and priorities. While participants struggled to define and articulate what uncertainty is, many discussed the positive role of uncertainty driving science, and the need to 'sit with uncertainty'. Participants stated that "you always have uncertainty", and felt that scientists "need to find a way to convey that uncertainty in a way that's meaningful to people", including explicitly stating or explaining the sources of uncertainty, its impacts, and how they might reduce that uncertainty. This finding supports calls from the literature for the communication of decision-relevant information through translational discourse [216] that must consider audience needs and perspectives prior to communication [34]. Achieving this requires integrating several emerging lessons from this study, as follows:

- Communicators should be transparent about the funding sources of research, and the rationale behind decisions for not just what has been researched but what has *not*. This increases decision-makers' understanding of the heterogeneity of research and increases awareness of areas where uncertainty may arise due to research gaps, funding priorities, as well as areas of potentially duplicated and unlinked work.
- The need to identify effective methods to constrain and effectively convey uncertainty related to people's expected or predicted responses to a natural hazard risk assessment or science advice, as those behavioural uncertainties can feed back into follow on risk assessments or decisions.
- The importance of recognising that decision-makers' will use their perceptions of the potential outcomes associated with a risk as a form of **scaffold** to assist their interpretation of the scientific information about that risk. Their expectation of what these outcomes will be provides a structure for them to rationalise scientific information associated with that risk, and interpret and manage related uncertainties. Thus, shared approaches to risk and uncertainty management, such as scenario planning and tabletop exercising [199,217–220], may help individuals identify these risk outcomes by helping to build the initial scaffold from which their mental model of uncertainty may evolve.
- The continued use of science advisory group structures to help coordinate science advice. There is also a need for more research to explore how to effectively convey the individual scientists' opinions within those SAGs, alongside the collective view, in a way that encourages and maintains trust and credibility.
- That publics and decision-makers may be more comfortable with uncertainty than scientists tend to recognise in their communications. Thus, communicators may be able to enhance credibility and uptake of their messages by acknowledging the positive role of uncertainty in the progression of science, recognising that not all uncertainty can be reduced or removed, and

indicating ways that uncertainty is being addressed by scientists or can be managed by different audiences. This promotes a transparent conversation about uncertainty, identified as important by our participants who expect uncertainty to be present in the science conveyed.

When interpreting our results, it is important to acknowledge the broad scope of 'science' we allowed our participants to consider in their discussions. In our interviews, we did not impose constraints on the breadth or type of science participants considered. So long as it related to natural hazard events, participants were free to discuss and explore all sources of uncertainty in science advice, whether that related to physical or technical science, or influences from social science, from other 'ways of knowing', or through different cultural worldviews [94,127,221–223]. Often participants' perspectives of uncertainty thus sat in a broader communication and decision-making landscape and were not limited to just their understanding of natural hazard phenomena. Thus, the collective 'concept' map (Fig. 1) and the themes discussed herein highlight the holistic nature of people's mental models of uncertainty, extending into human influences and moving beyond just the scientific methods or the data available, further reinforcing a need in communication practice to recognise those nuanced uncertainties.

As discussed in the next section, these tentative recommendations are drawn from what we have found in this study and they require further research to constrain them, to ensure they are appropriate for different audiences, and importantly how to adapt them to different decision time frames. They also require testing through real-world practice and evaluation.

4.8. Limitations and future research

In addition to the gaps noted above and throughout section 4, there are several limitations that exist in this research that indicate other future research requirements, as follows:

- The range of participants recruited for this study was restricted by the Covid-19 protection restrictions present in Aotearoa New Zealand at the time of this research. Therefore, recruitment was mostly restricted to accessible scientists and decision-makers, with few lay perspectives. Thus, future research should include broader public perspectives.
- The participants' prior experience of scientific agencies and science communicators was not considered, thus future research should also consider how this prior experience in crisis and non-crisis times influences individuals' perceptions of scientific uncertainty, and how it changes the perspectives of key themes discussed here (including the actors as a source of uncertainty).
- In this analysis we examined a collective mental map, based upon common themes from across individual maps. Detailed comparative analysis of the mental model maps produced by individual participants is thus required to enable deeper understanding of different sectoral and public perspectives of uncertainty. This is planned following additional lay interviews, discussed above.
- Several influences on uncertainty were identified, which can increase or decrease the uncertainty present. These included governance, funding, emotions, time, trust, and societal factors. Further research is needed to explore whether participants perceive these as distinct sources of uncertainty, or as enablers or mediators of uncertainty. In addition, research is needed to understand how these influence each other (e.g., funding, data collection, data analysis), and whether participants consider these uncertainties to exist in a hierarchy of importance [30,68,75–77], and what that means for effective communication.
- Throughout this research we encouraged participants to think about uncertainty in a natural hazards context. However, the discussion was not constrained to specific natural hazards. Future research is thus needed to identify how the sources of uncertainty may vary depending upon the type of event. It is important to understand how the unique circumstances of a hazard, from its timeframes to its origins, and the influence of human actions and decisions, may impact perceptions of uncertainty (e.g., land use planning and flooding). In addition, multi-, cascading-, and coincident-hazard scenarios require additional consideration in research (e.g., changes to flood risk post-earthquake).
- Our development of the conceptual map (Fig. 1) does not consider temporal changes in the location and type of uncertainties. It is likely that the structure and sources of uncertainty may change through the time frames of risk management, or through the steps of risk analysis or scientific enquiry. Future research should thus explore participants' perspectives of this evolution of uncertainty.

In addition, future research should explore how anxiety might drive individuals to search for information outside mainstream scientific communications, engaging in conspiracy theories and consuming misinformation as a maladaptive coping strategy to manage the uncertainty of science (section 4.4) [171,189–192]. Could an improved articulation of the history and source of uncertainties, perhaps through narratives and story (as discussed in section 4.2), help to moderate this maladaptive coping strategy? This may have value in situations where uncertainty is currently poorly explained and exists due to information gaps or conflicting information, or arises due to ambiguity associated with media portrayals of science, such as the presence of 'false balance' between conflicting science advice (Section 3.3.2).

5. Concluding remarks

Effective communication of science, and scientific uncertainty, relies upon fundamentally understanding the different audiences of scientific information and messages and how they develop and change over time, including their assumptions, values, perspectives, concerns, needs, and world views. This should also include an understanding of their mental model of the phenomena or issues. Herein we have presented the first stage of a research program that seeks to advance understanding of individuals' mental models of scientific uncertainty for natural hazards science advice, focusing on their identified sources of uncertainty. These include The Data (not having enough, its uniqueness, interpretation of), The Actors (including the scientists, the media, communicators, key stakeholders), and The Known Unknowns (including the range of possible outcomes, unexpected human responses, and the presence of unknown unknowns). Underlying and influencing these sources are a range of additional factors include governance and funding, societal and economic factors, the role of emotions, how perceived outcomes helped scaffold meaning making of uncertainty, the communication landscape, and influences from time and trust.

Participants thus felt that scientists need to find a way to convey uncertainty in a way that's meaningful to people, including explicitly stating or explaining the sources of uncertainty, its impacts, and how they might reduce that uncertainty while also acknowledging the role that other societal influences have on that uncertainty. Crucially, while many of the uncertainties discussed herein are not currently conveyed in communication of natural hazard science, individuals do expect them to exist. Thus, they may make assumptions about their expected presence that is potentially incorrect and detrimental to resultant decisions. If the range of uncertainties conveyed is incomplete, participants are unable to adequately use them to evaluate the scientific information being shared. In addition, the ambiguity about the presence or not of other uncertainties can also influence individuals' emotions and their 'internal affective state of not knowing', which can promote anxiety and fear which can both positively and negatively impact decision-making.

Constructing communication in ways that accommodate the above factors enhances transparency and trust in the science and the communicator. It can also enable an audience to evaluate the information within their own decision-making framework, by providing them with a more complete history of uncertainty. However, it is currently unclear how practical or possible this is when there are extreme time constraints, or when messages need to reach a very broad audience quickly. For example, how should complex nuanced uncertainties, such as the behavioural assumptions within a scientific risk assessment, or the 'social history' of uncertainty in a model forecast, be effectively conveyed? Should these be communicated in conjunction with the communication of more traditional scientific uncertainties? Or will this cause information overload, resulting in a disengagement with the science and affecting credibility with the communicator. So, rather, should we simply acknowledge that these social aspects and influences exist? Future research must constrain evidence to inform best practice communication for these nuanced and complex uncertainties.

In conclusion, findings from this research contribute towards advancing the theoretical understanding of perceptions of scientific uncertainty of hazards and risk, and to informing international strategic goals for disaster response and crisis communication before, during, and after events [33,224]. The Sendai Framework [31] seeks to "promote and improve dialogue and cooperation among scientific and technological communities, other relevant stakeholders and policymakers in order to facilitate a science-policy interface for effective decision-making in disaster risk management" (p. 11). Mental models approaches to communicating science and science advice have been successful in a range of contexts for achieving this goal (from health and safety messaging through to climate change communications and flood warnings). They enable a message to be crafted in a way that addresses the differences in understanding between scientists, communicators, policymakers, and decision-making publics [24,225–228]. In this research we thus present an initial understanding of scientific uncertainty using a mental models approach, to inform further research and encourage uncertainty communication that adapts to, and accommodates, the diverse perspectives involved in the shared responsibility of risk.

Declaration of competing interest

The author declares 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 data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2023.103948.

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