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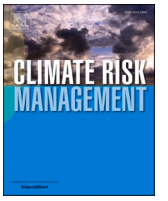

Dealing with uncertainty in flood risk management and land use planning decisions: Insights from Aotearoa New Zealand

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ABSTRACT

Flooding with increasing intensity and frequency is presenting significant challenges for risk management and land use planning in urban areas. This is further exacerbated by uncertainties regarding how flood patterns are changing because of climate change. However, how such uncertainties are considered to inform flood risk management and land use planning decisions can vary largely from place to place and remain unclear in the literature. This paper contributes to this by examining how uncertainty is dealt with in flood risk management and land use planning in Aotearoa New Zealand. Drawing on empirical data at the local level, findings indicate that Aotearoa New Zealand's decision-makers face challenges in considering and communicating uncertainty due to the prevalence of outdated approaches and regulatory constraints, fragmented risk governance, and lack of appropriate understanding of different perceptions and assumptions regarding flood risk between different stakeholders. Based on findings, the paper discusses the critical role of a national-level adaptive flood risk governance in helping to ensure consistency and coherency across different jurisdictions and levels of government, regarding the incorporation of uncertainty into flood risk management and land use planning. This includes the provision of national directives for incorporating uncertainty in decision-making whilst leaving room for innovation and targeted variability at the local level.

1. Introduction

Flooding is one of the most frequent natural hazards in many cities around the world. Over the last two decades, floods affected more than 1.6 billion people worldwide with an estimated flood damage exceeding the US$600 billion mark (Sieg et al., 2023). Flood risks are compounded by the increased frequency of extreme precipitation events as a result of climate change, rapid urbanization and development processes (Meng et al., 2022; Serrao-Neumann et al., 2023). Additionally, increased catastrophic impacts of flood events indicate the inadequate preparedness and ineffectiveness of existing flood risk management to address the dynamic and uncertain nature of flood risks (Lawrence et al., 2013). For example, in Aotearoa New Zealand, the devastating impacts of Cyclone Gabrielle in February 2023 (e.g., 10,500 people displaced, 11 casualties) were closely associated with the development in high flood-prone areas and the reliance on flood protection systems with design standards that were not able to withstand extreme events (Harrington et al., 2023; Kerr et al., 2023). The 2021 flood event that affected Germany (e.g., 189 casualties) and Belgium exceeded the intensity and impacts estimated in existing flood risk assessments despite the continent's high technical capacity (Sieg et al., 2023).

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The ongoing changing nature of flood risks has increased interest in recognizing the importance of uncertainty in flood risk management and planning (Lawrence et al., 2013). Uncertainty with respect to decision-making can be simply defined as the gap between the available knowledge and the knowledge that is needed by decision-makers to make the best policy choice (Marchau et al., 2019). In this regard, it has become evident that science alone cannot deliver the certainty and confidence that is sought by flood risk managers and regulatory planning practices (Lawrence and Manning, 2012). Additionally, there is a range of significant uncertainties around flood risk management, including climate change uncertainties, uncertainties embedded in data and models, and uncertainties of human, social and decision-making dimensions (Haasnoot et al., 2013). Rather than ignoring uncertainty or using it as an excuse for inaction[1] (Moure et al., 2023), it is critical to find new ways to effectively engage with uncertainty to better inform flood risk management and policymaking (Bevan, 2022; Doyle et al., 2019). The effective engagement with uncertainty involves both recognising its presence and incorporating it in decision-making processes, either by reducing uncertainty where possible or adapting strategies to accommodate it (Bijlsma et al., 2011; Lipshitz and Strauss, 1997).

Incorporating uncertainty in flood risk management, however, is challenging. The question of whether flood risk management is effectively incorporating uncertainty is highly dependent on local circumstances and institutional frameworks within which the decisions are made (Lawrence and Manning, 2012). For example, the use of static planning measures (e.g., flood defences designed based on single number estimates) that overlook the sheer dynamics of climate processes, the need for legal certainty in the planning system, the demand for protection by communities, and the siloed organisations can significantly hinder effective engagement with uncertainty in managing flood risk (Lawrence et al., 2013; van Buuren et al., 2018). To this end, it is important to understand the local intricacies and constraints affecting decision-making to gain a comprehensive picture of how local-level decisions can better deal with flood risk uncertainties in light of climate change (Bevan, 2022; Doyle et al., 2019; Moser, 2005). This paper aims to contribute to this understanding by investigating how decision-making in Aotearoa New Zealand (herewith ANZ) addresses uncertainty related to flood risk management and land use planning. We draw on empirical data collected as a part of a national flood risk research project, which commenced in October 2020.

The paper starts with a review of what characterises uncertainty associated with natural hazard risk management, especially relating to flood risks and corresponding implications for flood risk management and land use planning decisions. This is followed by the methods and results sections. Based on findings, we present insights on how local-level flood risk management and land use planning can better incorporate and deal with uncertainty.

2. Uncertainties associated with flood risk management and strategies for dealing with it in decision-making

Flood risk management practice has long been entrenched in the assumption of system stationarity –"the idea that natural systems fluctuate within an unchanging envelope of variability" considering static numbers and single 'best estimate' scenarios (Lawrence et al., 2013, p. 133; Milly et al., 2008, p. 573). This assumption has galvanised the use of flood defence measures such as levees, dikes, flood walls, and embankments, with certain design standards (e.g., 1 in 100-year event), above which they can fail through overtopping and breaches and thus expose communities to residual flood risk – that is, risk that is greater than the design standard of protective measures (Fu et al., 2023; Serra-Llobet et al., 2022). The expectation and desire for precision and static single numbers are also evident in the time-bound treatment of risk and spatial demarcation of fixed hazard lines on maps for controlling land uses, defining flood-prone areas, and devising flood-related regulations (Lawrence et al., 2013; Lawrence, 2015; White, 2013). The desire for precision, however, can be misleading as it mismatches the changing flood risk and multiple layers of uncertainty associated with climate change (van Buuren et al., 2018).

Consequently, many studies have attempted to conceptualise and identify uncertainty (Bevan, 2022; Lipshitz and Strauss, 1997; Walker et al., 2003), claiming to help provide a basis for decision-making on complex issues (Bevan, 2022), meet the ethical demands of transparent decision-making (Hamel and Bryant, 2017; Pappenberger and Beven, 2006), and identify appropriate tools and techniques for managing uncertainty (Bevan, 2022). Uncertainty can manifest itself within different steps of the decision-making process such as what is happening (i.e., preparation and context, sea-level rise and hazard assessment), what matters most (i.e., values and objectives), what we can do about it (i.e., identifying options and their impacts, identifying criteria to assess options, choosing an option or set of options), how we can implement this strategy (i.e., identifying management actions, enacting managerial actions), and how it is working (i.e., monitoring and evaluating them) (Bell et al., 2017; Cardenas and Halman, 2016).

Uncertainty tends to be described within the aleatoric (i.e., ontic/ ontological uncertainty) and epistemic (i.e., known as systematic) divide (Bevan, 2022). Aleatory uncertainty refers to inherent variability that can include randomness of nature, behavioural and societal variability which is considered to be irreducible for predictive purposes (Walker, 2020; Walker et al., 2003). Conversely, epistemic uncertainty refers to uncertainty due to limited and imperfect knowledge which may be reduced when more research and empirical data become available (Bevan, 2022; Walker, 2020). Other types of uncertainty include scientific uncertainty in data, models, and future climate projections and impacts (Moure et al., 2023), social uncertainty regarding what actors, institutions and stakeholders' values are involved in risk management and decision-making uncertainty. The latter is concerned with the unknowns and ambiguities in determining the level at which the change in climate is dangerous, what adaptation goals, needs, and options are sought, and how climate is changing (Kettle and Dow, 2016). Decision-making uncertainty can have the most significant impact on determining the support for the development of adaptation plans, allocation of human and financial resources, and improving local

[1] As stated by Moure et al (2023), a few studies have shown that uncertainty has been used as an excuse for inaction particularly in political arenas to avoid politically damaging decisions and to distract from uncomfortable knowledge.

response capacity and effectiveness (Kettle and Dow, 2016; Moser, 2005; Moure et al., 2023).

Recently, there has been an increasing amount of research focusing on identifying different approaches, methods and tools for aiding decision-making under different sources and levels of uncertainty (Lawrence et al., 2013; Marchau et al., 2019). Two of the main active approaches are reducing and acknowledging uncertainty. Some of the methods for reducing uncertainty include the delay in action and the provision of opportunities for adjusting decisions until sufficient evidence is obtained (Quigley et al., 2019), request of further advice, use of best available knowledge (Bijlsma et al., 2011), and the adoption of assumption-based reasoning (Lipshitz and Strauss, 1997). Others include improving readiness, avoiding irreversible action, weighing pros and cons (Bijlsma et al., 2011), and tools such as iterative risk-based adaptive planning, real options analysis, robust decision-making, and dynamic adaptive policy pathways (Haasnoot et al., 2013; Lawrence et al., 2013). These tools are based on robustness that allows for testing different strategies across a range of future climate scenarios, but they have specific usefulness and limitations (Bell et al., 2017). Hence, depending on the objectives to be achieved, the response options, and the level of uncertainties involved (e.g., clear risk threshold, high uncertain future), a combination of tools may need to be used (Bell et al., 2017).

Incorporating uncertainty in decision-making has proven to be difficult, especially considering the notion of path-dependency and institutionalism (e.g., the legacy of past decisions) that challenge decision-makers to be risk averse and to maintain the status quo (Lawrence et al., 2013). For example, the use of static planning measures that overlook the sheer dynamics of climate processes and the need for legal certainty in the planning system can hinder engagement with uncertainty in managing flood risks (Lawrence et al., 2013; van Buuren et al., 2018). Furthermore, the interpretation of uncertainty and how it is observed and acted upon is subjective. This depends on who is impacted by flooding, the level of risk-awareness of those not living in flood-prone areas, and those who have benefited from protective structures (Sword-Daniels et al., 2018). Additionally, while flood risk management has cross-sectoral implications (e.g., land use planning, disaster management), typical siloed decisions tend to impede the provision of flexibility for the incorporation of uncertainty (Serra-Llobet et al., 2022; van Buuren et al., 2018).

Finally, existing flood risk management and land use planning practices relying on or favouring single best estimates are no longer fit-for-purpose. Uncertainties are omnipresent in flood risk management, especially under climate change. While numerous approaches and various endeavours have been made to reduce uncertainties, they can never be eliminated. With the increasing disruptive impacts on human wellbeing, the natural and built environments, and local and regional economies (Scott, 2013), decision-making frameworks guiding flood risk management and land use planning need to accept and embrace uncertainties and foster transformation towards adaptive and resilience planning (Fu and Li, 2022).

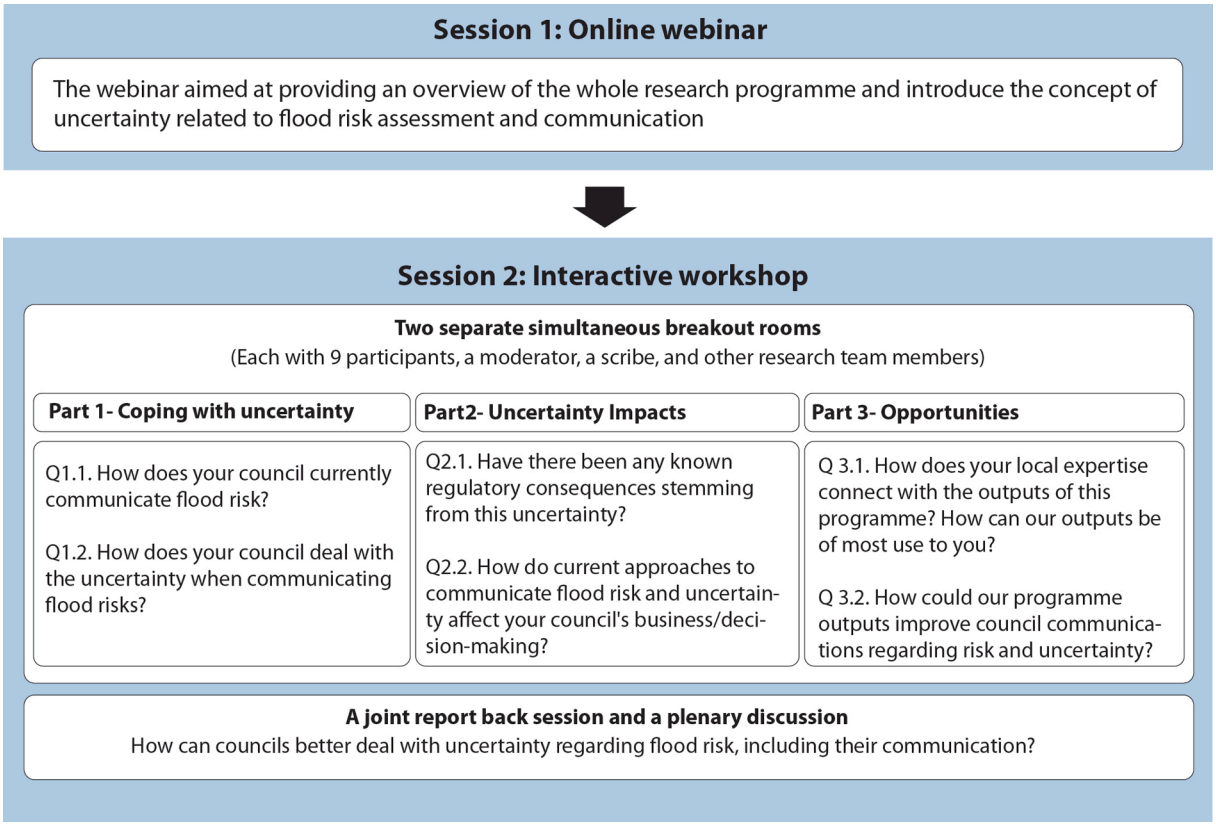


Fig. 1. Overview of the roadshow and the questions used to prompt discussions at the interactive online workshop.

3. Methods

To investigate how uncertainty is dealt with in flood risk management and land use planning decisions at the local level, this study adopts a single-case study approach (Yin, 2009) focused on ANZ. This study is a part of the 5-year Mā te haumaru ō nga puna wai programme which aims to develop a national flood inundation hazard and risk assessment for ANZ. The programme is underpinned by a transdisciplinary research approach (Serrao-Neumann et al., 2020), thereby facilitating two-way information sharing between researchers and practitioners through a series of Science-Practice Roadshows. This paper draws on data collected as a part of the second roadshow (held on the 24th of May) focusing on the effects of uncertainty on decision-making. Fig. 1 outlines the structure of the roadshow which comprised two sessions: The first session included an online webinar aimed at giving participants an overview of the research programme and introducing the concept of uncertainty in assessing flood risk by the research team. The second session comprised a 90-minute online interactive workshop to investigate participants' perspectives on the effects of uncertainties on decision-making related to flood risks and their communication. The interactive workshop included two separate but simultaneous group discussions framed around a series of questions (Fig. 1) and a subsequent joint report-back session. Data informing this paper only refer to discussions held at the interactive workshop.

Participants were selected through purposive sampling (Saunders et al., 2009) across levels of government and different sectors relevant to flood risk management (e.g., policy, planning, emergency management, engineering, and flood modelling). Local authorities (territorial authorities and regional councils) in ANZ are required by law (i.e., the Resource Management Act, RMA, 1991) to control the use of land and coastal marine areas to avoid or mitigate natural hazards, keep records of natural hazards and provide flood hazard information, undertake or commission research with particular regard to the effects of climate change, and manage the significant risks from natural hazards. Under the RMA, the main responsibilities for flood risk management in ANZ lie with regional authorities (i.e., regional and unitary councils) and territorial authorities (i.e., city and district councils). Regional authorities are responsible for the overall coordination and monitoring of floodplain management and maintaining soil conservation and river control and protection schemes (Bell et al., 2017; Greater Wellington Regional Council, 2015). Territorial authorities are responsible for managing flood and stormwater through their district plans. Considering these two levels of government, we contacted 53 people from regional and local authorities to participate in the study. 18 out of 53 agreed to participate in the workshop (see Table 1). Of the 18 participants, ten were from territorial authorities, six from unitary councils, one from regional councils, and one from council-owned professional water service providers at a regional level.

Within the workshop, we encouraged participants to use the questions (Fig. 1) as starting points from which the discussion could evolve to different topics as participants interacted. Participants were asked to input their ideas on a digital interactive whiteboard with the assistance of scribes where needed. The sessions were video recorded and later transcribed verbatim. Data analysis followed a qualitative content analysis process (Hsieh and Shannon, 2005) to inductively develop codes and common themes that were related to how participants discussed uncertainty, mechanisms for dealing with uncertainty and the effects of uncertainty on their decision-making and communication. The definition of codes and themes was carried out through iterative reading of workshop transcripts, whiteboard notes, and multiple views of the workshop recording (see Supplementary Material for details).

4. Findings

Based on the results from data analysis, findings are presented in three parts. Part one deals with current approaches for considering uncertainty in existing flood risk information; part two discusses fragmented risk governance to deal with uncertainties associated with flooding; and, part three outlines the varied understanding of flood risk information and its associated uncertainty (see Table 2).

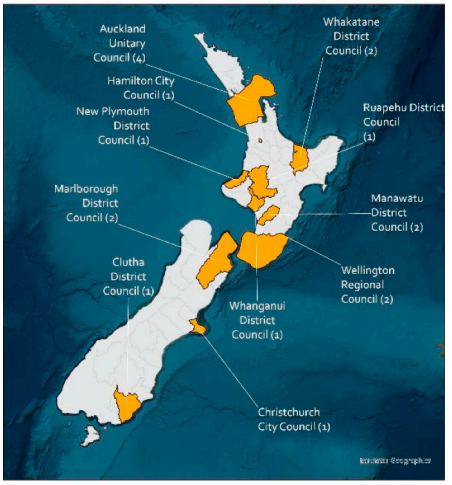
4.1. Current approaches for considering uncertainty in existing flood risk information

There was a general agreement among participants that while uncertainty is an ever-present feature in flood risk data, there is a lack of active and robust approaches to consider uncertainties associated with flood risk information. Many participants were unsatisfied with their existing flood risk information. Some reported that they have to work with outdated information, some as old as 20 years, primarily due to the lack of capacity and resources. Some explained that despite facing many regulatory constraints, they make the effort to update flood data every few years to reduce uncertainty and better reflect the changing patterns of climate. Several explicitly discussed that the currently used Annual Exceedance Probabilities (AEP design events) and conventional infrastructure planning based on the most probable conditions and historical data are not responsive to climate change. Local authorities employing climate change projections noted that even then, there are limitations inherent to uncertainties associated with climate science.

When asked how uncertainty is incorporated into flood risk information, the majority reported that it is within the risk assessment phase of the consenting process.[2] They also reported that they are confronted with different types of uncertainty ranging from environmental and scientific uncertainty (e.g., lack of accurate data) to social uncertainty (e.g., the unpredictability of people's behaviour in terms of use of space) and decision-making uncertainty (e.g., misalignment between different statutory provisions). Additionally, they usually request further scientific advice and assessments (e.g., from hydraulic engineering companies) to base their decisions on more detailed modelling, pre-empt unforeseen problems, and rely on what they are certain about and have greater clarity

[2] A permission from the local council to carry out a specific building work that it is not as of right of district or regional plan (Ministry for the Environment, 2021). This equates to development assessment process in other international jurisdictions.

Table 1
Distribution of participants by jurisdiction and sector.

Map of jurisdictions: Regional Councils (RC), Unitary Councils (UC), and Territorial Authorities (TA)	Sector	TA	UC	RC
	Regulatory Management	1		
	Policy Planning	2		
	Engineering	1	2	
	Regional Planning Management		1	
	Natural Hazard/ Flood Advisory Planners	1	1	
	Emergency Management/ Community Resilience	2	1	1
	Water/ Modelling		1	1
	Strategic Project/ Asset Management	2		
	Corporate Service	1		
	Total number of participants	**18**		

instead:

> There's a number of properties where the risk is based on what might be described as macro factors, that when further refined or finetuned, could demonstrate that the risk is minor or non-existent. However, we are required to identify the risk if the best information available to us demonstrates a risk. (Participant 4, strategic project management sector)

Setting freeboard values (the allowance in floor levels above the modelled flood level) was among the main strategies authorities used to acknowledge scientific and technical uncertainties in flood information and account for failures in flood modelling. Many tend to use the standardised freeboard ranging between 0.2 m (for non-habitable buildings and detached garages) and 0.5 m (for habitable dwellings and attached garages). Others have attempted to develop a varied freeboard value based on sensitivity analysis (e.g., to gauge sensitive parts of a model to bridge blockage and consideration of different climate change scenarios). Regarding social uncertainty, participants explained that in many cases, public behaviour was influential in the increase of exposure to flood damages. These include, for example, non-compliant conversions of outdoor buildings (e.g., garages, sheds, lifestyle block amenities) into habitable spaces. Some authorities, in response, have attempted to set specific conditions in resource consent processes to be transparent about enforcement regulations, but this only applies to new consent applications. In the face of decision-making uncertainties (e.g., lack of directiveness of policies and inconsistencies between council regulations and functions), decision-makers tend to use the best available information even if this might result in adopting a worst-case scenario approach:

> It's quite difficult when you have applicants coming in for development and then they're getting different advice on flood levels between the regional council and the district council. They often don't really have the resources or financial ability to engage the technical quality resource required to justify defending a position. I often end up being forced to take the worst-case scenario which adds cost to development. (Participant 4, strategic project management sector)

Participants, however, highlighted that decision-making under uncertainty requires timely access to up-to-date and accurate flood risk information and support from the existing regulatory context. Otherwise, their decisions are challenged in the Environment Court[3] based on rules set out by the RMA or can go under determination[4] processes set out in the Building Act 2004. This is especially the case in the absence of a national policy that could act as a directive in the face of conflicting objectives (e.g., development intensification versus management of natural hazards (Serrao-Neumann et al., 2023)). As a result of significant growth pressures, flood risk managers noted that they have very limited capacity to restrict development in floodplains and flood-prone areas, as local planning regulations often allow development to go ahead if risk mitigation strategies have been provided. This is evident in Auckland, where more than 1400 new house consents have been granted in floodplains and 798 consents in flood-prone areas since the devastating damages from Cyclone Gabrielle in February 2023 (Newton, 2024).

[3] The Environment Court primarily handles the appeals related to the content of regional and district plans as well as those arising out of resource consent applications.

[4] A determination is a legally binding ruling made by Ministry of Business, Innovation and Employment (MBIE) which deals with solving disputes and debates about the rules that applies to buildings.

Table 2
Topics emerging from the workshop discussions.

Topics	Sub-topics		Description
Current approaches for considering uncertainty in existing flood risk information	Barriers to incorporating uncertainty in decisions and communication about flood risks		Reliance on out-of-date flood risk information; reliance on historical data and probable events for infrastructure design events; reliance on conventional design standards for infrastructure rather than considering the changing Annual Exceedance Probabilities (AEPs).
	Coping with uncertainty when communicating flood risks	Suppressing uncertainty	In many decisions uncertainty cannot be quantified; uncertainty is not communicated in a meaningful way; uncertainty is a scientific concept; inability to accommodate uncertainty within regulatory environments.
		Reducing uncertainty	Asking for scientific advice; outsourcing to engineering companies; putting the onus back onto applicants to collect additional information; regular updates of flood plains and hydraulic modelling.
		Acknowledging uncertainty	Use of freeboard; indicating flood-sensitive areas; developing a range of scenarios and alternatives to demonstrate potentials and impacts; using the best available information; uncertainties are taken into account by adopting the worst-case scenario.
Fragmented risk governance to deal with uncertainties associated with flooding	Regulatory discrepancies and inconsistencies		Lack of consistency in risk appetite in statutory provisions; misalignment between flood data and the regulatory frameworks; inclusion of static flood hazard maps as a part of district plans; lengthy processes of plan changes and scheduling; failure in meeting the expected level of service.
	Methodology discrepancies and cross-agency inconsistencies		Lack of guidance on how rapidly changing climate could be taken in modelling uncertainty; differences in the depth of information gathered and methodology for showing flood risk between different councils; spot modelling done by regional councils rather than broad modelling (unmapped areas); lack of guidance on how local and regional councils can work together.
Varied understanding of flood risk information and its associated uncertainty	Different levels of knowledge, values, needs, and risk tolerance between different groups of communities		Difficulties aligning different levels of risk tolerance with the council's targeted level of service; discrepancies between users' and councils' starting points of view; differences in the terminology used and people's perception; information portals requiring pre-existing technical knowledge and not being user-friendly.
Opportunities for better incorporation of uncertainties in flood risk management	Educational Purposes		Identify the triggers individuals use to make decisions about managing their flood risks; education on expectations for individuals and groups (e.g., developers) to understand their flood risk; importance of understanding the use case for the modelling or the type of projects and decisions.
	Enabling better collaboration between different organisations and scales		Interface with other mapping done by insurance companies, etc; enabling a better collaboration between city and regional councils.
	Enabling a nationally consistent approach to flood risk management		Providing national consistency around the language, tools, methods, framework, and data considering the existing situation.
	Providing access to a range of accurate flood data and decision support tools		Providing the ability to use the best information for decisions considering the plethora of maps and models available out there; the need for having different models to make comparisons and verify different models; covering the unmapped areas at a regional scale.

4.2. Fragmented risk governance to deal with uncertainties associated with flooding

Whilst the responsibility for flood risk management in ANZ has been devolved to local authorities, the central government can provide national direction to local government. To date, no such national policy statements, standards, or land use planning guidelines exist (McSweeney, 2006). As a result, there are significant variations across government jurisdictions in how flood risk information is generated and communicated (Serrao-Neumann et al., 2023). This variability is especially evident in the choice of risk appetite[5] in statutory provisions and planning documents, lack of consistency in modelling approaches, and lack of guidance for incorporating climate change scenarios.

There was a general agreement that the lack of consistency in statutory provisions regarding risk appetite has created challenges for flood risk management. Within the statutory provisions, the New Zealand Coastal Policy Statement 2010 requires planning for at least

[5] The amount or level of risk that a unit or organisation is willing to accept or tolerate in order to meet their strategic objectives (Aven, 2013).

a 100-year[6] timeframe for coastal hazards. For flooding, no standard is specified by the RMA or any other national statutes. However, it is common practice to consider 100-year return periods. The Building Code specifies a 50-year return period that applies to flood floor level requirements for housing, communal residential, and non-residential buildings. Regional policy statements and plan rules stipulate different AEPs that on some occasions do not align with their territorial authorities' flood data. Different timeframes also apply to other planning mechanisms such as the 30-year timeframe[7] for Infrastructure Strategies. This lack of legislative direction and consistency represents a main source of decision-making uncertainty that hinders efficient flood risk management:

> … the other issue around the AEP as well, is that we're trying to grapple when we're making these decisions. Under the Building Act, you've got Building Act natural hazard sections that don't actually stipulate an AEP at all, it's just a high-level risk assessment. But then you've got the building code sitting underneath, it's only a 1 in 50; at this stage we've got a regional plan asking for a 1 in 200, and there's even mention of a 1 in 500 in some documents as well … I'm like really we need to – the very first thing is identify what is our risk appetite for development and infrastructure where it's in those sorts of things; and set that, so it's some consistency nationally and work back from there; so our decision-making is a lot more consistent." (Participant 10, regulatory management sector)

In addition to the lack of consistency in statutory provisions, participants raised concerns over the weak links and coordination between different governance levels. For example, they reported a lack of cross-agency coordination between regional and territorial authorities regarding modelling methodologies, such as the inclusion or exclusion of stop banks and stormwater networks, which has made the flood data confusing. As one participant mentioned, 'there is an unwillingness to drill into some of the details to justify the methodology that's being used' (Participant 4, strategic project management sector). Moreover, the spot modelling approach used by some jurisdictions rather than broad modelling in rural areas has resulted in the absence of accurate data for some rural areas. This lack of consistency and agreement between different sources of information, baselines, and modelling approaches as well as the variability in the abovementioned statutory provisions, have created uncertainty for flood risk managers, as highlighted by one participant:

> I Think for us, the tension there is: Who holds the knowledge? who holds the data? versus who makes the regulatory call? And, so, that doesn't always line up." (Participant 14, regional planning management sector)

As a result, one of the recurrent topics in participants' responses was the need for having consistency and directives in both legislative frameworks and the way flood risk information is generated to assist decision-makers in flood risk management. Concerning modelling methodologies, given the changing flood risk due to climate change, a national level of agreement on how to incorporate uncertainty into flood modelling could provide a baseline for local authorities:

> It would be useful I think to have a consistent way to show uncertainty and to have a methodology for that, but without having to do ten or twenty different model runs. A methodology that we could replicate at that local level without adding a whole bunch of work. (Participant 1, natural hazard/ flooding advisory)

Considering the changing rate of climate risks, some local authorities in ANZ have attempted to continually update their flood and hydraulic modelling to reflect the best information available in their flood hazard maps. However, participants raised concerns over these attempts:

> It's like wading through thick mud, it's horrible; we're going slowly and we're trying to get there. But you've always got a continual process going, because your rules are either changing or your climate change factors are either changing. (Participant 14, regional planning management sector)

According to participants, some of the difficulties associated with incorporating climate change in flood risk data are related to the process of updating regulatory maps and the lack of directives for incorporating climate scenarios. To update regulatory flood maps, local authorities in ANZ must follow process set out by the Schedule 1 of the RMA. This process is not always considered responsive enough to address changing risks or new information as it is often lengthy, requiring consultation, notification, submissions, and hearings that according to some participants are 'not appropriate for a flood hazard evaluation' and 'not a good use of people's time' (Participant 12, policy planning sector). For example, specific plan changes take around 1.8 years from notification.[8] Lack of adaptability in planning maps can lock in risks of development and create further exposure in the mid- and long-term:

> Some councils are communicating flood risk via their planning process or in the plans themselves, and that can be quite problematic because of course then you can't update your flood plains easily and then you're left with applying the rules to areas that you've got [mapped, and] risks that you can't manage and risks that you shouldn't be managing, or they don't exist. (Participant 14, regional planning management sector)

In some cases where authorities have been unable to deliver sufficiently accurate flood mapping, they have relied upon non-statutory maps, which enable adaptability but create uncertainty in relation to planning regulation. In terms of considering climate change scenarios in flood modelling, the Ministry for the Environment (MFE) has provided guidelines for local governments on the use

[6] 100-year hazard event is a common term for referring to 1% AEP event or an event with a 1-in-100 chance of occurring in any year.

[7] A local authority must, as part of its long-term plan, prepare and adopt an infrastructure strategy for a period of at least 30 consecutive financial years.

[8] https://planning.org.nz/Category?Action=View&Category_id=1227.

of climate change (or sea-level rise) scenarios in modelling (Bell et al., 2017; Ministry for the Environment, 2010). However, there is a lack of formal direction as to which scenario to choose:

> Going forward, at the moment we're running 2.1 and 3.8 [climate scenarios]. We haven't yet hit the point where we need to decide which one are we actually publishing. Are we publishing both or just one, and if so, which one and which one do we use to make decisions on land use? (Participant 1, natural hazard/ flooding advisory)

The lack of directives for climate change is also accompanied by the absence of climate change considerations in other statutory provisions which has engendered disagreements and conflicts between authorities and landowners:

> Our freeboards are set based on the level above the floodplain with climate change included for; so, with 2.1 degrees I should say. It could be worse. There's a bit of a gap because the building code makes no mention of climate change; so, a developer could argue: "no I will use the lower level plus freeboard. (Participant 1, natural hazard/ flooding advisory)

4.3. Varied understanding of flood risk information and its associated uncertainty

In ANZ, there are different means of communicating flood risk information, which influence how people perceive and act upon flood risks and their uncertainties. Regional and territorial authorities often provide freely available online maps utilising different methods for indicating flood risk, whether through marking floodplains, overland flow paths, flood extent, and flood-prone areas or depicting various flood exposure profiles through different AEPs. These maps delineate flood risk through static flood lines, and there is no depiction of uncertainty regarding flood boundaries. All territorial authorities also issue a Land Information Memorandum (LIM) upon request, which involves monetary costs. These LIM reports provide a range of information on property, including natural hazard information. Nonetheless, there are no explicit visual indications of uncertainty, except for disclaimers explaining that there are potential inaccuracies with flood data and modelling and the factors that might cause these uncertainties (e.g., omission of wave actions from modelling, the dependency of flood mapping to the accuracy of other models such as sea level rise scenarios and ground elevations).

Some participants raised concerns that available public data are not necessarily user-friendly nor understandable by the general public. They often require some level of technical knowledge. Determining what constitutes a risk and what terminology it entails significantly differs between decision-makers and the public:

> … from a regulatory function point of view, your start point is quite separate. But from a user point of view, [your start point is] hey, can I build something here? You know, who cares where the water comes from. (Participant 13, policy planning sector)

Moreover, there are no explicit and clear expectations of what communities are supposed to learn from flood risk information, for example, whether maps are supposed to be only informative or they can be used as a decisive tool:

> I'm curious to know like at what levels people make real decisions around those lines on the maps. I guess, is this a 'false flag' discussion in terms of are people viewing the maps and making real decisions around what they do build or no build, or how they change their lives, or is it just there's going to be flooding here and then move on … I don't know if our maps are used in a decisive way. (Participant 2, Stormwater Modeller)
>
> Something we struggle with is people see the line on the flood plain and the flood is here and it's not going to flood 10 cm away, so what are we asking people to do with the information and having that kind of supporting educational piece. (Participant 1, natural hazard/ flooding advisory)

Workshop participants discussed that communicating the constraints of current approaches such as the use of physical conventional structure and demonstrating uncertainties associated with current mapping and flood risk information could help people to make more informed decisions about purchasing and developing new properties and adopting different protective measures (e.g., property insurance, relocation, property retrofitting (Fu et al., 2023)). This is particularly important as workshop participants observed that property purchases tend to involve emotional considerations rather than rational ones, and risk tolerance considerably differs between different groups of societies (i.e., between people with direct experience of flooding and those without). As a result, transparent communication and an increasing level of education could counteract the false sense of security in floodplains which has only increased the ongoing development in at-risk areas and thus increased the residual flood risk (Fu et al., 2023) and managed retreat risks in future (Hanna et al., 2020):

> … when we are talking about communicating uncertainty and so forth, I think there's another thing that we do need to remember to communicate, and that is for example with stop-banks, that they have a design event. In Ashburton, when the stop-banks failed, everybody thought they didn't work, but they actually did. It was just that the event was bigger than they were designed for, and so communicating those design events is actually really important in this whole thing. (Participant 11, natural hazard/ flooding advisory)

Banks, insurance, and other financial services companies also play an important role in flood risk management. They rely on a range of information including their own collected data, information retrieved through LIMs, district plans, other available public local and national databases, and international databases. Some participants noted that in recent months, more queries have been made by insurers and banks to confirm flood risk and some insurance companies have started to do property-level risk-based assessments for their pricing models. Adopting a more risk-based approach may lead to applying higher excess or premiums to properties located in

higher-risk areas and thus may eventually result in the reduction of insurance penetration across the country and insurance retreat. However, as identified by Fu et al. (2023), it may also contribute to moving from disaster response to a disaster risk reduction approach. Some participants speculated that there will be more changes in the insurance companies' pricing modelling approach to better incorporate uncertainty in the changing flood risks[9]:

> I am curious with the insurance companies; they've previously mostly been concerned with historical flooding. I guess if they're modelling flooding now then perhaps it is future flooding they're consented to [*sic.*]. (Participant 1, natural hazard/ flooding advisory)

To conclude, given the different levels of knowledge, values, needs and risk tolerance between different groups of communities and stakeholders, one of the recurrent themes in the workshop was the need for a coherent and perhaps a national level of education around flood risk information, its uncertainties, and how flood risk information can better connect to people's needs and expectations.

5. Discussion

Consistent with the broader natural hazard uncertainty literature (Lawrence and Manning, 2012; Pappenberger and Beven, 2006; Quigley et al., 2019), our findings confirmed the existence of similar issues affecting decisions related to flood risk management in ANZ with implications for land use planning elsewhere. Local circumstances and institutional frameworks within ANZ affect how different sources of uncertainties deriving from scientific (Moure et al., 2023; Walker et al., 2003), decision-making (Moure et al., 2023), and social processes (Doyle et al., 2014; Kettle and Dow, 2016; Moser, 2005) have been considered and incorporated into flood risk management and land use planning.

With respect to the scientific process, our findings confirm that the current flood risk management approaches in ANZ have not yet been appropriately adjusted to the sheer dynamics of climate change. Current approaches primarily focus on 'flood resistance strategies' (cf. Gersonius et al., 2016) exacerbated by the fact that many jurisdictions still rely on out-of-date flood risk information, conventional AEP design events, and conventional infrastructure planning primarily due to the lack of capacity and resources. While the results of this study show that flood risk practitioners and managers in ANZ utilise different strategies to overcome the uncertainties in decision-making, such as seeking scientific advice and pre-empting unforeseen impacts during the development assessment process, the escalation of extreme precipitation events due to climate change continues to challenge these efforts. Specifically, climate change exacerbates the known temporal gap between the time it takes to generate new scientific information at a spatial resolution that is sought by planners and the pressure to make planning decisions with the best available information (Quigley et al., 2019). The reality is that for most planning systems, the ideal, robust information will not be readily available, and decisions will still need to be made. In particular, the changing nature of flood risks due to both climate and floodplain development changes makes adaptive management a pillar of flood risk management because it can help reduce uncertainty and improve knowledge about the risk over time (Goytia et al., 2016; Hall and Solomatine, 2008). This needs to be supported, however, by an adaptive flood risk governance framework that enables targeted variability at the local scale – that is, local issues should be addressed with specific fit for purpose solutions based on the best, most up-to-date information (Fournier et al., 2016; Goytia et al., 2016; Serrao-Neumann et al., 2023).

With respect to decision-making, it is important to acknowledge that uncertainty affects flood risk management in at least two dimensions. The first concerns decisions at the government level and the second at the individual, landowner level. At the government level, decisions have been constrained by the legal requirement for certainty in the ANZ planning system, hindering adaptive mechanisms that can incorporate the latest, evolving science. This, in association with lack of resources and supportive processes for incorporating uncertainty in flood risk information and assessment, can challenge decision-makers to effectively engage with uncertainty and constrain their ability to innovate in managing flood risk (Lawrence et al., 2013). For example, our findings confirmed the significant variations in flood risk governance across different jurisdictions and government levels in ANZ (Fu et al., 2023; Serrao-Neumann et al., 2023). Not only does this variability in flood risk governance cascade into how uncertainty is determined and communicated, but it also represents a source of decision-making uncertainty (Moure et al., 2023). This is evident in the lack of sufficient consistency in risk appetite for development control in statutory provisions and building standards (and whether they have factored in uncertainties related to climate change science), and the lack of supportive and streamlined regulatory processes to accommodate uncertainty in plan changes. The ad hoc variability in flood risk governance has also led to siloed institutional functions between regional and territorial authorities operating under their statutory mandates. This has led to disparities and inconsistencies in methodologies used to assess flood risk between different government levels or the lack of consideration of future climate scenarios in spatial planning and land use planning (Lawrence, 2015).

In parallel, flood risk management decisions also fall within the responsibility of individual landowners and their expected behaviour to mitigate or avoid flood risks – or the bottom-up behavioural turn in disaster risk reduction which delegates responsibility to individuals and communities (Weber et al., 2024). Basically, flood risks can be reduced or avoided through land use planning regulations and building design standards. Nonetheless, for individuals and communities to make informed decisions, uncertainty related to flood risks need to be well communicated and understood. Importantly, such communication needs to be cognizant of the various levels of flood risk understandings, knowledges and perceptions within the community to avoid exacerbating vulnerabilities and social injustices (Thaler, 2021). For this, active communication of uncertainty inherent to flood risks is essential to also enable

[9] In 2018, ANZ private insurer Tower Insurance was the first example to adopt a spatial risk-based approach for pricing flood insurance in the country.

people to identify and strengthen their coping mechanisms if flooding cannot be avoided (Rollason et al., 2018) – without losing sight of the level of social acceptability of policy instruments used to support this (Raikes et al., 2023).

While participants acknowledged the deployment of strategies seeking to address uncertainties in the flood risk management process, findings demonstrated that there are differences on how risk tolerance, perceptions and behaviour, and levels of knowledge, values and needs of communities are understood by different actors, including scientists, planners, decision-makers, stakeholders and financial institutions. As existing literature on flood risk management is increasingly advocating for transitioning from centralized and top-down decision-making to a more holistic multistakeholder approach (Puzyreva et al., 2022; van Buuren et al., 2018), and from flood resistance to a flood resilient paradigm (Gersonius et al., 2016), it is becoming increasingly important to understand these differences to ensure strategies addressing flood risks are effective. For example, when statutory mechanisms through regulated zoning, urban and building design fail to prevent development in at-risk areas, they further compound existing legacies of past planning decisions and create long-term implications, especially with the acceleration and escalation of climate change impacts on flood risk (Boer, 2010). This can perpetuate locked-in path-dependent futures focused on hard infrastructure protection; thereby creating a never-ending cycle of the safe development paradox (Burby, 2006; Stevens et al., 2010). As a result, corresponding economic and societal costs are often experienced directly (e.g., property owners are left on their own to deal with losses) or indirectly (e.g., governments need to step in and compensate losses) by society, deepening social inequalities (Camacho, 2009; Lawrence et al., 2020).

Some of these limitations could be overcome by having a national-level approach to improve how flood risk management deals with uncertainty, underpinned by an adaptive flood risk governance.[10] As argued by Serrao-Neumann et al. (2023), from a flood resilience perspective, flood governance in ANZ requires improved national consistency whilst enabling targeted variability at the local scale. This means that planning for and addressing flood risks need to be considered, at least, at the catchment scale. In some cases, this involves multiple jurisdictional (administrative) boundaries requiring inter-jurisdictional cooperation and coordination to share data and knowledge/ technical capacity. Hence, any national-level approach, on the one hand, needs to seek diversification of flood risk management strategies (i.e., implement policies for flood prevention, defence, mitigation, preparation and recovery). On the other, a national approach should address fragmentation in flood risk governance to ensure policy alignment between different regions and local and regional authorities and avoid sectoral trade-offs and maladaptation (e.g., policies enabling development growth and urban intensification which, if not managed properly, could contribute to increased impervious surfaces potentially leading to greater stormwater runoff and urban flooding risks). Additionally, legal frameworks need to enable adaptive flood risk governance to achieve flood resilience. For this, they need to both provide legal certainty whilst enabling the adaptability of rules to accommodate new knowledge and, therefore, reduce uncertainty (Keessen and van Rijswick, 2012).

Confirming our results, reports from the Ministry for the Environment indicated that local authorities have long called for the central government's support to assist decision-makers in flood risk management, particularly around decision-making about new developments in high flood-risk locations (Ministry for the Environment, 2023). In response, the government has proposed developing a national direction for Natural Hazards in the next couple of years (Bishop, 2024). It is hoped that a comprehensive national direction can address many of the current issues around identifying, assessing and managing risk from natural hazards (Ministry for the Environment, 2023). While the national direction is not yet available, we believe its development can assist local authorities in dealing with uncertainty by providing a baseline for selecting appropriate sources of data for their area, modelling approaches, different ways of quantifying and displaying risk, and clearer directives for choosing climate change scenarios in different situations. This could assist decision-makers in dealing with conflicting policy objectives involved in land use planning and flood risk management such as the ones encouraging urban densification potentially in areas that could be at greater flood risk due to increased precipitation events. A national-level approach could also provide directives on how risk and hazard analysis methods, assumptions, limitations, and management of uncertainty could be clearly and effectively communicated between different stakeholders, therefore assisting local authorities in enhancing their flood information. For example, instead of indicating single static lines, flood risk maps could indicate the natural variability and model uncertainty on the flood extent boundaries to determine the implications, or obligations, this can have for communities, such as graduated flood insurance rates (Smemoe et al., 2007).

Finally, a national-level approach to flood risk management seeking to achieve resilience in the face of uncertainties requires a more holistic form of 'redundancy' (cf. Fournier et al., 2016). In particular, the uncertainty related to climate science makes it even more difficult to identify and deal with cascading impacts (Cradock-Henry et al., 2020; Lawrence et al., 2020). Hence, embedding redundancy through and within the diversification of flood risk management strategies is important (Hegger et al., 2016). This is beyond the redundancy of critical infrastructure. For example, if residual flood risks cannot be avoided due to impending financial costs to upgrade flood defences to withstand the escalation of precipitation events, there is a direct need for increased investment in emergency management planning. This not only involves having the ability to activate alternative evacuation routes to keep people safe (e.g., enabled through infrastructure redundancy) but also redundancy to provide appropriate levels of immediate and long-term recovery for affected communities (e.g., enabled through public and private financial systems). Thus, by focusing on addressing communities' vulnerability rather than primarily the hazard, there could be, at least, less uncertainty in how the societal impacts of floods are addressed (Pescaroli and Alexander, 2018).

[10] Adaptive flood risk governance involves multiple level of management requiring collaboration and cooperation across different levels of governmental, non-governmental and individual actions (Fournier et al., 2016).

6. Conclusion

This paper aimed to investigate how uncertainty is being incorporated in flood risk management and land use planning decisions in ANZ. Drawing on empirical data, we found that local and regional authorities are aware of, concerned with, and challenged by existing uncertainties in flood risk management. Our findings also indicate that the prevalence of outdated flood data, conventional methods, legal certainty needed in the planning system, and institutional barriers due to the fragmented risk governance across different national, regional, and local levels are hindering attempts to effectively consider uncertainty in flood risk management and land use planning decisions. Further, the lack of a national-level adaptive flood risk governance has led to disparities in how flood risk is assessed, determined and understood, and resulted in increased urbanization of floodplains supported by conventional infrastructure planning based on historical flood data. It also led to a lack of appropriate consideration of local communities' needs, values, and perceptions in the flood risk information and communication.

Dealing with uncertainty in flood risk management and land use planning decisions demands a multi-level adaptive flood risk governance ranging from national, regional, to local levels. One that moves beyond system stationarity and conventional methods to accommodate flexible mechanisms for addressing and incorporating different sources of uncertainty at different levels. In ANZ, there is an indication that the development of a national-level adaptive flood risk governance framework could help local and regional authorities to better incorporate and communicate uncertainty in flood risk management and land use planning decisions whilst enabling targeted variability at a local level – in such a way that local communities' needs and vulnerabilities are understood and addressed.

We acknowledge that the current study has some limitations that illustrate opportunities for further research. We attempted to include participants from different sectors ranging from government policy and planning to emergency management. However, our study has not explored how uncertainty is incorporated by the private sector including financial institutions such as insurers. This study did not also engage with local communities to examine how they deal with and perceive uncertainty in flood hazard risk management. Future studies could attempt to investigate communities' and insurers' viewpoints about uncertainties in flood risk management. Importantly, managing flood risks also comprises flood preparation and recovery and, albeit uncertainties regarding these phases of the emergency management cycle were not covered in this study, they should not be left out of the resilience approach and could be further explored. Other future studies could explore the incorporation of uncertainty across the whole decision-making process such as in the identification of values and objectives guiding decisions, through to the identification and implementation of natural hazard management options and their impacts, including monitoring and evaluation. Moreover, the results of this study highlighted that the lack of consistency in risk appetite in statutory provisions is a source of uncertainty for decision-makers. This finding could be further assessed by how much risk ANZ is willing to tolerate in flood risk management and development planning.

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CRediT authorship contribution statement

Sepideh Afsari Bajestani: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Silvia Serrao-Neumann:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Christina Hanna:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization. **Xinyu Fu:** Writing – review & editing, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crm.2024.100666.

Data availability

Supplemental data for this article can be accessed online at the end of manuscript.

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