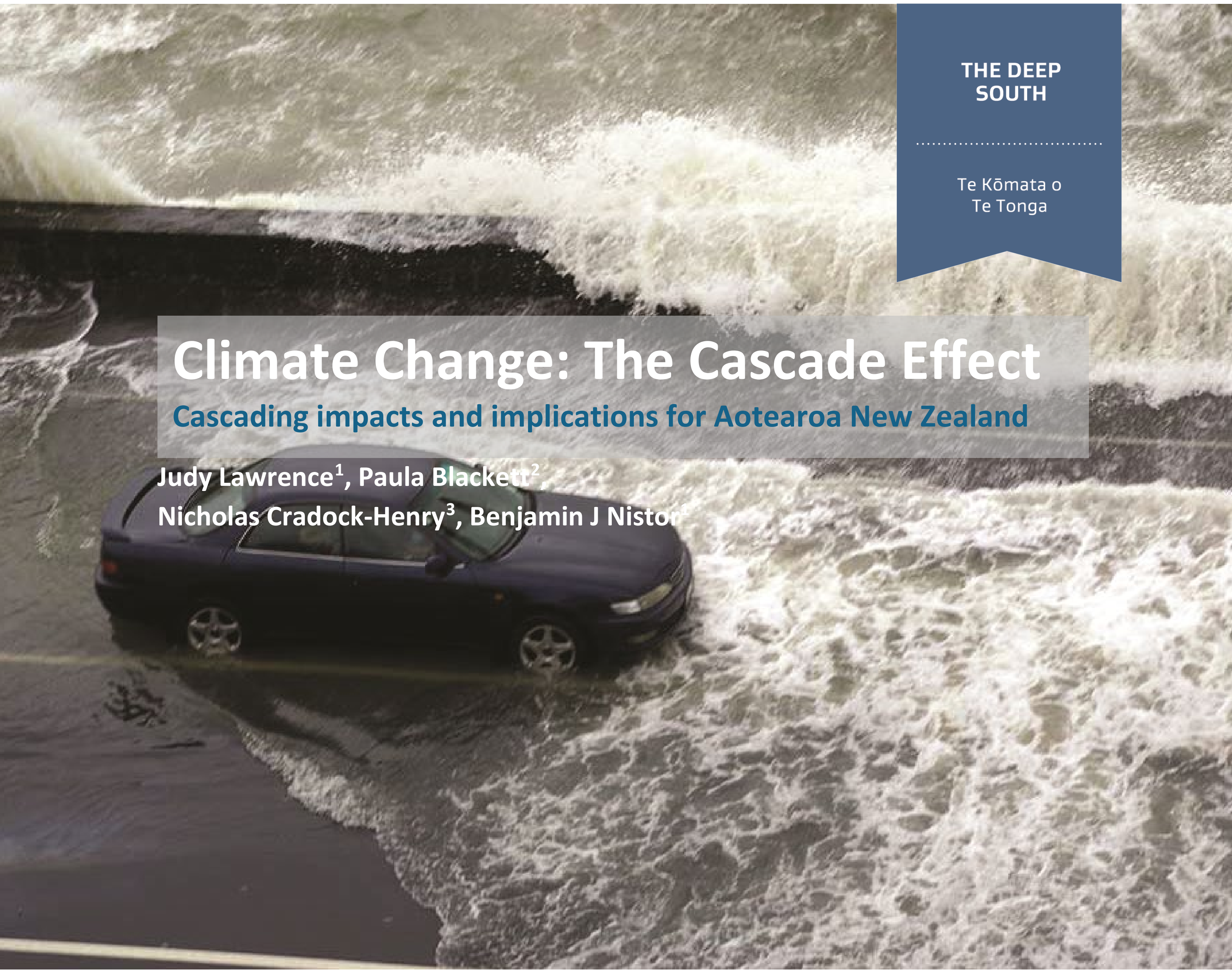
TE WHARE WĀNANGA O TE ŪPOKO O TE IKA A MĀUI
VICTORIA UNIVERSITY OF WELLINGTON

National SCIENCE Challenges

THE DEEP SOUTH

Te Kōmata o Te Tonga



Climate Change: The Cascade Effect

Cascading impacts and implications for Aotearoa New Zealand

Judy Lawrence[1], Paula Blackett[2], Nicholas Cradock-Henry[3], Benjamin J Nistor

[1] NZ Climate Change Research Institute, Victoria University of Wellington, New Zealand
[2] National Institute of Water and Atmosphere (NIWA), Hamilton, New Zealand
[3] Manaaki Whenua Landcare Research, Lincoln, New Zealand

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Executive Summary

Introduction

Climate change impacts and implications propagate as cascades across physical and human systems, compounding to form multiple impacts across sectors. Such effects arise because of the interdependencies between natural and socio-economic systems as they change and from feedback loops that occur between them. As such, cascading impacts have significant implications for community wellbeing, adaptive capacity, and governance. Cascades affect the ability of individuals, governments, and the private sector to adapt in time before damaging impacts occurs. This has implications for governance and institutions' ability to address the resulting instability within society and across economic domains.

To date there has been little research that examines how climate change impacts propagate as cascades across human systems and about their implications. Our research therefore explores cascading impacts of climate change and their implications. We focus on urban systems, water and utility network systems, and financial services domains which are of critical concern for the effects of increased frequency of high-intensity storms, sea-level rise impacts on top of increased frequency of storm tides and drought.

The tools

We used mixed methods to undertake this research, including workshops and interviews with stakeholders from each domain of interest. Narratives were developed at workshops using the CIrcle tool to find critical dependencies between infrastructure systems; systems mapping was used to illustrate how cascades arise from a climate impact and move across space and organisations, affecting ecological, social, and economic domains.

> The *Circle tool (Critical Infrastructures: Relations and Consequences for Life and Environment)* developed by Deltares, The Netherlands was used to identify the consequences of dependencies and interdependencies between the different networks examined—the three waters, flood stopbanks, transport, and communications. This helped identify indirect and cascading effects that have larger impacts over time than the direct effects. The value of using the tool was to understand the critical dependencies that, if systems failed, would have widespread consequences.Available at: https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/
>
> *Systems thinking* or systems dynamics was used to understand the crucial factors of a system, their relationship with each other and how they interact, interconnect, and function as a whole. The value of using systems thinking is to enable systems functioning to be understood and visualised at a scale that is appropriate to the question of interest.

Cascades

We found that the impacts of climate change can move through connected social-ecological systems, recombining or compounding in response to external policy decisions or concurrent impacts or events.

For example, an extreme rainfall event or higher than normal tide can create standing water that impedes drainage. This in turn, has impacts on road networks, power and water supply, waste water services and people's home and business activities which compound to affect the ability to undertake social and economic activity. For example, people leave the area and services are reduced for those remaining with consequent reductions in quality of life. This results in greater pressure being brought to bear on councils or network operators to upgrade levels of service as the rating base and the accessibility of borrowing and insurance, diminishes. This cascade of impacts becomes a viscous cycle until a decision trigger point is reached and adaptation decisions can be made. Similar cascades for wastewater, stormwater, water supply, stop bank breach, transport networks and power and gas supply were developed and the dependencies on and between the financial services sector (insurance and banking) were examined.

Implications across all three domains

Common implications emerged that affect risk assessments and adaptation decisions taken on them, by decision makers:

- The strategic significance of the dependencies between three waters infrastructure, flood risk management and utilities planning critically influences effective avoidance and management of climate change impacts;
- The coincidence of many hazards in some locations necessitates an integrated catchment management and multi-hazards approach to the adaptive strategies and planning approaches required, so that policies and the decisions based on them are flexible enough for changes to be made as climate impacts worsen over time;
- There are limits to the current, largely reactive mode of responding to climate events as they happen, which a more anticipatory approach would address, given the irreversibility of some climate change impacts, such as sea-level rise;
- Collaborative models of public engagement can elevate public understanding of the problem and involve communities in developing short- and long-term options and facilitate actions by difference levels of government;
- Monitoring of decisions over long timeframes is necessary to facilitate actions ahead of damage;
- Linking land use and infrastructure planning for managing risk and vulnerability could mitigate the legacy of cascading impacts of climate change, as the impacts worsen over time;
- Interconnectivity between different domains of interest (three waters, flood risk management, utilities, asset planning, land-use planning, reserves management, and financial management), means that a bridge is needed between domains that can contribute to more effective risk management;
- A better understanding of the cascading nature of climate change impacts would enable adaptations to be designed and deployed that better ‘fit the problem space’ of changing risk and uncertainty; and
- Finding opportunities while managing risk will be a positive way forward, e.g., using overland flow paths and retention basins with community amenity benefits, will buy some time to design new flexible systems before decision triggers are reached, enabling societal and economic disruption from climate change impacts to be better managed.

Governance implications

Cascading impacts have implications for governance of climate change risks across all domains of interest. Integrated governance can help bridge the silos of practice across the different levels of governance supported by engagement with communities.

Governance implications include:

- *the adequacy of the institutional arrangements* to meet the changing risks and consequent loss of service levels to the community (including the statutory frameworks);
- *the design life* of the assets (materials, methods, design, location) and the need for land-use change and how to manage it;

- managing community expectations about *levels of service*;
- how to deal with *uncertainty*;
- working with *communities* to manage change;
- *political leadership (cross-party initiatives)*;
- *funding* stressors such as plan veracity, costs, debt levels, and financial management; and
- *legal liability and legal challenges* for councils and infrastructure agencies.

Communication of cascades and their implications

Shifting the focus from the current reactive mode to climate impacts, to a more anticipatory and strategic one may be achieved through:

- Comprehensive community discussion about options that can de-risk their exposure to climate change impacts;
- Use of longer-term planning horizons that align with asset lifetime (at least 100 years);
- Consideration of the implications of the transfer of risk developer, real estate, and insurance sectors to individuals and governments over time that can motivate equitable burden sharing;
- Use of experiential learning using narratives based on adaptive experience (success and failures), adaptive tools, and games to motivate effective adaptation, tailored for different groups;
- Use of systems tools to present cascades and identify targeted interventions and priorities for action;
- Use of cascades within scenarios to better understand consequences with and without adaptation and to highlight ongoing change that will accelerate differently in different settings or domains;
- Conveying consequences of adaptation inaction to reveal equity implications, and the consequences of sudden responses that create further cascades across society;
- Communicating impacts as 'multiple hazards' that intensify and compound across other domains, to demonstrate the effects on wealth, pest management, water supply, ability to insure, and willingness to pay when councils' rating bases are declining;
- Use of narratives to inform those who have not yet experienced the changing risks, because incremental adaptations will have limits as the impacts of climate change move outside our experience.

Conclusions

It is necessary and urgent to think about climate impacts as a system, comprising multiple interacting and reinforcing sub-systems that cascade across domains with multiple entry points. To do otherwise, could lead to blind spots in adaptation and an over-confidence in New Zealand's ability to cope with what is a highly pervasive risk in time and space.

Narratives and systems mapping tools are an effective way to identify connections and communicate the consequences and governance implications of ongoing and changing climate risks. By examining the dependencies and feedback loops between different systems of concern when stressed with changing climate impacts, risk assumptions can be 'stress-tested' with decision makers. This enables adaptation actions to be designed in a flexible, yet robust manner under different future conditions, and thus reduce and avoid damaging impacts beyond the ability of communities to cope.

1. Introduction

We were funded by the New Zealand Deep South National Science Challenge *Impacts and Implications* programme to explore cascading impacts of climate change and their implications, and, in particular, to examine how the impacts might cascade within, between, and across areas such as urban systems (including the underlying support systems that enable the provision of services and exchange for urban populations), the delivery of water services (stormwater, wastewater, and water supply), and the financial services sector (insurance and banking). This report examines cascading impacts of climate change from a conceptual, methodological, and grounded position using examples from urban systems, delivery of water services, and the financial services sector.

Much has been written about specific climate change impacts such as temperature increases, sea-level rise, increased heavy rainfall, and their associated heat stress and inundation damage (Pachauri *et al.,* 2014). There is also an increasing focus on managing climate risk, limits to adaptation approaches (Dow *et al*., 2013), on tools to address uncertainty such as dynamic adaptive policy pathways (Haasnoot *et al*., 2013), and using games and scenarios to stress-test adaptation plans (Lawrence & Haasnoot, 2017).

Literature is also now emerging on how climate change impacts compound to form multiple impacts (Räsänen *et al*., 2016) and the transmission of climate risks across international borders (Challinor *et al*., 2018) through the mechanisms of international trade, markets, and policy (Adger *et al*., 2009). However, much less is known about how such impacts flow within a country across sectors, their dependencies and feedbacks, and what the implications are for community wellbeing, adaptive capacity, and governance.

There is evidence to suggest that climate impacts and implications propagate as cascades across physical and human systems (Rocha *et al*. 2018). Although the scope and scale of their effects are not well understood, they may be significant. Increased frequency of climatic events, such as high-intensity storms and the slow emergence of sea-level rise impacts on top of increased frequency of storm tides, will affect the capacity of individuals, governments, and the private sector to adapt in time before the damaging impact occurs. This has implications (for the institutions, rules, and values that affect our adaptive capacity) for how we govern for cascading impacts that create instability and uncertainty within society and across economic domains.

Both Koks (2018) and The World Economic Forum (2018) demonstrate emerging thinking on the importance of understanding the extent, scope, and implications of cascading changes.

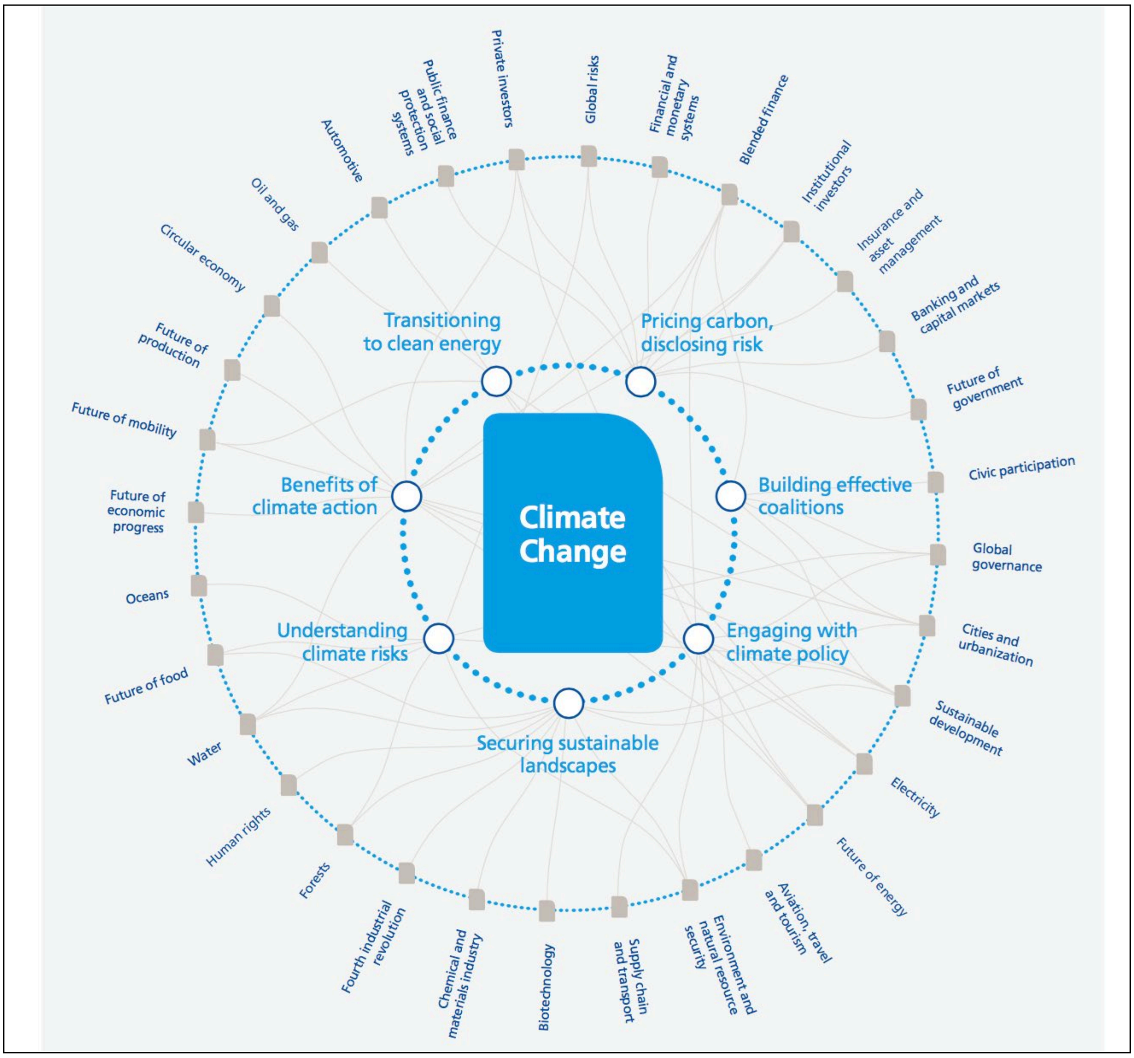
Koks (2018), when discussing Willner *et al*. (2018), concludes that cascading effects of flood risk pose additional economic risks globally that can be of the same order of magnitude as asset damages within and outside the affected region. For example, Koks (2018) comments that dependencies on infrastructure systems can be far away from the affected area. There may be no damage to those dependent on such infrastructure systems, so such cascading impacts would not be apparent using traditional risk assessments where the losses are to production.

The World Economic Forum, in *The Global Risks Report 2018*[4], recognises extreme weather events, natural disasters, and failure of climate change mitigation and adaptation as three of the top five global risks that the world faces. The global risks are shown as many

[4] World Economic Forum. (2018). *The Global Risks Report 2018* (13th ed.). Geneva: World Economic Forum [available at http://www3.weforum.org/docs/WEF_GRR18_Report.pdf]

interconnected risks (Figure 1) as they cascade across many different domains. The Forum warns that systemic challenges have intensified over the past year with signs of uncertainty, instability, and fragility. The Forum highlights the need for preparation for sudden and dramatic disruptions, some of which will slowly evolve but are, nevertheless, equally disruptive. Climate change is central to the risks that exhibit interdependencies. For example, climate change exacerbates natural disasters and droughts, which affect food security and global insecurity (Challinor *et al*., 2018). Such cascades signal impacts that have hitherto not been analysed for their implications for how we respond, our capacity to respond in time, how we organise ourselves to respond, and what the implications of our response options might be.

Figure 1. Interconnected risks (Zurich Insurance Company, 2018 , p. 6. Adapted after World Economic Forum, 2018)



It is against this backdrop that the importance of understanding cascading impacts and implications of climate change emerges, not just at a global scale but at the level of agency within affected systems, regions, and countries where key decisions are made. It is at the country level where our research was undertaken We examined different types of climate change impacts – slowly emerging ones, extremes, and increased variability, while reflecting that there will also be surprises and combined impacts, and some will occur concurrently in time, for example, sea-level rise and rising groundwater. Our focus is on how the impacts might cascade within, between, and across domains of interest such as urban systems (including the underlying support systems that enable the provision of services and exchange for urban populations), the delivery of water services (stormwater, wastewater, and water supply), and into the financial services sector (insurance and banking). Cascading impacts as they relate to these particular domains of interest were chosen, first, because there is a gap in understanding in those domains (Lawrence *et al*., 2016), and second, because these domains critically affect the ability of communities to function and, therefore, cascading and compounding impacts on them have national implications. In short, they affect agency within a particular country setting. Examining cascading impacts at a country scale enables us to place the cascades within the particular and unique governance arrangements of a country – New Zealand in this case. From this, there can be generic learning relevant to other jurisdictions.

In an earlier examination of climate change impacts and implications (Lawrence *et al*., 2016), the authors identified that understanding cascading impacts of climate change across a wider range of domains was necessary and urgent. On scanning the global literature for similar research we found a gap in understanding of how climate change impacts can cascade into other domains and, in particular, from urban (and rural) systems into infrastructure and the financial services sector. Our aim, therefore, was to examine the scope and scale of the cascading-impacts problem and its implications for community wellbeing, adaptive capacity, and governance. We conclude with reflections on how the cascading impacts and their implications can be communicated to different audiences.

2. Methodology

Not all impacts of climate change emerge in the same way, which may affect the way the cascades are propagated – some emerge abruptly, others emerge slowly, and there can be multiple impacts. In addition, they can occur concurrently in different combinations spatially and temporally across urban settings, infrastructure, and the financial services sector.

To characterise and empirically document cascading and compounding impacts, we developed a methodology based on systems thinking and risk assessment. In-depth qualitative data was obtained using workshops and interviews, relevant literature was reviewed and synthesised to inform the initial typology, and systems models including the CIrcle tool were used to gain insight into the interconnected nature of impacts and implications in different domains.

First, we characterised the impacts of interest as follows:

- Slowly emerging – e.g., sea-level rise and associated rising groundwater;
- Widening climate variability – e.g., increased drought, flood, and coastal storm frequency;
- Extremes – e.g., coastal storm surge, intense rainfall, and wind;
- Combined impacts – e.g., coastal and river flooding, and heavy rainfall and debris flow; and
- Surprises – e.g., as yet unknown impacts from atmospheric changes.

Second, we developed a framework for thinking about cascades of impacts - how impacts interact, who is affected, where interdependencies and co-dependencies occur, and how far impacts and implications might extend across multiple geographic locations, scales, and sectors.

Third, we identified three different New Zealand locations for workshops with practitioners where decision makers are grappling with climate change impacts, viz., Wellington, Hamilton (Hauraki Plains), and Christchurch. These localities represent different scales and types of systems (a capital city constrained by geography for access and egress surrounded by coasts; a landlocked city adjacent to rural areas with flood risk, and conservation and tourism demands; a city set around low-lying estuaries and coast, recently lowered by earthquake subsidence, with significant flood and stormwater challenges).

Fourth, we conducted three workshops using the following methodology:

1. To introduce the idea of cascading impacts we discussed two narratives and two cascade diagrams that had emerged from a precursor research project in New Zealand (Lawrence *et al*., 2016).

2. Pre-testing of the approach to developing cascades took place at the Wellington workshop and the material from that workshop was integrated into the narratives and implications analysis. The dependencies were workshopped only in groups (see 4 below).

3. To identify the impacts across the domains of interest, the participants at the Hamilton and Christchurch workshops attached sticky notes to an aerial photograph of the geographic area at possible impact locations.

4. To develop cascades by making the linkages between the cascade elements in each critical area of interest, we used a visual network tool (the CIrcle tool), developed by Deltares in the Netherlands[5], to map the interdependencies between the primary impacts identified on the aerial photograph (Box 1). The resulting data was recorded and this, along with the discussion of impacts, enabled the narratives (see Boxes 3 to 8) to be developed from which cascades were drawn and critical nodes identified where impacts intersect most often - indicating potential priority areas for decision makers' attention (Box 1).

Box 1. The CIrcle tool methods

The CIrcle tool (*Critical Infrastructures: Relations and Consequences for Life and Environment*) was developed by Deltares, The Netherlands (publications, background and visualisations) to identify the cascading impacts of flood damage in one infrastructure or a combination of them (see Figures 5 & 7). The tool can be used to identify the consequences of dependencies and interdependencies between different networks, such as an energy, transport or communication network. This enables indirect effects and cascading effects that have larger impacts over long time periods than the direct effects, to be identified. The interactive CIrcle Tool used in a deliberative process helps analyse and visualise cascading effects of critical infrastructure. It can be downloaded from the website shown in footnote 5 below with instructions for its use.

We used the tool to identify the number of times each input category interconnected with another in the system. This enabled us to establish critical dependencies that, if they failed, would have widespread consequences. We used the CIrcle tool following the workshop discussions to develop narratives of connections and thence cascades. Several New Zealand-specific categories were included, such as, river protection structures; bridges; nature; ferry and coastal structures; gas pipelines; groundwater; and governance. We then generated several of our own exemplar "connections" between different nodes for use in the workshop to help the participants start using the tool.

At the workshops, participants were first given an overview of the workshop purpose and then tasked with mapping the critical infrastructure within the study region based on their local and professional knowledge, using large maps and sticky notes. These were then consolidated and classified on the basis of type of impact emergence, for example, slowly emerging impacts, widening climate variability, or extremes.

The CIrcle tool was then introduced with a demo using the exemplar developed prior to the workshop. This was followed by a facilitated discussion about how the loss of previously identified critical infrastructures could impact and cascade into other components of the system. A recorder populated the CIrcle tool with participant contributions about connections, while another recorder took notes of the qualitative information being generated. After the qualitative discussion and recording of the dialogue, the workshop discussed the implications of the results.

5. To explore the governance implications of the cascades, we undertook a facilitated brainstorm discussion with participants.

Fifth, we developed systems maps of relevant cascades using systems thinking methods (Box 2) and all workshop materials (i.e., CIrcle tool data, narratives, and discussion notes).

[5] CIrcle (Critical Infrastructures: Relations and Consequences for Life and Environment). Refer to https://www.deltares.nl/en/software/circle-critical-infrastructures-relations-and-consequences-for-life-and-environment-2/

Sixth, six targeted interviews were conducted with selected workshop participants from local government asset management; water, transport and emergency management; and from the financial services sector to test the veracity of the cascades. The systems map, which had been pre-tested with a sub-set of key informants in a small workshop, was used to guide interviewees through the conceptual and empirical framing of cascades, to confirm system functionality, and to address any gaps. We also asked participants what were the implications of the cascades for their sector or organisation, the challenges addressing them, and how they might communicate the implications of the cascades to decision makers, including their dependencies and interdependencies.

Box 2. Systems thinking methods

Systems thinking or systems dynamics seek to articulate and understand how systems function – what the crucial factors of a system are, their relationship with each other and how the factors interact, interconnect, and function as a whole. The value of using systems thinking is that system boundaries are flexible and can be set at a scale that is appropriate to the question of interest. In this case, boundaries were drawn to include factors that influenced the function of infrastructure, where infrastructure was broadly defined as three waters (wastewater, stormwater, and water supply services provided by local government in New Zealand), flood and inundation protection structures, utilities, and road networks, for example.

The underlying presumption is of inter-connectedness and the natural integration of biophysical, physical, cultural, social, political, organisational, and economic elements that enable co-construction of systems to explore and explain what is observed in the real world. The relationships between the factors in the system have a direction, extending the discussion from ‘A is related to B’ to, for example, ‘as A increases B decreases’, which enables identification of reinforcing loops within the system. Accordingly, vicious or virtuous cycles can be exposed.

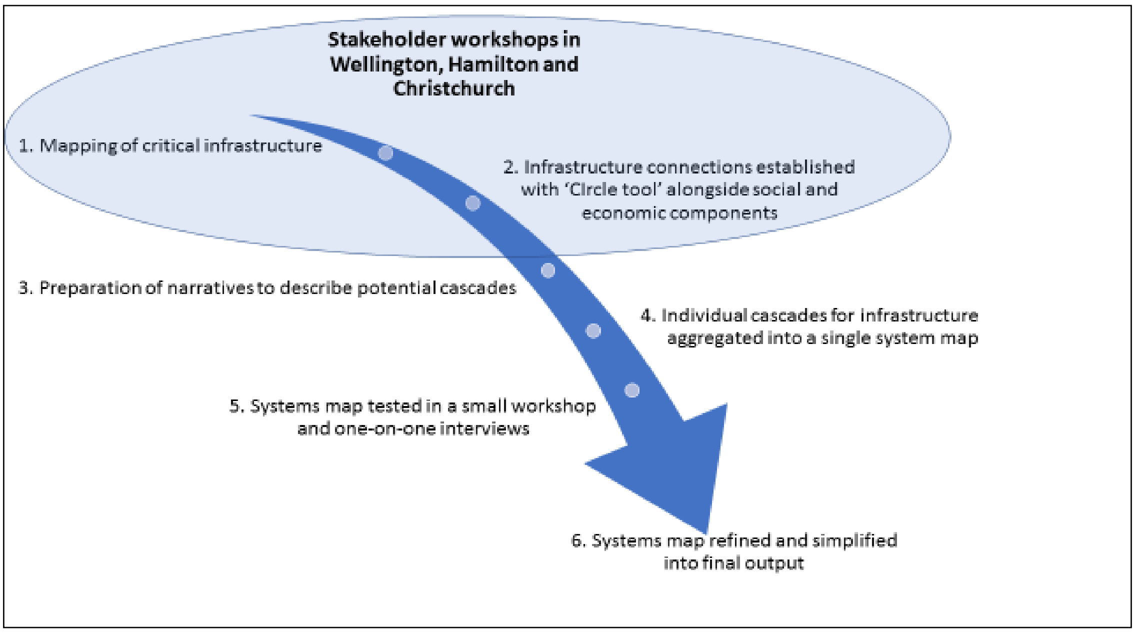
Once a system was described and drawn, we considered how the systems may be affected by climate change (i.e., slowly emerging, widening climate variability, or extreme events) or specific policy intervention to address those impacts – where interventions are deliberate actions to achieve a desired change(s). The implications of changes or interventions were traced through the system and examined for any unintended consequences.

The information that underpins the systems map (Figure 8 and Appendix 3) was generated from multiple sources, using mixed methods. The primary data collection stage started with the three workshops which generated different perspectives on critical infrastructure, how climate changes impact the infrastructure, and how they are connected with each other and with other social and economic components of the system. Potential cascades were then discussed and recorded. This information was used to inform the building blocks of potential cascades and a systems map by describing how parts of the system were understood to be connected. Individual cascades relating to particular infrastructure were aggregated into a single systems map, because it was evident that strong commonality existed between how the individual systems operated. As a result, the systems map (Figure 8 & Appendix 3) represents all types of infrastructure for all the climate impacts considered. The systems map is also known as a causal loop diagram, since it shows dependencies and interdependencies.

Last, following the interviews, the system map was refined into five domains to illustrate the cascades within and across the domains.

Figure 2 summarises the methodology we applied.

Figure 2. Methodology



3. What does the literature tells us?

For climate change adaptation to be effective, a better understanding is required of how climate change impacts cascade and what their implications are, to ensure that adaptation actions are targeted at the most appropriate places, and in time to avoid the worst consequences of climate change. We, therefore, examined the literature on cascading impacts and implications and undertook a systematic review (Appendix 2) of relevant conceptual and empirical research. Here we present a summary of that literature across the themes that dominate to date, and that are relevant to cascading climate change impacts and their governance implications for adaptation.

3.1. Cascades concepts

Climate change will have significant impacts and implications for communities, sectors, and activities (Arnell & Lloyd-Hughes, 2014; Cinner *et al.*, 2012; Pachauri *et al.*, 2014; Knox *et al.*, 2012). There is, however, only limited understanding of the ways in which impacts will cascade across and through interconnected domains and sub-systems (Adger *et al.*, 2009; Eakin *et al.*, 2009; Lawrence *et al.*, 2016). Literature on teleconnections, where impacts in one location has impacts in another at some distance, demonstrates that climate change impacts will have wider spatial and temporal effects than might otherwise be expected (Adger *et al.*, 2009; Eakin *et al.*, 2009; Liu *et al.*, 2013; Moser & Hart, 2015). Such effects will flow-on to ecosystem functionality, economies, social systems, and governance, having significant implications for adaptation planning and preparedness for future climate conditions.

Cascade thinking traverses many domains of interest starting with ecosystems dynamics and their intersection with human-environment systems (Blenckner *et al.*, 2015; Carey *et al.*, 2017; Johnson *et al.*, 2011), multiple hazard cascades, tipping points of harm, thresholds and surprise (Gill & Malamud, 2016; Walker *et al.*, 2009), policy responses, and governance (Galaz *et al.*, 2011; Reyer *et al.*, 2012). Cascades have been defined and applied in a number of domains including urban (da Silva *et al.*, 2012; Tyler & Moench, 2012), infrastructure (Bollinger &

Dijkema, 2016; Hu *et al*., 2016), and disaster risk reduction (Pardoe & Birkmann, 2014; Pescaroli & Alexander, 2016).

However, consistent framing for examining cascades and for understanding the stressors within and between the different domains of interest is required for an empirical analysis with respect to climate change.

The earliest conceptual work on cascades comes from resilience thinking, focused on a social-ecological system (Walker *et al*., 2004). Whether coupled human-natural systems (Carter *et al*., 2014) or coupled socio-environmental systems (Turner II *et al*., 2016), it often incorporated land, water, or hazards management practices; land use; or ecosystem services (Anderies & Janssen, 2011; Walker *et al*., 2004). Over time, socio-ecological systems can change states when system variables of different spatial and temporal scales and in different domains cross system-critical thresholds. This results in a cascading effect that induces or accelerates the crossing of other thresholds in connected domains and sub-systems (Kinzig *et al*., 2006).

Galaz *et al*. (2011) further developed a conceptual basis for cascades, highlighting the institutional and political challenges surrounding change that moves through domains in society – 'cascading ecological crises' (CECs). Interdisciplinary studies of crises and change in complex and interacting social-ecological systems (Ostrom, 2007), and organizational theory and political decision making studies (Boin *et al*., 2005; Smith & Elliot, 2006) postulated three characteristics shared by CECs. The second of these has relevance to cascades – those posing significant management challenges due to their cascading and recombining capacities, which require coordination of responses and decision-making by actors at multiple levels.

In the field of disaster-risk reduction, cascading impacts and implications of hazards events and/or crises have also been conceptually and empirically examined, for example, infrastructure failure during or post-disaster. Pescaroli and Alexander (2016) describe cascading effects in disasters, where the impact of a physical event or a technological or human failure, generates a sequence of events in human sub-systems that result in physical, social, or economic disruption. 'Cascading disasters' occur where cascading effects progress over time, generating unexpected secondary events of greater impact, for example, the failure of physical structures, and the social functions that depend on them, including critical infrastructure facilities; or where disaster reduction strategies are inadequate, such as evacuation procedures, land-use planning, and emergency management strategies.

3.2. Empirical studies

Empirical studies of cascades have largely focused on critical infrastructure and lifelines (such as telecommunications, electricity, and water) (Pescaroli & Alexander, 2016), hazard-network interactions (Gill & Malamud, 2016), and responses. Shimizu and Clark (2015), for example, discuss the difficulties in addressing suitable responses to earthquakes and hurricanes at a governance/institutional level that focus on interconnected issues, such as public policies, infrastructure, economies, production and supply chains, and risks and uncertainties, which lead to unexpected consequences due to those interdependencies.

Other empirical studies have looked at cascading effects of terrestrial and marine systems or other physical ecosystems and human environment domains (Carey *et al*., 2017; Fountain *et al*., 2016; Latham *et al*., 2015). For example, in marine ecosystems, change within and between species can occur where climate change impacts affect systems by exacerbating existing stressors (Niiranen *et al*., 2013). The complex, compounding, and cumulative nature of these impacts demonstrates how a better understanding of a system illuminates potential climate change effects. Such understanding can be gained through exploring a further field of study – system dynamics.

3.3. Systems dynamics

Systems dynamics, which first appeared during the 1950s (Forrester, 1961), seeks to understand the structure and behaviour of complex systems and find appropriate policies to tackle particular problems (Vennix *et al*., 1996). Proponents of systems dynamics describe it as a holistic approach that has the potential to bridge academic disciplines, as well as the gap between science, policy/management organisations, and the public (Costanza & Ruth, 1998). As a result, it is often presented as a potential means to explore, and potentially resolve, complex, multi-stakeholder, multi-domain, trans-disciplinary problems, like those regularly encountered in environmental debates (Williams *et al.,* 2017), such as climate change. A systems-dynamics framing can enable dependencies and interdependencies to be identified and, thus, provides a framing for consideration of cascading climate change impacts.

Systems dynamics has several unique properties that distinguish it from other approaches and make it useful, for example, for obtaining insights into how impacts cross domains, how multi-stakeholder problems function, and where interventions might occur (Holling, 2001; Williams *et al.,* 2017). Williams *et al.* (2017) describes these properties as interconnections, feedback loops, and the ability to demonstrate and explore adaptive capacity, self-organisation, and emergence.

3.3.1. Interconnections

The building blocks for mapping systems are the key variables (or factors) and the relationships of these variables with each other (van den Belt, 2004). Relationships can be described quantitatively or qualitatively, depending on the purpose of the research, data available, and the nature of the problem under study. Factors/variables will include relevant elements to any given problem, at the selected scale, irrespective of disciplinary divisions (i.e., if the variable is biological, economic, or social). This has considerable merit where complex problems overlap traditional disciplinary boundaries or different domains.

3.3.2. Feedback loops

Where factors/variables are connected in a circular manner, either directly or mediated through other factors or variables, feedback loops are established. Such loops create change in the magnitude of the other variable(s) in a way that reinforces either a positive (virtuous cycles) or negative effect (vicious cycle) (Sterman, 2000). The argument is that understanding feedbacks is essential to successful interventions (or intended changes to the system) and that linear descriptions of systems that do not account for feedback loops risk misrepresenting the system, resulting in interventions that generate unintended consequences or unexpected outcomes. In some cases, the impacts may be in another domain or a different sector – a cascading impact.

3.3.3. Adaptive capacity

Williams *et al*. (2017) suggest that a systems dynamics approach allows actors/stakeholders/key decision makers within a system to begin to understand and explore the adaptive capacity of the system. That is, how much change can be accommodated before system transformation is either necessary, or forced due to exogenous factors. Essentially, how resilient is the system to change and where is this resilience located? It is important to note that system inertia can be a favourable or an unfavourable characteristic depending on the objectives of those in, or affected by, the system.

3.3.4. Self- organisation and emergence

Many systems may have components of their structures that self-organise, or develop without any direct management, oversight, or planning. These may involve or emerge as a result of the interactions between different parts of the system, particularly where there is no managed (or regulated) connection between the different systems or sub-systems. For example, in the relationship between the provision of and uptake of insurance, there is no regulation or management, rather it is based on choice of individuals or organisations. Exploring the self-organising and emergent aspects of a system provides an essential foundation for understanding its capacity for change and stability (Williams *et al*., 2017).

3.4. Application of systems dynamics and critical systems thinking to environmental domains

While systems dynamics has been applied primarily within the business or organisational management context (Burton *et al*., 2008), its application has grown in environmental management of air quality (Stave, 2002), park management (Kruse *et al*., 2004; Nicolson *et al*., 2002), water issues (Collins *et al.*, 2007; Costanza *et al*., 1998; Moxey & White, 1998; Tidwell *et al*., 2004; Tidwell and Van Den Brink, 2008; van den Belt, 2004; van Eeten *et al*., 2002), sustainability management (Williams *et al*., 2017), and soils salinity management (Inam *et al*., 2015).

There is limited systems dynamics or critical systems thinking literature that has focused on the impacts or implications of climate change. Some examples include impacts on energy constraints and policy (Ansell and Cayzer, 2018), water resources (Winz *et al*., 2009) and water demand (Givens *et al*., 2018; Li *et al*., 2019; Gastelum *et al*., 2018), food security (Paterson *et al*., 2018), heat-related health impacts, and early thinking on resilient architectural design (Weisz, 2018). The focus is on parts of the system, using numerical modelling and principally on biophysical or physical science subsystems. This leaves social systems largely unexamined in a systems dynamics framing, both by themselves or connected to the biophysical and physical world.

To conclude, the conceptual basis for understanding cascading systems comes from diverse domains. Many of these – including ecology, social-ecological resilience, natural hazards research, and systems and organisational theory – have learned from each other, evidenced by the shared emphasis on 'linked-up' network thinking or systems thinking, and a focus on critical thresholds in natural, built, and human systems, and interactions and feedback loops.

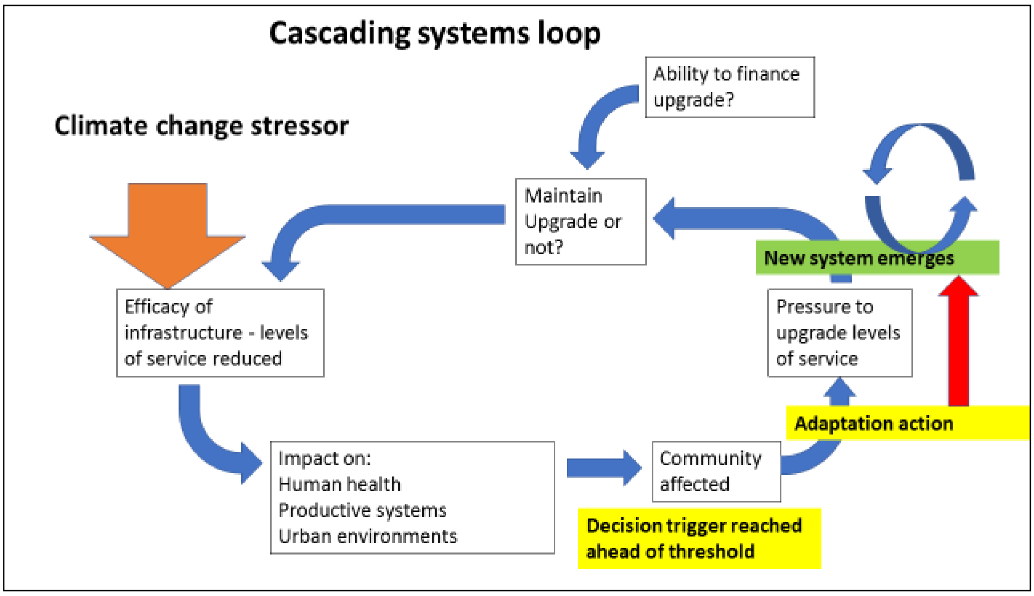
Gaining insight into the scope of interconnectivity between internal and external stressors and sectors using critical systems thinking to describe cascading impacts and their implications, can support adaptation planning, helping to avoid maladaptation, and reducing the likelihood of negative cascades across the economy (Cash *et al*., 2006; Wilbanks & Kates, 2010). A better understanding of the complexity of interacting and interconnected impacts can also help stakeholders to conceptualise the nature of climate change impacts, and thus facilitate developing linked-up approaches to adaptation planning that consider upstream and downstream decision implications (Eakin *et al*., 2009; Fleming *et al*., 2014).

4. Results – the narratives and dependencies

The results are presented in several different ways and levels of detail and scale, in order to show the different elements of the cascading impacts of climate change and to allow consideration of cascades in the many contexts within which they have been found to occur.

First, narratives of cascading impacts derived from the workshops are presented with a cascading systems loop diagram based on the narrative (Figure 3). The narratives are plausible stories, and in some cases have occurred. Cascading systems loops can help decision makers think about the implications of cascades, which might otherwise be framed as discrete impacts in place and time.

Figure 3. A generic cascading systems loop



Climate changes and, in turn, the system of concern will change	e.g., more frequent events and simultaneous impacts, including extremes and slowly emerging ones, each requiring different types of decisions
Multiple system effects and potential for vicious cycles	e.g., stopbanks, roading, natural systems, insurance, and lending
Multiple demands for protection, frequent and simultaneous	e.g., urban systems, land uses, and emergency services
Decisions required on what to invest in, when, where, and for whom	e.g., protect, retreat, opportunity for natural systems, community viability, and equity
Monitoring of decision triggers ahead of threshold effects required	e.g., level of service, tolerability, and properties in the market

Second, the critical dependencies and connections using the CIrcle tool are presented to provide further evidence of connections and interdependencies beyond that described in the narratives, and to stimulate thinking about critical dependencies before developing systems maps and considering the implications of the cascades.

4.1. Narratives of cascading impacts

The narratives derived from the workshops and the dependencies identified using the CIrcle tool are presented below. The narratives in Boxes 3 to 8 show three different impact types across six infrastructure types including the "three waters". Table 1 shows which climate change impacts relate to each narrative.

Table 1

Narrative/impact type	**Slowly Emerging Impacts**	**Widening Climate Variability**	**Extremes**
Stopbank breach (Box 3)	✓		✓
Wastewater (Box 4)	✓		
Water supply (Box 5)		✓	✓
Stormwater (Box 6)			✓
Transport systems (Box 7)		✓	✓
Power/gas (Box 8)	✓		✓

Box 3. Stopbank breach cascades on the Hauraki plains (Extreme event cascade)

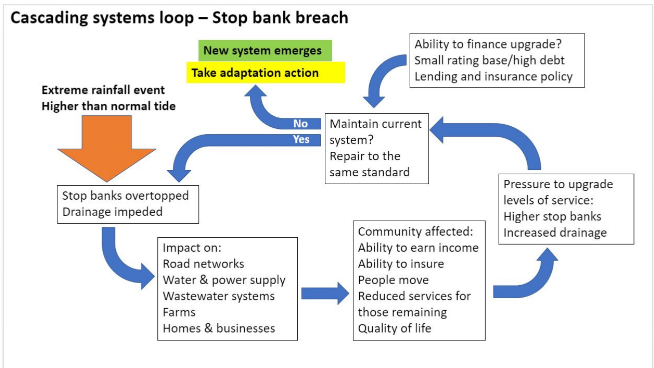
1. Floodwaters Surround Farmhouses. Credit Alan Blacklock, NIWA.

2. Flooding. Credit Alan Blacklock, NIWA.

Cascade narrative

During an extreme rainfall event, exacerbated by a higher than normal tide, the stopbanks along the rivers of the Hauraki Plains are overtopped, impeding drainage. The flood event exceeds the over 50-year-old standards to which the stopbanks were constructed. Roads are closed. Power supply, water supply, wastewater, homes, property, and businesses are damaged, affecting functionality and contributing to loss of service. Dairy farms cannot pump flood water away fast enough and water stagnates on farms, affecting pasture growth. Electricity outage affects milking and road closures and milk cannot be collected, affecting farm profitability. Companies servicing farms lose income as farmers restrict spending to mitigate production losses. Local businesses are similarly affected, as employees and customers cannot get access to affected properties. Loss of stock and damage to equipment or buildings affects the ability to earn an income. This reduces the vitality of the local community and people leave thus compounding the cascade. Those who remain pressure the council to invest in maintaining the stopbank at the target level of service. Further investment in additional protection, may not occur, depending on the ability to raise rates, the community acceptance of increased council debt, and perceptions of the flood risk.

Raising finance will depend on the ability to rate or allocate internal resources (from Long-Term Plans), or to borrow the money (capped under the Local Government Act). Insurance coverage, and bank decisions on lending, will be influenced by national policy (e.g., Reserve Bank), decisions at the international level (e.g., reinsurance), and by perceived risks from climate change. Where rating bases are constrained, or existing debt is high, ratepayers may not want further protection funded for at-risk areas.



If capital can be raised, upgrading the level of service may last only until the next extreme event, and the entire cycle repeats because there are limits to ongoing protection. This vicious cycle flows on to other sectors, creating further pressure on decision makers to reinvest in flood protection. Decisions made to stop investment in flood protection, triggers other infrastructure providers (e.g., power and roads) and insurance to withdraw or reduce service provision. Pumping stations cannot cope with increasing intensity of rainfall and the ponding that results, leads to lower profitability of primary production through increases in pest and weeds, or a failure of grass species. The cost of maintaining roading networks becomes unaffordable. Over time, only those with a strong personal attachment to the area or who do not have the resources to leave, remain, raising significant equity issues.

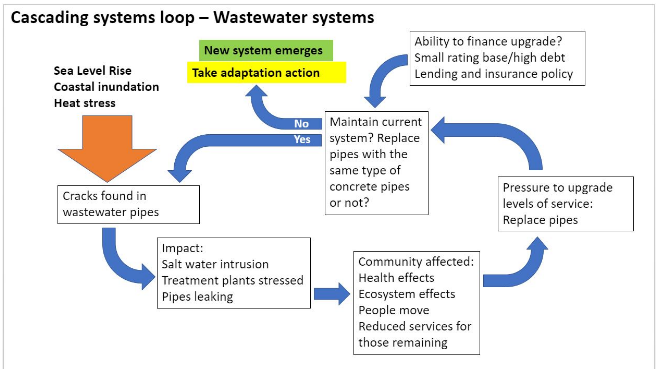
Box 4. Wastewater (sea-level rise and coastal inundation cascade)

1. Storm in Wellington South Coast. Credit Dave Allen, NIWA.

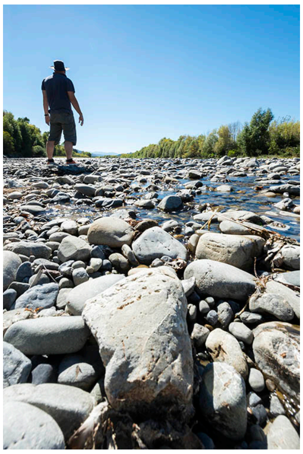
2. River Pollution. Credit Dave Allen, NIWA.

Cascade narrative

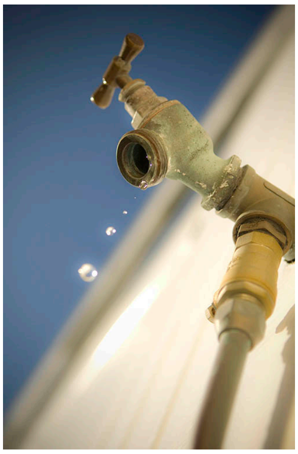
Using CCTV inspection, the Council asset monitoring programme finds cracks have formed in underground concrete sewers that allow infiltration of groundwater. Sea-level rise and coastal storm inundation cause saltwater intrusion into groundwater that damages both the inside and outside of pipes. Cities near the coast are most severely affected, with billions of dollars of underground sewer assets threatened. Exposure of pipe reinforcing rods to salt water causes rapid corrosion of the reinforcing rods. This weakens the pipes and cracks appear and open, accelerating the corrosion until the pipes are in danger of collapse. This causes a loss of infrastructure efficacy, which then leads to a loss of service, and disruption while the road is dug up to expose and repair broken sewer lines. In turn, local businesses and communities are disrupted through loss of access to shops, carparks, and to work and school, which influences community functionality.



Box 5. Water supply (drought cascade)



1. *Hutt River in drought. Credit Dave Allen, NIWA.*



2. *Drought. Credit Dave Allen, NIWA.*

Cascade narrative

Drought can cause issues that could begin to affect water supply infrastructure with greater frequency as soils become drier with higher temperatures than the region typically experiences.

Wellington summer heat results in record number of leaks in drinking-water pipes

Source: Devlin, C. & Cann, G. (2018, March 12). *Dominion Post.* Retrieved from https://www.stuff.co.nz/dominion-post/news/102195675/wellingtons-summer-heat-results-in-record-number-of-leaks-in-drinkingwater-pipes

Wellington City Council documents show a "record-breaking" 2140 leaks were reported in drinking-water pipes across the region in December – 762 more than in the same month the previous year.

The council's quarterly report, ending December 31, states old and brittle drinking water pipes were particularly vulnerable to cracking as the ground around them dried out.

Residents faced delays of several days or longer before repairs could be undertaken, resulting in extra crews being brought on and more late-night repair work. One Evans Bay Parade resident was furious when a crew turned up to repair a leaking pipe at 10.30pm – five days after the leak was reported.

City council resilience principal adviser Zac Jordan said many jobs were related to joints in the pipes.

The council's target for responding to non-urgent calls was 36 hours, but in the December quarter this stretched out to about 45 hours.

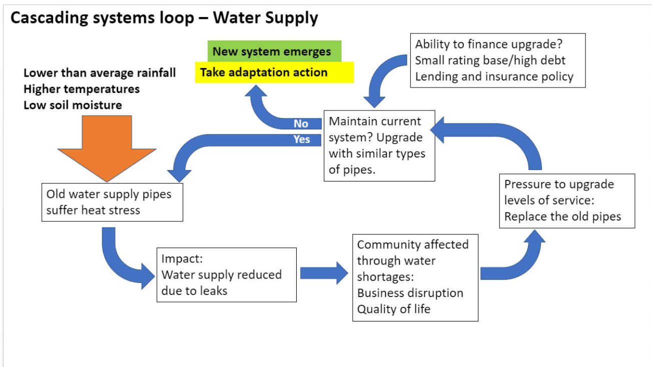
The worst-affected pipes were cast iron and about 80 years old, but many leaks were in newer pipes, he said.

The connection points between the public and private supply, in the new pipes, were stressed by compression as the ground shrank in the heat, resulting in the joints splitting.

"Across the region, somewhere in the order of $300,000 could be attributed to leak responses, and it's more a case of prioritising our responses rather than additional cost pressures."

Heat and a lack of rainfall can cause a loss of infrastructure service, decreasing satisfaction with services, which results in a further demand for repairs. The council prioritises the work, using additional staff and contractors to keep up with the backlog. Staff work nights (which is not normal), placing strain on their families. This affects community functionality and residents get disgruntled. Maintenance costs increase, which may mean another service is reduced or another revenue stream is needed to continue the same level of service across all sectors.

Long hot dry summers will combine with greater frequency of higher intensity rainfall events, creating compounded impacts that will also flow on to the ability of the maintenance teams to keep up. As a consequence, the planning for new infrastructure will be affected. This will also accelerate the demand for new design standards and approaches with institutional flow-on effects.



Box 6. Stormwater (heavy rainfall cascade)

Christchurch Flood. Credit Pieter Havelaar, NIWA.

This week marks one year since the last of the water subsided. For much of that March and April [2014], residents in pockets of the city close to rivers and streams watched floodwaters rise and recede and their neighbourhoods almost dry out, only for the cycle to repeat itself . . . There were three major floods in those two months but your total number of washouts varied depending on which flood plain, or which bend in the river, you lived . . . $315 million is earmarked for the work over the next 10 years in the council's draft Long Term Plan, which extends over the next 30 years. Fixing Flockton Basin is top of the list. Work on Dudley Creek is scheduled to be finished by mid-2017. There's also the work of the Stronger Christchurch Infrastructure Recovery Team, which is about half way through repairs to the city's stormwater network, the widening and deepening of Dudley Creek, repairs of flap gates on the Avon and Heathcote rivers, clearing silt and debris from waterways and installing more temporary pumps. It sounds good. But for someone like Griffen, in a newly-renovated house in the middle of a flood-prone street, the need is a bit more pressing . . . "It's 12 months on and they still haven't decided [what to do]." [Christchurch floods: one year on. (2015, May 3). The Press.]

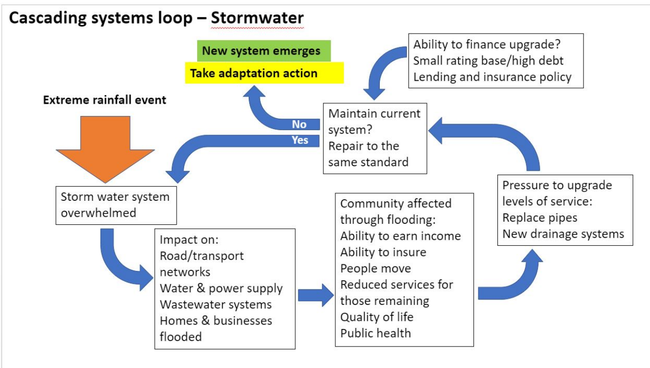
Cascade narrative

More frequent higher-intensity rainfall impacts compounded by infill housing increases exposure resulting in stormwater systems, being overwhelmed more regularly. This leads to localised flooding; inflow of stormwater to wastewater systems; damage to property, roads, and stormwater networks; public health risks; sedimentation; and potential death and injury. In Christchurch, some low-lying areas are affected by subsidence from earthquakes which exacerbates flooding. Elsewhere in New Zealand low-lying areas will be similarly affected by more frequent intense rainfall events, especially older settlements with aging stormwater systems and houses built close to waterways or with floors close to the ground.

In such locations near estuaries and the coast, hazard risk is being compounded by sea-level rise and increased rainfall intensity and frequency. Systems put in place to manage stormwater, such as pumping stations, have made the area more suitable for housing under past and current climate conditions. This increases the exposure to changing climate impacts and, in turn, systems cannot cope, leading to a loss of service levels. Under ongoing climate changes, risk protection levels are being exceeded with ongoing loss of service levels. Failure of stormwater systems leads to failures in other infrastructure, such as roading networks and potable water supplies, creating public health issues, such as enteric diseases, and the ability of health providers to cope.

Frustration builds within the community from repeat flooding, the disruption and cost of evacuations, and the inability of organisational systems to cope. The resulting mitigation of risk by the council, which provides immediate protection, raises expectations of further protection and perceptions of 'safety'. Whilst people want to remain in the area, some people want to move, but face difficulty selling their property or losing money and landowners feeling stuck.

Anxiety and frustration are vented through demands for immediate solutions. The ability to address changing climate risk profiles requires funding models to navigate local government debt limits and rating limitations in communities, such as cost sharing with communities, the government, and the private sector (using bonds sold internationally and rated by credit ratings agencies). The time lag to set up such funding arrangements for addressing the ongoing impacts creates general community stress and frustration.



Box 7. Transport systems (climate induced landslides)

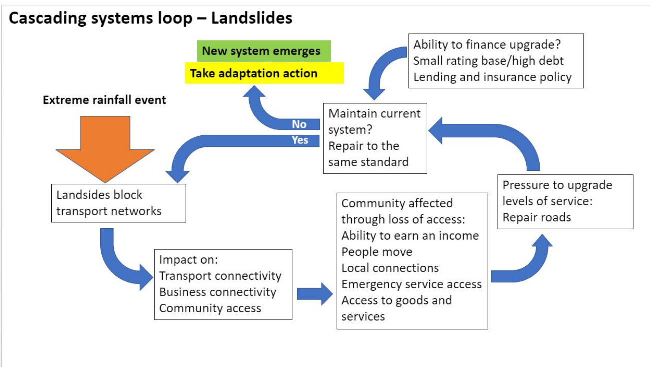
Slip Takarau Gorge Road. Credit Dave Allen, NIWA.

Cascade narrative

Currently, slips are typically cleared from the transport network within a matter of hours or possibly days without too much disruption. There is often some forewarning of a storm system, allowing some people to delay travel until the all clear is given. Often there is an alternative route available, but not always. Such events are a cost to communities' ability to function and be serviced, and to businesses like freight companies, for which the consumer pays at the end of the day. Disruption from landslips associated with heavy rainfall events are becoming more frequent and people's coping capacity is being tested. Council maintenance costs, employee overtime costs, family personal costs, and business interruption and supply-chain costs are all rising and compounding. This is driven by the frequency of heavy rainfall events on both saturated and drier soils. Landslips have been documented affecting access to farms and horticultural land. Road closures also affect contractors and their ability to earn a living. A farm may lose land as a result of responses to finding alternative transport routes, or have their farms split in two, for which there are additional compensation costs to the taxpayer. Individuals are impacted differentially, which can create inequities even if the result is good for the region in the long term.

Some communities, like the Coromandel have single transport access points and have to resort to water-only access, which places pressure on those services as repeat events occur and more people are affected. Some of the costs also fall on central government (the taxpayer), where they are responsible for roading funding. But, in most cases there are multiple agencies affected, since roads give access to rail, power, gas, and other utilities and national supply lines. Multiple agency involvement at multiple governance levels adds to the complexity and time to respond, which is compounded by central government being distant from the immediate local demand pressures that fall on councils for services.

As a consequence, further delays in response set in. Experience shows us that this causes tensions between locals and central government, when central government prioritises potential roading projects across the country, while local councils have extensive local roading networks to manage and maintain.



Box 8. Power/Gas (Storm event cascade)

1. *Storm in Wellington South Coast. Credit Dave Allen, NIWA.*

2. *Haumoana, Hawke's Bay, erosion and inundation. Credit Alan Blacklock, NIWA.*

Cascade narrative

Source: Power restored for parts of the Bay but remains out for Coromandel. (2017, March 8). *NZ Herald.* Retrieved from https://www.nzherald.co.nz/bay-of-plenty-times/news/article.cfm?c_id=1503343&objectid=11814032

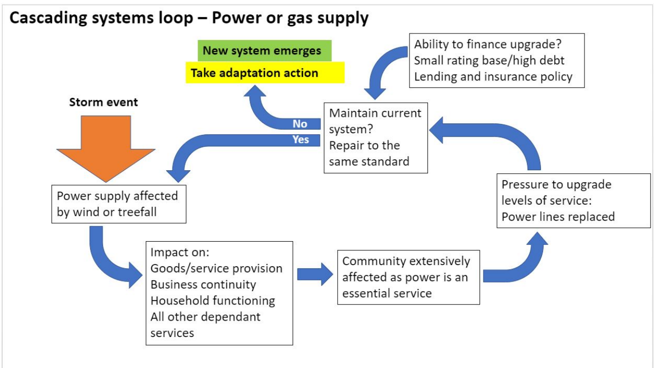
In Whangamata, power has been restored to all but 200 homes following outages earlier on Wednesday morning March 8 2017, but eftpos and cellphones are down, and there's no petrol.

There is a strong interdependency when it comes to power outages caused by storm events. Cell phone communication ceases. People cannot pay for anything by EFTPOS. Petrol supplies become critical, affecting the most vulnerable who cannot get to medical services, buy food, or get to work. With no electricity, access to essential services such water and waste services are cut off. Where cash is a dominate means of exchange, supermarkets close, compounded when their supply-lines are cut and stock runs out. Community functioning is significantly affected.

Risk management and monitoring of systems can work for a while but where dependent on cell phone coverage they become vulnerable. Back-up systems kick in but become exposed as the frequency of events increases, leaving little time for recovery, in turn placing the entire community at risk.

Failure of wastewater and stormwater pump stations (if they do not have back-up power generators) causes longer residence time of flood waters. This flows on to environmental damage and health risks. The public and businesses expect power and telecommunications will work and get up-and-running quickly after climate events.

Power supplies are essential for people's health and wellbeing, particularly the sick or elderly being cared for at home (e.g., those using dialysis machines and oxygen respirators), and for home heating in winter. If electrical networks are not up to standard when climate events occur, risk will compound.



4.2. Critical dependencies

4.2.1. Hauraki Plains example

The Hamilton workshop considered the Hauraki Plains (Figure 4), a low-lying coastal region in the Waikato.

Figure 4. The geographical extent of the area discussed at the Hamilton workshop

(Source: NZMS250 – Map5, BB34, BC34 and BC35 – https://www.linz.govt.nz/land/maps/linz-topographic-maps/map-chooser/map-5)

The Plains – which comprise a large peat dome (Kapuatai) – were progressively drained during the late 19th and into the 20th century to create farmland. It also comprises many stopbanks to protect that farmland from flooding from the Waihou, the Piako, and several other rivers draining the area. The rivers were generally widened and straightened to take flood waters from the area more efficiently. The drained area is now subsiding, making management of the multiple land-use functions and activities challenging. There are several small towns with water infrastructure and other infrastructure including roads, bridges, electricity, and utilities. The area also provides access to the Coromandel for communities and tourism, an area that receives high rainfall events on a regular basis.

The key impact categories and dependencies are shown on Table 2 and the CIrcle output in Figure 5. The peat dome is the most 'critical facility' that is affected by and affects the most other categories. The key impacts include ecosystem services, stormwater drainage, recreational values, and commercial maritime activities; which are impacted by land use, river protection, roads and bridges, stormwater systems, and water supply. Electricity affects many other categories by impacting functionality, though was not identified to be significantly affected from other areas.

Table 2. CIrcle impact categories and incidence of dependencies - Hamilton workshop

Categories	Affects	Affected by
Critical facilities	6	6
River protection structures	6	3
Roads, tunnels, and bridges	6	1
Electricity	6	0
Water supply	4	2
Stormwater system	4	2
Commercial facilities	3	5
Wastewater	3	1
Citizens	2	8
Financial services	1	6
Emergency services	1	0
Healthcare and public health	0	3
Communications and IT	0	2
(Air)Port	0	2
Ferry link structures, wharfs	0	1
Gas pipelines	0	0

Figure 5. CIrcle derived dependencies between impact categories - Hamilton workshop

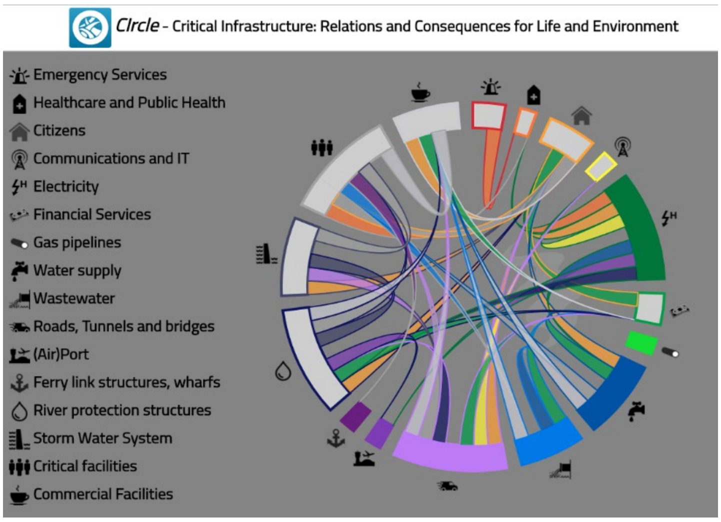


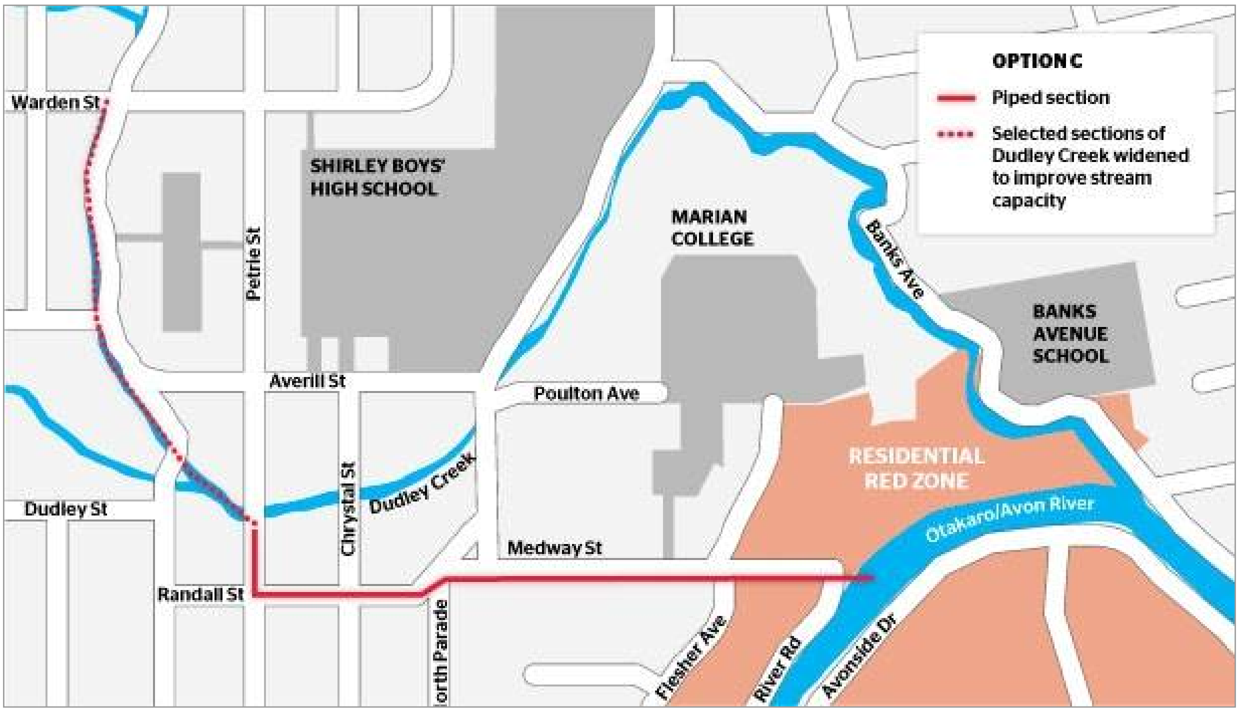
Table 3. Hamilton workshop issues (Detailed notes see Appendix 1)

Hamilton workshop	
Three waters /river protection structures	• Some thresholds exceeded • Flood risk affecting services, economic viability of businesses, property values, and mental health • Limits to further protection due to debt caps for protection, lack of rating finance • Need to consider impact of wastewater on water supply • Stopbanks have limits and loss of them bring negative (flooding and impact on people and businesses) and positive impacts (environmental services)
Utilities	• Power loss leads to loss of communications; pumping for water supply; and vulnerabilities at hospital, airport, and individual dependencies on power • Some adaptations, e.g., transformers for pump stations raised above ground
Commercial/ financial	• Impacts beyond local means • Loss of jobs in industries • Risk for investors and local businesses
Environmental	• Loss of ecosystem function, e.g., peat dome, RAMSAR, stormwater, recreation, and culture • Sedimentation affecting fisheries and service industries
Transport infrastructure	• Frequent road closures due to weather events • Other communications also affected • Response to damage creates impacts on others sectors, e.g., food supply, emergency services, and ecosystem services
Governance	• A lot of non-rateable land because Crown-owned. Impact costs come back to Crown eventually • Est. one third ratepayers not in area • Loss of Service (LoS) will change over time but risk not reflected on LIMs and little risk education

4.2.2. Flockton Basin, Christchurch example

Flockton Basin is a low-lying area of Christchurch City (Figure 6 and also Box 6) that subsided significantly as a result of the 2010/2011 Canterbury earthquake sequence.

Figure 6. Geographical extent of case study area for Christchurch workshop (Source: Christchurch City Council, 2016)



The earthquake-slumped land is prone to flooding from high-intensity rainfall, and the changes in topography have compounded drainage issues with water ponding after rainfall events. Groundwater was identified as an important node that intersects with key impacts on performance of built infrastructure, natural systems, health, and provision of service. Electricity is ranked highly though introduction of other categories. Governance emerges as an important node that is connected to everything, especially citizen activity and critical lifelines (e.g., emergency services). The key impact categories and dependencies are shown on Table 4 and the CIrcle output in Figure 7.

Table 4. CIrcle impact categories and incidence of dependencies - Christchurch workshop

Category	Affects	Affected by
Groundwater	7	1
Electricity	3	1
Governance	3	1
Nature	2	3
Wastewater	2	2
Stormwater system	2	2
Emergency services	1	1
Financial services	1	1
Water supply	1	1
Roads, tunnels, and bridges	1	1
River protection and other structures	1	1
Healthcare and public health	0	4
Commercial facilities	0	3
Citizens	0	1
Communications and IT	0	1
Gas pipelines	0	0
(Air)Port	0	0

Figure 7. CIrcle derived dependencies between impact categories - Christchurch workshop

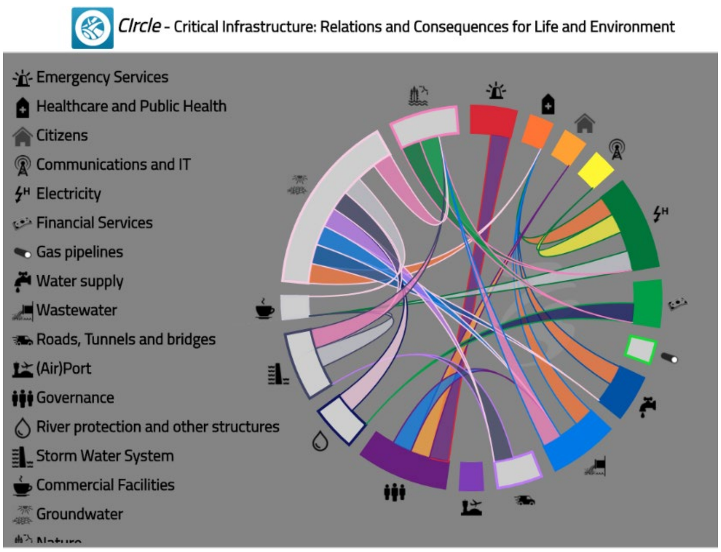


Table 5. Christchurch workshop issues (Detailed notes see Appendix 1)

Christchurch workshop	
Three waters	• Groundwater/wastewater links as GW rises and high-intensity rainfall coincide • Damp homes and poor health outcomes • Road access impeded • Flooding affects social infrastructure, e.g., schools, hospitals, and shops • Stream contamination, salinity and vegetation affected • Pipe integrity affected by saline water
Governance	• Governance (financing and infrastructure) – connects to critical lifelines: water supply, and emergency services at all levels • Increase in residual risk affecting capacity to act • Need to establish what infrastructure strategies look like now • Spatial plans need ongoing renewal and in relation to three waters planning • Planning – short-term actions and long-term planning beyond the three year cycle, shift to 100-yr, proactive and holistic rather than reactive
Infrastructure (Electricity/grid/network)	• Electricity a driver – gets disrupted by events – business, communications, and housing
Financial services	• Application of financial services can create a 'safety paradox' affecting movement of people from affected areas
Iwi	• Connect governance to people, e.g., Ngai Tahu - proactive, multigenerational, holistic, integrating mitigation and adaptation • Long-term perspective regarding retreat from sea-level rise

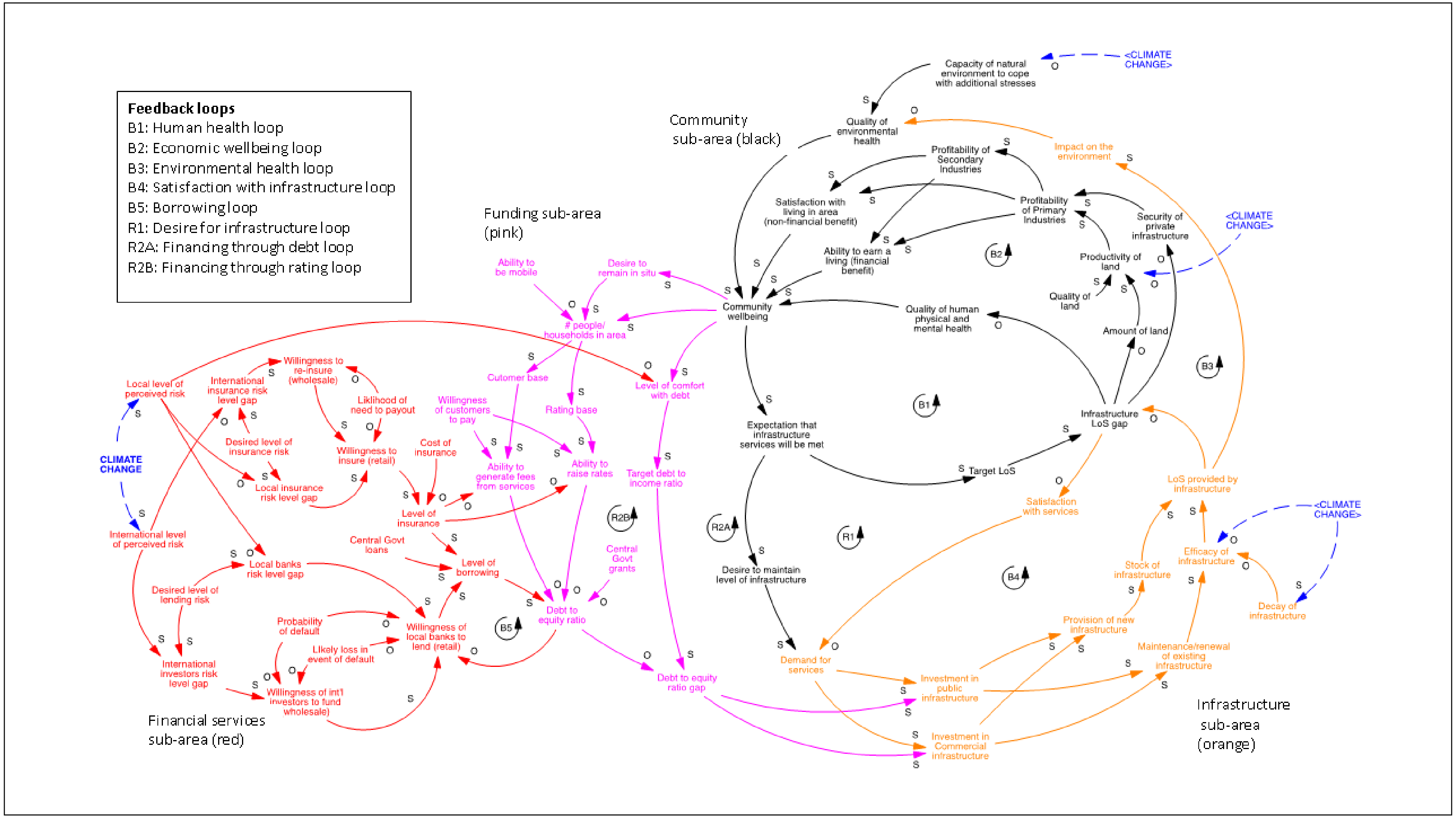
4.3. Systems mapping of cascading impacts

A causal loop diagram (systems map) was constructed to show how the different types of climate change impacts (extreme events and slowly emerging impacts) have similar interdependencies, feedback loops, and generating similar cascades across other domains. The systems map (Figure 8) shows interdependent cascades based around seven feedback loops across four sub-areas of the system (infrastructure, community, and funding and financial services). Importantly, the systems map shows how the cascades arise from a climate impact and move across space and organisations, affecting ecological, social, and economic domains. The cascades can move through a connected social-ecological system, combining or exacerbating because of external policy decisions or concurrent impacts or events. While the three climate-derived impacts of concern can be characterised for the purposes of building cascades, the different types of impacts can occur simultaneously at the same geographical location. This could create multiple simultaneous cascades that recombine in potentially unpredictable ways or create a more rapid progression towards a threshold. In addition, the incidence of surprises cannot be characterised because they cannot be predicted.

The seven feedback loops (reinforcing and balancing – see Appendix 3 for detail on how the systems map was developed) and dependencies are the critical elements of the systems mapping process. The systems map presented here in Figure 8 is a summary of the overall system of four sub-areas (community – black; infrastructure – orange; funding – pink; financial risk – red) and factors driving the expectations from, and investment in, each domain. Box 2 describes how the cascades were generated and the following example shows how to navigate through the systems map.

> *Begin with the climate change stressor (blue) and move into the infrastructure sub-area (orange). As the climate change impacts increase, the efficacy of infrastructure will decrease (e.g. stop banks, storm water or sewerage system). The desired level of service provided by the infrastructure decreases, with several impacts on human and natural systems. For example, the land available for farming and its productivity decrease and the profitability of the primary sector decreases the ability to earn a living. The local community vibrancy and functioning (wellbeings) also decrease due to people leaving the area). As the community wellbeing (black) is reduced, the expectation that infrastructure services will be met increases, which leads to increased demand for maintenance of the service or for new services. However, delivery of these is contingent on the ability to obtain finance. Moving to the funding sub area (pink), money for infrastructure comes from three areas, depending on the provider. Rates depend on the number of households in an area and the willingness to pay for increases. Services charges depend on willingness of the customer to pay for the service or infrastructure. As the willingness to pay decreases, the ability to raise additional finance decreases. Borrowing is the other option in the financial services sub area (red) which changes the debt to income ratio, for which communities and organisations have different tolerances. The policy settings of the insurance and banking sectors will affect borrowing, which will in turn be affected by the sectors' perception of the risk, and how they respond to climate change impacts and to external international reinsurance and banking markets. This then flows back to domestic policy decisions of the sector affecting their willingness to insure or lend. This in turn shifts demand to other sources of funding to address cascading impacts on infrastructure. If the money is available on acceptable terms, new infrastructure will be provided (or existing upgraded) and the level of service can be returned to previous levels or improved, until the climate change stressor increases and the cycle begins again, but with different outcomes depending on the balance between all the sub areas.*

Figure 8. Systems map showing cascading impacts across multiple domains (sub-areas)



4.4. Implications

First, the implications of the cascades described in Boxes 3 to 8 are presented here by domain and type of climate change impact, and second, a thematic analysis of interviews with key informants, based on the systems map, provides clear insights into the implications of cascading impacts.

4.4.1. Implications of the cascades

Wastewater systems (sea-level rise and coastal inundation cascade)

Wastewater systems located in coastal settings are affected by the prevailing policy assumptions. For example, funding allocation by local government for pipe repair has been based on a design lifetime that is much shorter than was expected when it was built. This is in part driven by pressures on decision makers to reduce rate rises, which results in tendering for repair work at lowest cost. This means that the potential for alternative pipes made of more resistant material is often ruled out. In addition, there is a limited ability to borrow more money to finance repairs, due to competing demands from other council functions and fiscal and legal risks associated with increasing council debt above statutory limits. Further, ongoing problems with corrosion have been identified across sewer networks, such as accelerated corrosion of pump station components not designed to withstand salt water, as well as problems with overall wear and tear due to an increase in pump run hours because of increased flow volumes from stormwater and groundwater infiltration. Consideration of such impacts and their implications for the policy assumptions around tendering and costing will be necessary going forward to reduce maintenance costs. Such cost reduction on maintenance may offset new materials costs and contribute to more sustainable investments in wastewater systems over the long term. Given that underground infrastructure is tied to urban development that lasts in situ for at least 100 years and longer, monitoring of signals and triggers of change in performance levels, will be necessary.

Water supply systems (drought cascade)

The impact of drought on water supply systems has implications for design, maintenance, and timing of decisions and for land-use decisions more widely. This requires councils and their assets team to carefully plan for sufficient resources and capital towards design, repairs, and replacement strategies in a context where there are uncertain and changing future conditions to address, such as climate change impacts and how they may play out over time. Councils are required to plan strategically for infrastructure and for its financing over at least 30 years, including allowance for planned increases or decreases in levels of service, and for managing risks related to natural hazards (which includes climate-related hazards). In coastal areas, the timeframe required is “at least 100 years” (NZCPS).

Without incorporating considerations of known and expected climate change impacts, including drought, it is likely that sedimentation within pipes and their performance under dry conditions, and wider impacts on traffic flows described in the narrative, will re-occur when similar ground conditions persist. To manage such risks, and to avoid the cascade of associated impacts, councils will need to introduce new design standards for new builds and replacements that are capable of adapting to drier, hotter conditions and to the simultaneous effect of high-intensity rainfall events affecting the water pipe systems. A multi-hazards approach will be essential to enable a range of future hazard, including sea-level rise, scenarios to be assessed for their implications for options in the decision process, including land-use options that can manage the uncertainty and change over the planning period to be considered - before large capital investments are made that may lock-in current land uses and reduce flexibility to change development pathways in the future depending on how the future evolves as monitored using signals and triggers of changing performance levels.

Stormwater systems (heavy rainfall cascade)

Some greenfield developments within New Zealand cities are using stormwater management systems that include swales, retention ponds, and open spaces to reduce/contain flooding. Currently, options for brownfield developments are more limited until opportunities arise when sites are redeveloped. Each stormwater catchment will require its own catchment management plan that assesses where the risks are, and develop options for how they can be managed over at least a 30-year lifetime and in the case of coastal areas "at least 100 years" (NZCPS requirement) and monitored accordingly using signals and triggers of change.

New guidelines are needed using more up-to-date data and longer time-series. However, due to uncertainties around the frequency and intensity of heavy rainfall events in urban areas, several scenarios of a range of plausible conditions will be required to test pipe efficacy and to identify measures for attenuating runoff and new water management system design in catchments. A precautionary approach to manage this uncertainty would be to design systems that can retain excess water and be readily modified, or design redundancy into the system to enable replacement with new technologies as they come on-stream. This approach will require new business and investments models to be sustainable going forward in a changing climate. Without such strategic approaches on a catchment basis, councils will be faced with costly system replacements at uncertain timing in the future that will be difficult and very costly to manage.

Stopbank breach (Extreme flood event cascade)

Stopbanks are another class of infrastructure service for flood protection and control (flood risk management). They too do not manage all risks, leaving a residual risk that needs to be considered. Long-term maintenance, monitoring and re-setting of risk design is an essential part of maintaining efficacy of stopbanks. These too will be challenged by funding availability through rates and through increasing maintenance costs as the climate changes. Stopbanks have been perceived as physical protection as they are visible and, most of the time, do stop flood damage. However, they have the effect of instilling a false sense of security in those 'protected' by them, witnessed by the assets and people continuing to build up behind them. This increases exposure to risk, and the damage that follows when bigger-than-design flows are exceeded. Providers of such critical infrastructure are beginning to be affected by the cascading impacts of climate change.

Again this has implications for the policy assumptions made by decision makers, necessitating re-evaluation of design settings and land-use planning controls to avoid the worst damage from the rising risk from what are regarded as extreme events that will likely become more frequent as a result of climate changes. Additionally, for slow onset impacts, such as increasing coastal inundation from sea-level rise, there is a need for decision makers to start now to reassess the appropriateness of land uses, due to the irreversible nature of sea-level rise over human timeframes. For example, service providers may consider changes to current decision settings at different points in time by monitoring signals and triggers of change. Scenarios such as, pumping stations no longer able to cope with higher groundwater levels, or services being withdrawn before stopbanks are withdrawn, leading to land-use planning provisions signaling no further development in coastal areas at imminent risk of damage.

Power/Gas/ Internet (Storm event cascade)

Following storm events that impact on utility functioning, lines, telecommunications, and other lifelines companies respond by restoring service as quickly as possible. While such companies manage risk in a proactive way, for example, by building redundancy and resilience into networks to better cope with storm-event outages, these proactive actions are largely based on current climate conditions and the costs managed via charges built into consumers' monthly bills. There are limits to such a strategy over the long term, as most utilities are in place above and under the ground for much longer, servicing communities that are, for all intents and purposes, permanent once built. The added impact of storm events (wind, snow, flooding, and storm tides on top of sea-level rise) on utilities will challenge current rating bases and borrowing limits, thus necessitating monitoring of signals and triggers.

4.4.2. Common implications of the cascades

Common implications from the narratives have emerged that affect risk assessments and decisions taken on them by decision makers.

The need for a more strategic approach to three waters infrastructure flood risk management and utilities planning is a common implication, not least because all of these infrastructures are linked to the communities and developments they serve. Alongside this is the coincidence of many hazards in some locations that necessitates an integrated catchment management and multi-hazards approach to the strategy. Such a strategic approach also necessitates planning approaches that enable dynamic adaptive components to be built into the options assessed, and the actions tested against plausible scenarios of the future, that enable policy settings and the decisions based on them to be flexible, in order to change paths as climate changes evolve over time. There are limits to the current, largely reactive mode of responding to climate events that necessitates a shift in the way decisions are taken, towards a more anticipatory approach, given the irreversibility of some climate change impacts, such as sea-level rise. Collaborative models of public engagement can elevate public understanding of the problem and involve communities in developing options for how the problem can be addressed over the short and long term. Such models also enable many different stakeholders and governments to engage in contested areas of decision making. For some of the irreversible impacts like sea-level rise, this will involve consideration of more transformational options, which in turn leads to consideration of incentives and funding options for paying for the changes that will be needed in some locations.

New systems of monitoring change using signals and triggers for decisions ahead of damage to community assets will need to be designed, and new ways or better use of existing provisions for maintaining monitoring regimes will need to be employed. Councils have fiduciary duties and risk management responsibilities that together suggest that monitoring of climate change impacts and their tolerability by current generations, and for future generations, will be necessary.

The linking of land-use planning and infrastructure planning is critical for managing risk and vulnerability so as to avoid adding to the legacy of cascading impacts of climate change as they progress over time. Interconnecting the different domains of interest (three waters, flood risk management, utilities, asset planning, land-use planning, reserves management, and financial management), within and across governance systems, and between institutional and organisational silos, provides a way of bridging between domains and, therefore, managing risks more explicitly in a connected manner.

This implies a better understanding of the impacts and how they cascade into the different domains. This understanding can enable adaptations to be designed that better ‘fit the problem space’ of changing risk and uncertainty. Finding opportunities while managing risk will be a positive way forward. For example, using overland flow paths and retention basins designed to provide community amenity while delivering on flood risk management objectives, will enable our largely gravity stormwater systems to be complemented, and the need for expensive pumping systems to be avoided. This will buy some time to develop completely new systems that can be used once the decision triggers are reached. Triggers may include the deployment of greater insurance risk rating (already occurring in some localities), risk reflected in real estate sales, and quality of life and health indicators, which together will reflect community intolerance of the changing risk. Without such incentives, further legacy development will be built in areas of increasing risk. This greater exposure will eventually require greater adjustment costs, or result in stranded assets, leading to a reduction of choices for communities and, in particular, for those most vulnerable people.

4.5. The interviews - three domains of interest

The narratives and systems map were used to underpin the interviews with key informants. The informants were shown the systems map and narratives relating to their domain, which formed the basis of discussion of the consequent implications of the cascades for that domain of interest. Key themes emerging from the discussion are summarised in each domain. Urban systems and infrastructure have been combined because of their interdependency. Links to Figure 8 systems map are depicted by sub-area (colour) and feedback loop nomenclature (e.g. B1 or R1).

4.5.1. Urban systems and infrastructure

Urban systems include the underlying support systems that enable provision of services and exchange for urban populations. In workshop discussions with local government, a number of potential cascading impacts and implications were identified. For example, it is likely that climate change will result in more frequent flooding in low-lying urban areas (climate stressor). Flood waters may take longer to drain due to higher volumes and lower freeboard levels (as a result of rising groundwater as sea-levels rise). Standing water particularly affects older homes, especially in areas of higher socio-economic deprivation, which may have poor heating and ventilation, exacerbating adverse health impacts from dampness and mold (B1-health). The majority of the discussion, however, and the focus of the research, is on the three waters infrastructure and stopbanks protecting urban areas (Orange-infrastructure). The following discussion explores these aspects in more detail, while some of the other cascading impacts and implications are highlighted elsewhere in the report.

Rising seas and groundwater, and increased flood risk from riverine and heavy rainfall events, will challenge New Zealand's largely gravity-based stormwater systems as the climate changes. This means the dependency between urban development and the infrastructure servicing urban systems becomes critical (Orange-infrastructure). Local government interviewees corroborated the potential for cascading impacts of climate change. These effects include the indirect impacts of standing water on health and wellbeing depending on existing vulnerabilities in the community (Black –community). Households in low-lying areas, for example, may have limited adaptive capacity to address increased exposure to respiratory complications as a result of increased dampness and mold, to raise floor levels, or to move to another area away from the hazard.

According to interviewees, impacts would result in diminishing levels of service (B4-satisfaction with infrastructure) unless an integrated systems change was developed in areas affected by those impacts in order to avoid the worst effects on communities. The level of redundancy in stormwater system design, which leads to designing a subdivision that can 'absorb' greater run-off from the changes in rainfall, was an example of a new practice required to address cascading impacts. This then led to a discussion of the ability of our current governance systems and human resource capability to adequately address the scale of the shift required. Closely related to governance issues was the adequacy of funding mechanisms (Pink-funding) to address the greater stresses on our natural, physical, and human resources in a way that incentivises a reduction in exposure to climate change impacts from the increasing exposure to risk that is current practice.

For example, it was reported that some councils are designing planning measures and granting consents in low-lying coastal areas and flood plains at thresholds that are tailored for current tolerability in communities. As one infrastructure provider said, *"Some councils are deliberately designing thresholds for sea-level rise that they can get away with through* *building controls, rather than using levels that are robust under different future scenarios. This approach will make a big problem for the future."*

While this may satisfy current landowners, there are long-term implications for future generations if the measures encourage further development, accelerating the well-documented 'levee effect' (Collenteur *et al*., 2015). As an insurance sector interviewee said, *"If the wrong sorts of protections are put in place there is the possibility of false confidence, because greater levels of assets may then be developed assuming that the protection will be there and continue to be there in the future. Having a district plan, and how this is translated into the physically on the ground, is what insurers want to see."*

This, along with the availability of insurance, acts as a strong signal that can incentivise household decisions about the location of their property purchases, according to a council advisor:

"If I cannot get insurance, then my perception of the feasible options narrows quite significantly."

Interviewees also raised the issue of dependence between place and transport networks as part of community functionality and for tourism as being important for consideration of cascading impacts of climate change. Urban infrastructure is an essential part of community function (Orange-infrastructure to Black-community).

4.5.2 Financial services

The stocktake undertaken by the Climate Change Adaptation Technical Working Group (2017) assessed the financial sector as having significant work to do on the attributes of effective adaptation – being informed, organised, and taking dynamic action. Insurance sector interviewees were generally aware of the risk of climate change in the residential housing sector and had made some recent risk-based pricing adjustments in climate and sea-level rise risk-exposed areas. The banking sector was aware of the increasing mortgage risk exposure, especially if the insurance sector were withdrawing from hazardous areas or increasing premiums Red-financial). Bankers were aware that insurance sector responses could initiate a sudden issue for them that they had reduced ability to control. The insurance sector, on the other hand, has the ability to respond to changing risk because it can adjust annual insurance contracts with customers.

The sector understands that with sea-level rise advancing, assets will, by mid-century, diminish in value to zero because of the hazard risk, including compounding risk (e.g., coastal and river flooding, drought, wind, and intense rainfall events), but they do not know the timing, which they understand will vary between regions because of different levels of exposure. As one banking representative said, "*Insurance behaviour will become an early indicator of where that direction is going."*

A banker's comment that, "*We don't insure certainties but only risks",* is also a sign of the sector's concern as climate impacts advance with sea-level rise impacts being a certainty, while the rate of rise is uncertain because it is dependent on which greenhouse gas trajectories emerge and how the polar ice sheets respond. This creates an uncertainty about the way in which the banking sector may respond, for example, "*everyone wants a straight line that will be well contained and as narrow as possible and that is only achieved by certainty".* It is clear from the interviews, however, that the financial services sector do not want to see "*early panic, or ignorance and delayed panic, neither of those suit us".* The sector *"requires a well-defined trajectory for change so the impacts can be managed".*

These responses from the financial sector suggest that anticipating the certain change in the short term, and reducing the risk exposure by avoiding and adjusting to that risk, would help cushion the impact of policy responses on their risk exposure. Adjusting to different classes of risk within the financial services sector (especially banking) takes time within organisations driven by prescriptive regulations and where panic behaviours by customers, in response to risk-based signals, can occur very quickly and affect people’s lives and asset values. In such circumstances, the risk is often transferred to the state or to people least able to bear the consequences (Black-community & B2 economic well-being)).

The flow-on effects can be two-fold with respect to mortgages: the customer’s ability to service the debt, and the change can affect the value of the security (Red-financial). Which one is dominant depends on the individual circumstances of the customer. With respect to insurance, customers either pay higher deductibles to reduce increased premiums if they can afford to, or they do not hold cover (which locks them into staying put, abandoning their assets and moving, or becoming unable to afford to move and becoming dependent on the state). For commercial properties, the impact of the price signal can be more dramatic, depending on the relationship between the insurance costs and the net income from the commercial activity, because the value for a commercial property is derived from the income that can be generated from it. The cascading impacts are a transfer of risk to the individual or company, the taxpayer, and the ratepayer. There are further cascades to the State if people cannot afford to adjust.

The type of climate change risk will propagate different cascading impacts. The discussion so far has focused on evolving sea-level rise, manifest as increasing coastal inundation. This is a certain risk. There are greater uncertainties for high-intensity storm events, drought, wind, and wildfire, which all exhibit great variability in time and space. Different groups within society have different adaptive capacities to the impacts of climate change, for example, those in the rural sector have long adjusted to changes in climate within current variability, but may be challenged by the shift in variability ranges depending on debt-to-income ratios (B2- economic well-being). Others, like home owners, may have less capability as the sea advances and extreme events become more frequent B1 & B2 health and economic well-being). Nevertheless, insurance signals before and after climate events are manifest and will act as early warnings of the need for individual and collective policy adjustments to be made.

A banker described the stark reality that *“the relationship of availability of insurance and availability of borrowing is a hard on/off switch”* because *“insurance can be out within one year, but banks are stuck in it for 30 years and local government for even longer.”*

If it is hard to get property insured, this will depress property values, and if borrowing is reduced for business start-ups, this will impact on economic activity Red-financial & B2 economic well-being). And so a viscous cycle emerges.

Policy responses by local government and central government also have the potential to create vicious cycles that lock-in assets and people in areas that will increasingly become affected by climate change impacts. For example, the insurance sector highlighted that the interplay between council decisions to continue to consent buildings and subdivisions in areas known to be at risk from climate changes, will affect the sector’s willingness to insure. The sector flagged that a change to the insurance business model could make a clearer link between insurance and planning to avoid further damage, with a funding regime to support this.

Councils' willingness to withdraw services or not maintain protection levels as the risk increases are levers available to councils within what is legally possible [6], and may become increasingly necessary to signal risk to communities, although not without equity issues (Black-community). If councils signal where development can be located safely, this will incentivise development by increasing the confidence to invest using available investment capital and new funding instruments to manage the investment. However, the insurance sector expressed concern that many councils have poor information on the state of their current assets, which means that risk assessment by the industry for insurance and lending purposes (B5-borrowing) and for investment is hampered. If risk-based planning tools and measures were to be used more widely by local government and monitored by the Office of the Auditor-General routinely across the local government sector, the financial sector indicated it would have more confidence, which would be reflected in greater certainty for householders and the Government. They commented that the insurance sector can walk away, but the Government cannot. The implications for funding of climate change impacts (R2A & R2B funding through debt and rates respectively) flowed from this comment in the sense that the burden on reactive strategies to address loss and damage as an increasing residual risk through EQC or directly by government at a local and national scale, would place greater burdens on the State.

Greater attention to signals that can trigger risk-based decision making was raised by local government, the financial sector, and infrastructure providers. Building greater knowledge of the actual and potential cascading nature of climate change impacts was considered essential for building community and sector confidence for transitions to less-exposed locations, supported by investment in adaptations and economic activity. Planning and effective community engagement were raised by many of the interviewees as essential bases from which to build such a transition. Another key factor raised was the need for interconnected management of cascading impacts with greater understanding of the flow-on consequences of the impacts and decisions about them.

[6] Laing, D. (2018, February 13). *Ability to stop or limit the provision of services infrastructure and potential liability consequences*. Legal advice prepared for Local Government New Zealand. Wellington: Simpson Grierson Barristers and Solicitors. Retrieved from http://www.lgnz.co.nz/assets/Uploads/Legal-opinion-2-Ability-to-stop-or-limit-the-provision-of-services-infrastructure-and-potential-liability-consequences2.pdf

4.6. Governance implications

All of the flows from the cascading impacts discussed above have implications for governance of climate change risks across all domains of interest. For example, *the adequacy of the institutional arrangements* to meet the changing risks and consequent loss of service levels to the community (including the statutory frameworks); *design life* of the assets (materials, methods, design, location) and the need for land use change and how to manage it; managing community expectations about *levels of service*; how to deal with *uncertainty*; working with *communities* to manage change; *political leadership*; *funding* stressors such as plan veracity, costs, debt levels, and financial management; and *legal liability and legal challenges* for councils and infrastructure agencies. These implications are intimately tied to governance, and the enablers that support it, and provide an opportunity for governance to bridge the silos of practice across and within the different levels of governance and to support engagement with communities.

4.6.1. Institutional arrangements

Local government has a great many functions delegated to it in New Zealand. The current context is one of increasing pressures from economic development on the environment, creating legacy effects and increasing climate pressures on land and water resource use. This is intensified by heightened differences between community values as the competition for resources and equity effects from allocative decisions compound. Climate change intensifies these pressures and highlights the irreversibility of some impacts on an already stressed environment, especially coasts, catchments, and water resources (both its quantity and quality). We are seeing multiple and interconnecting hazards playing out as pressures on land and water uses intensify. The cascading impacts identified here bring a new lens to this conundrum, and an opportunity to take stock of the dependencies between these pressures.

The practices under our institutional arrangements have thus far failed to anticipate these changes or provide adequate processes for their management with an eye on the irreversibility of change in the environment. This is despite statutory direction and guidance to do so (e.g., NZCPS, RMA, and various national Guidance documents). A fresh look at how more integrated and sustainable management pathways might be achieved is surely in order.

In the last five years, New Zealand has experienced one major stopbank failure (Edgecumbe); many seawall breaches or over-toppings (e.g., Island Bay); homes, roads and underground infrastructure regularly inundated by the sea (Mission Bay, Granity, Hector, and Ngakawau); continued land subsidence from legacy drainage schemes (Hauraki and Rangitaiki Plains); loss of valued natural habitat (Hauraki); drought conditions, wind, and snow storms detrimentally affecting agricultural production and rural activities (North Canterbury and Central South Island), and urban underground infrastructure (Wellington); and groundwater and flooding impacts on low-lying urban areas, especially where earthquakes have exacerbated these effects (Christchurch).

In response, we are witnessing insurance companies not insuring some areas of known risk, or risk-rating premiums at a level that will see risk transferred to individuals. The consequence of this is that the vulnerable will be unable to pay, or will be transferred to the Government, as experience has demonstrated in the past (through flood and drought relief schemes).

Pressure for rapid housing development to meet increasing demand has seen new developments located in low-lying and coastal areas, such as Bay of Plenty, Thames-Coromandel, and Nelson, facilitated by special legislation that appears to operate outside the hazards and climate change provisions in the RMA.

While councils are starting to examine the risks and the means by which they can be addressed, the current disconnected institutional arrangements and reactive mode of 'management' are not adequately considering the interconnected nature of these problems, nor the wider cascading impacts and their costs, now and in the future. Responses in the different domains of interest in isolation from other domains of interest will exacerbate the planning and decision-making responsibilities devolved to councils across New Zealand.

4.6.2. Planning and design life of assets

Land use and infrastructure decisions set in train long-term implications and expectations by those who rely upon the decisions. There is a legacy effect set up. This means that planning approaches that consider the design-life of the land use in a changing climate context are most appropriate. Sea-level rise will be ongoing, permanent, and irreversible over many centuries. If we stop emissions today, there is a long lag time before we see an effect on the sea level. What has already been emitted is still to be felt fully in the sea levels. This has significant implications for how and where we live and use coastal areas, for example. Increased frequency of drought has significant implications for the type of agricultural land uses undertaken and for the longevity of current water augmentation methods and for competing uses of that water in urban areas. Increased frequency of heavy rainfall events has significant implications for the design of cities, replacement of the primarily gravity stormwater systems, wastewater and flood risk management, and for their design. New technologies, such as 'sponge cities' or ' water-sensitive cities', are gaining currency in the major cities of the world (Zevenbergen *et al*., 2018) to manage water and wastewater and the expected increase in rainfall intensity and rising seas. These new technologies hold hope for addressing the cascading impacts and the dependencies between domains in an integrated way and through consideration of the long life-time of infrastructure and its dependency on land-use planning for the developments it serves. However, there are big lag times between acknowledging the need for new system design and its consenting and implementation.

4.6.3. Managing community expectations regarding future levels of service

Local government responsibilities for providing services under a changing climate is creating tensions around managing community expectations for future levels of those services. Interviewees were candid about local government capacity to continue current levels under existing rating bases, especially in small councils. In addition, it is difficult for councils to manage expectations of protection when ratepayers *"don't understand the link between levels of services and rates"*. Councils are asking themselves, *"do levels of service change our design criteria?"* Sustaining the affordability of the current levels of service is moot. For example, how performance measures of level of service (LoS) are expressed becomes very significant – if current flood frequencies are used, they will change, reaching tipping points for communities' coping capacity and with secondary impacts. How councils respond to these challenges will be pivotal to their being able to fund the services. For example, 80% of council budgets go into hard infrastructure, which suggests that more cost-effective innovations in service design for dealing with increased flood risk in low-lying areas inland or at the coast will be necessary. As a major period of infrastructure renewal coincides with ongoing increased risk from climate change impacts and increases in development exposure, a drop in level of service is inevitable, unless other forms of funding can be accessed, for example, green bonds and other funding instruments. New instruments will need to form part of the adaptation enablers going forward, along with innovations in service design and planning to reduce the current legacy effects and to avoid creating new ones.

4.6.4. Addressing uncertainty and changing risk profiles

Currently, consideration of the uncertainty and changing risk profiles associated with cascading climate change impacts is under-developed in practice, although there are signs that there is recent interest arising from the revised Ministry for the Environment Coastal Hazards Guidance motivated in part by the visible effects of sea-level rise and increased frequency of heavy rainfall events and drought.

Shifting from a predict-and-act and reactive mode of managing risk, which cannot give confidence in an uncertain and changing risk context, will not enable climate change impacts that cascade across domains in time and space, to be addressed. Stress testing a range of options for short-term actions and for the long term, against a range of plausible scenarios, can provide better assurance to decision makers that they have built-in flexibility to change in the future as the limits of current approaches are reached. Flexibility in the system enables dependencies, and lock-in of investment that will increase the future adjustment costs, to be avoided. There are limits to building back in locations where there are increasing exposures to cascading impacts. Building back better or somewhere else, creating redundancy in system design, connecting the dots between decisions taken today and their future functionality under different conditions, and by considering how impacts cascade to the different domains, will reduce a huge risk transfer across communities and vulnerable groups in society, and avoid stranded assets, that will flow to the future taxpayers and ratepayers of New Zealand.

4.6.5. Community engagement

Communities are exhibiting a paradoxical hunger for engagement around the obvious impacts of climate change. Paradoxical because it has been motivated by what councils have tried to do to avert future impacts on its ratepayers. There are expectations of 'protection' now in the short term that have the potential to be acted on, creating lock-in to current development trajectories. Protection breeds ongoing expectations of protection, which may, at least in coastal areas, have short-term benefits for current property owners, but make it more difficult for future generations to make adjustments to more sustainable approaches before future damage is incurred. Likewise, provision of water to sustain current primary production models is likely to generate further development of current practice, rather than signal that there are more droughts on the way, especially in eastern areas of New Zealand. More sea-level rise will affect abstraction rates of groundwater for water use by urban and rural populations, which could motivate more sustainable land and water uses. Collaborative planning models can engage the public in long-term thinking and planning that connects domains of interest with temporal and spatial decision making. Such approaches can reduce the practice in decision making as expressed by one council advisor: *"We seem to spend a lot of time trying to solve the problem once the problem has occurred, which is one of the biggest follies. We are not very proactive"* and *"they [councils] make decisions on what the public want and you don't get the best outcome".*

4.6.6. Funding and legal liability

High-level and partial attempts have been made to cost the impacts of climate change (Parliamentary Commissioner for the Environment, 2015), notably for above-ground impacts on houses and roads from a number of sea-level rise increments. Most of local government assets are underground. The value of three waters infrastructure is estimated at $44 billion by Local Government New Zealand (LGNZ). This needs to be seen alongside the potential cascading costs of climate change impacts, such as those described in this paper; the secondary and tertiary impacts on health, social services, wellbeing; and to the many domains to which the cascades flow. Such costs are part of the value proposition.

Councils' inertia to move to more anticipatory and integrated models has been in part associated with the short-term political cycle and lack of regional and district functional governance integration (unitary councils excepted). This has combined with the perceptions of costs for which there are inadequate funding mechanisms, which raises demands on national-level government funding. The legal liability for addressing hazard risks, cumulative impacts, and needs of future generations for foreseeable risks, have been trumped by the stronger motivator of the risk of being taken to court in the present. Visible hazard damage is increasingly motivating a nascent shift amongst some councils. Some have started to look at funding models for coastal hazard risk management (Hawke's Bay); others have begun multi-hazard assessments or 100 year strategies (Christchurch and Hawke's Bay); and others have already developed strategies that are shifting development on the coast to higher ground elsewhere (Tasman). Auckland city has embedded rules that reflect sea-level rise scenarios, alongside rules to reduce risk over 100 years. However, there are mixed messages developing, for example, from special purpose legislation for housing that is silent about natural hazards and the links with the RMA. The actual and potential effect is to make it harder in the present to reduce risk exposure, and to transfer legacy effects and potential future costs from developments located in risky areas to future generations and to the State. Those creating the lock-in will not be those who will pay for it.

4.6.7. Political leadership

The implications discussed above have significance for political leadership between levels of government and across parties in Parliament. Signs are emerging of cross-party collaboration. Cross-governance level responses have been elusive to date but there leadership is emerging as the Governments climate change policy programme starts to implement an adaptation response motivated by the Paris Agreement and recent advice of adapting to climate change (Climate Change Adaptation Technical Working Group, 2018). This may herald what one workshop attendee described as, "*a shift – we can no longer rely on crises as a driver of change".*

4.7. Communication of cascading impacts and implications

As part of our research we considered how to communicate the cascading impacts and implications to those making the decisions that are affected by the cascades. The importance of this was raised by workshop participants and the interviewees. The most frequent reasons given were the short-term focus of local government elected officials, driven by the three-year electoral cycle, and an entrenched focus on responding to immediate 'problems' as they occur and to immediate community pressures to respond to proximate issues.

However, elected officials operate alongside of advisors and private sector influencers, so all interviewees also stressed the importance of tailoring the messages to different audiences. For example, a local government strategic advisor and a planner commented respectively,

"Some might look at the systems map and get it. Others may want to spend some more time to understand the various components and what is meant by all of it," and

"There are different levels and layers of information that have different challenges and opportunities that can be communicated using a summary layer in simple form then people can drill down if [they] want to."

Concern was expressed that currently councils are focusing on how existing tools for considering climate change adaptation can be used and modified, but only acting when the hazard is realised through emergency management and lifelines management, rather than having a comprehensive community discussion about options and working toward de-risking their exposure to climate change impacts. Dealing with people was reflected in comments from several interviewees, for example, *"will take more time, but it will make it easier in the long run,"* remarked one interviewee. This becomes significant, as *"increasingly, people's retirement plans are caught up in land development potential or sale of a property".*

Accordingly, cascades can help agencies to look beyond the immediate and the 10-year plan horizon and to take opportunities as they arise as asset life nears completion; for example, taking the opportunity when doing an upgrade of a road or bridge to discuss wider access issues that affect housing developments and making links with developers, real estate, and insurance sectors for discussions about how these decisions flow through other systems and affect people longer term. There are recent examples of cascades that raise such wider implications, for example, for the Wellington region, algae growth in the water supply as temperatures rise; in the Hutt, Hawke's Bay, and Canterbury, land uses change and maintenance of sources of drinking water where bacteria or nitrates can impact on human health outcomes. Such possible outcomes can be anticipated if cascading consequences are discussed in the context of changing climate risk profiles over the longer timeframes of the infrastructure lifetimes, many of which will be well within 100 years.

There is well documented evidence that experiential learning helps internalise the understanding of risks over long timeframes (Baird *et al*., 2014). To paraphrase John Locke's 1689 Essay *Concerning Human Understanding:* Learning is experience. Everything else is just information. Information is not knowledge. The only source of knowledge is experience. In the context of cascading impacts, this implies the sharing of narratives based on adaptive experience (success and failures), using adaptive tools, and the use of games to internalise understanding that can motivate effective adaptation. Such communication can occur internally within organisations to break down siloed and short-term thinking, with communities about quality of life, and with sector stakeholders such as developers, real estate agents, and the financial sector about the implications of transferred risk in cascades. Again, the layered approach ranging from the simple to the more complex will inform different groups.

Responses to impacts will be driven by different perceptions of the risk, which in turn will be affected by willingness to pay. Interviewees thought that cascades presented as systems can get people's attention, and thus help focus on the nodes or triggers where action can be most effectively targeted.

Use of cascades as scenarios to better understand consequences was suggested as an application of cascades thinking, for example, using a cascade that reflects adaptation compared with one that does not (refer to Figure 3) or depicting cascades as ongoing change that will accelerate differently in different settings or domains. Conveying consequences of not acting includes showing equity impacts, and that consequences can be managed without sudden responses that create further cascades across society.

Using framing language of 'multiple hazards' that intensify and compound across other domains, was something that interviewees suggested would resonate with decision makers, for example, affecting wealth, pest management, water supply, ability to insure, and willingness to pay when councils rating bases (from which increasing costs are funded) are declining.

Other communication options suggested include the discussion of opportunities for new approaches for community wellbeing and delivery of services that may be necessary depending on how the rest of the world manages emission reductions and adaptation to the already built-in climate change effects. Use of 'good' and 'bad' cascades to discuss different scenarios could help decision makers and communities explore options for the future. Using concrete examples for conveying the character of cascading impacts was suggested. The following examples were suggested where there are opportunities for new 'design' thinking across systems:

- Where a step change in river behaviour, consequent upon a significant system change, raises issues about how to deal with a stormwater problem where it didn't exist before and the pipes fill with sediment which increases the maintenance costs beyond the capacity to fund ongoing use of the current system.
- Where insurance starts to drive government policy as an infrastructure service sector gap emerges, which drives flood protection and its design, for example, more room for the river creating choices between opportunities for urban wellbeing, or dredging the river every year with consequent unacceptable environmental impacts.

When communicating cascading impacts and their implications it is important to highlight that some impacts are more or less visible. As a council engineer noted,

"At the coast it is there every day to remind us. With the river you only don't sleep when it rains" and "you can go in there with a bulldozer and make it look like it is okay."

"The coast is harder to control than a river, which has more flexibility, but it isn't as permanent as we think."

Many communication media were suggested, including games to explore many options; use of infographics to explain the cascades and nodes where risk compound; real-life experiences in narratives conveyed in YouTube; short policy brief; leverage community activities to integrate cascading impacts and implications; simple messages for IOD linking cascades to director liability.

By combining the systems map with the narratives (Boxes 3 to 8), CIrcle tool information, and the interviews it is possible to develop extended narratives that highlight connections across the sub-systems and further elucidate the cascades and key implications for decision makers. These can be used to begin communication of cascades.

5. Conclusions

This research has examined how climate change impacts set up cascades that are far reaching and amplify the initial climate change impacts by setting up feedbacks that can result in virtuous and viscous cycles. By constructing narratives and understanding dependencies using collaborative research methods and systems tools with practitioners, we have shown that linear consideration of impacts conceal flow-on and feedback loops, which can lead to maladaptive responses that breach thresholds. Such linear thinking can constrain consideration of the full suite of impacts that impinge on the robustness of decisions.

We have also shown that the distance from impact to an action may be quite large – between systems geographically and temporally. Such teleconnections can be scaled at a systems level, driving implications elsewhere at smaller scale.

Cascades thinking can help bridge the gap between hazards risk reduction and climate change adaptation, because it enables the full import of the initial stressor to be transparent, in space and time as the hazard risk changes and increases with time. It also enables the full human systems exposure and its change to be considered as climate change impacts intensify, suggesting responses that can be more transformative.

The implications of combined extremes events, with widening variability concurrent with slowly emerging impacts (such as sea-level rise and greater frequency of heavy rainfall and droughts), can be examined using cascades in a dynamic systems framing. This will give a richer assessment of the risks than using traditional linear risk assessment methodologies.

By examining the dependencies and feedback loops between different systems of concern when stressed with changing climate impacts, we are able to 'stress-test' our risk assumptions. This enables us to design adaptation responses that are flexible yet robust under different future conditions, and thus avoid reaching thresholds that are damaging beyond the ability of communities to cope. Linking consideration of dependencies between urban systems with the financial sector and human wellbeing outcomes is one example. By understanding these linkages and prioritising the critical nodes we can avoid responses that trigger thresholds that cannot be managed. This suggests the role that integrated management can play in decision making in complex systems, where there is much at stake, using deliberative processes and tools that facilitate deep understanding of systems stressed by climate change.

A local government advisor summed up the value of thinking about climate change impacts and implications using systems thinking and frameworks in the following terms:

"We don't think systems but we need to . . . we have a lot of black box models especially around transport and water. Some engineer has designed a system and they know how to run [it], but all we get is an answer . . . Nobody knows what goes on inside it. [This research is about] trying to expose a system and say this is the system now how can we use it to make decisions. You have gone about the process of engaging with people, trying to explore what a system looks like. A water engineer – they just put sensors in places and measure the flows of stuff and then model it – but you are saying it is a bit more complicated than that."

A systems approach enables closer consideration and documentation of the ways in which climate change impacts may propagate as cascades, and the widening circle of implications that entails. Such an approach can assist those responsible for identifying adaptation options, considering consequences, and tasked with making decisions about adaptation, to examine the consequences of climate change impacts that may be linked across spatial and sectoral domains. Unless this is done, the impact of our adaptation choices will be insufficient; the focus will remain on responding to single impacts, overlooking the generative effect of compounding stresses, and ignoring the greater costs across many domains of interest. This strategy runs the risk of ineffective adaptation. By identifying the governance implications of the cascades, the approach adopted here examines enabling institutional arrangements for delivering effective adaptation that can be developed alongside mitigation.

6. References

Adger, W.N., Eakin, H. & Winkels, A. (2009). Nested and teleconnected vulnerabilities to environmental change. *Frontiers in Ecology and the Environment, 7*, 150-157. https://doi.org/10.1890/070148

Anderies, J.M. & Janssen, M.A. (2011). The fragility of robust social-ecological systems. *Global Environmental Change* 21, 1153-1156. https://doi.org/10.1016/j.gloenvcha.2011.07.004

Ansell, T. & Cayzer, S. (2018). Limits to growth redux: A system dynamics model for assessing energy and climate change constraints to global growth. *Energy Policy, 120*, 514-525.

Arnell, N.W. & Lloyd-Hughes, B. (2014). The global-scale impacts of climate change on water resources and flooding under new climate and socio-economic scenarios. *Climatic Change, 122*, 127-140. https://doi.org/10.1007/s10584-013-0948-4

Baird, J., Plummer, R., Haug, C. & Huitema, D. (2014). Learning effects of interactive decision making processes for climate change adaptation. *Global Environmental Change, 27*, 51-63.

Blenckner, T., Österblom, H., Larsson, P., Andersson, A. & Elmgren, R. (2015). Baltic Sea ecosystem-based management under climate change: Synthesis and future challenges. *AMBIO, 44*, 507-515. https://doi.org/10.1007/s13280-015-0661-9

Boin, A., 't Hart, P., Stern, E. & Sundelius, B. (2005). *The Politics of Crisis Management – Public Leadership under Pressure*. Cambridge: Cambridge University Press.

Bollinger, L.A. & Dijkema, G.P.J. (2016). Evaluating infrastructure resilience to extreme weather – the case of the Dutch electricity transmission network. *EJTIR, 16*, 1, 214-239.

Brown, H.L., Proust, K., Spickett, J. & Capon, A. (2011). The potential role of Health Impact Assessment in tackling the complexity of climate change adaptation for health. *Health Promotion Journal of Australia, 22*, 48-53.

Burton, R., Rønningen, K. & Wedderburn, L. (2008). *Conducting integrated research: A critical literature review of interdisciplinary and transdisciplinary research* (Report No. 12/08). Trondheim: Centre for Rural Reserch, Norwegian University of Science and Technology.

Carey, M., Molden, O.C., Rasmussen, M.B., Jackson, M., Nolin, A.W. & Mark, B.G. (2017). Impacts of glacier recession and declining meltwater on mountain societies. *Annals of the American Association of Geographers, 107*, 350-359. https://doi.org/10.1080/24694452.2016.1243039

Carter, N., Viña, A., Hull, V., McConnell, W., Axinn, W., Ghimire, D. & Liu, J. (2014). Coupled human and natural systems approach to wildlife research and conservation. *Ecology and Society, 19*, 3: 43. https://doi.org/10.5751/ES-06881-190343

Cash, D., Adger, W.N., Berkes, F., Garden, P., Lebel, L., Olsson, P., Pritchard, L. & Young, O. (2006). Scale and cross-scale dynamics: Governance and information in a multilevel world. *Ecology and Society, 11*, 2: 8. https://doi.org/10.5751/ES-01759-110208

Challinor, A. J., Adger, W. N., Benton, T. G., Conway, D., Joshi, M. & Frame, D. (2018). Transmission of climate risks across sectors and borders. *Phil. Trans. R. Soc. A,* 376, 20170301. http://dx.doi.org/10.1098/rsta.2017.0301

Cinner, J.E., McClanahan, T.R., Graham, N.A.J., Daw, T.M., Maina, J., Stead, S.M., Wamukota, A., Brown, K. & Bodin, Ö. (2012). Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. *Global Environmental Change, 22*, 12-20. https://doi.org/10.1016/j.gloenvcha.2011.09.018

Climate Change Adaptation Technical Working Group. (2017). *Adapting to Climate Change in New Zealand*. Stocktake Report from the Climate Change Adaptation Technical Working Group. Wellington: Climate Change Adaptation Technical Working Group. ISBN: 978-1-98-852527-3. Available at: http://www.mfe.govt.nz

Climate Change Adaptation Technical Working Group. (2018). *Adapting to climate change in New Zealand*. Recommendations from the Climate Change Adaptation Technical Working Group. Wellington: Climate Change Adaptation Technical Working Group. ISBN: 978-1-98-852528-8. Available at: http://www.mfe.govt.nz

Collenteur, R.A., de Moel, H., Jongman, B. & Di Baldassarre, G. (2015). The failed-levee effect: Do societies learn from flood disasters? *Nat Hazards, 76*, 373–388. https://doi.org/10.1007/s11069-014-1496-6

Collins, K., Blackmore, C., Morris, D. & Watson, D. (2007). A systemic approach to managing multiple perspectives and stakeholding in water catchments: some findings from three UK case studies. *Environmental Science & Policy, 10*, 564-574.

Costanza, R., Andrade, F., Antunes, P., van den Belt, M., Boersma, D., Boesch, D., Catarino, F., Hanna, S., Limburg, K., Low, B., Molitor, M., Pereira, J., Rayner, S., Santos, R., Wilson, J. & Young, M., (1998). Principles of sustainable governance of the oceans. *Science, 281*, 5374, 198-199. DOI: 10.1126/science.281.5374.198

da Silva, J., Kernaghan, S. & Luque, A. (2012). A systems approach to meeting the challenges of urban climate change. *International Journal of Urban Sustainable Development, 4*, 125-145. https://doi.org/10.1080/19463138.2012.718279

Dow, K., Berkhout, F., Preston, B.L., Klein, R.J.T., Midgley, G. & Shaw, M.R. (2013). Limits to adaptation. *Nature Clim. Change, 3*, 305-307. https://doi.org/10.1038/nclimate1847

Eakin, H., Winkels, A. & Sendzimir, J. (2009). Nested vulnerability: exploring cross-scale linkages and vulnerability teleconnections in Mexican and Vietnamese coffee systems. *Environmental Science & Policy, 12*, 398-412. https://doi.org/10.1016/j.envsci.2008.09.003

Fleming, A., Hobday, A.J., Farmery, A., van Putten, E.I., Pecl, G.T., Green, B.S. & Lim-Camacho, L. (2014). Climate change risks and adaptation options across Australian seafood supply chains – A preliminary assessment. *Climate Risk Management, 1*, 39-50. https://doi.org/10.1016/j.crm.2013.12.003

Forrester, J.W. (1961). *Industrial dynamics*. Cambridge, Mass: MIT Press; New York: Wiley.

Fountain, A.G., Saba, G., Adams, B., Doran, P., Fraser, W., Gooseff, M., Obryk, M., Priscu, J.C., Stammerjohn, S. & Virginia, R.A. (2016). The impact of a large-scale climate event on Antarctic ecosystem processes. *BioScience, 66*, 848–863. https://doi.org/10.1093/biosci/biw110

Galaz, V., Moberg, F., Olsson, E.-K., Paglia, E. & Parker, C. (2011). Institutional and political leadership dimensions of cascading ecological crises. *Public Administration, 89*, 361-380. https://doi.org/10.1111/j.1467-9299.2010.01883.x

Gill, J.C. & Malamud, B.D. (2016). Hazard interactions and interaction networks (cascades) within multi-hazard methodologies. *Earth System Dynamics, 7*, 659-679. https://doi.org/10.5194/esd-7-659-2016

Givens, J. E., Padowski, J., Guzman, C. D., Malek, K., Witinok-Huber, R., Cosens, B., Briscoe M., Boll, J. & Adam, J. (2018). Incorporating Social System Dynamics in the Columbia River Basin: Food-Energy-Water Resilience and Sustainability Modeling in the Yakima River Basin. *Frontiers in Environmental Science, 6*, 104. doi:10.3389/fenvs.2018.00104

Gastelum, J.R., Krishnamurthy, G., Ochoa, N., Sibbett, S., Armstrong, M. & Kalaria, P. (2018). The use of system dynamics model to enhance integrated resources planning implementation. *Water Resources Management, 32*, 2247-2260.

Haasnoot, M., Kwakkel, J.H., Walker, W.E. & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change, 23*, 485-498. https://doi.org/10.1016/j.gloenvcha.2012.12.006

Holling, C.S. (2001). Understanding the complexity of economic, ecological, and social systems. *Ecosystems, 4*, 390-405. https://doi.org/10.1007/s10021-001-0101-5

Hu, X., Hall, J.W., Shi, P. & Lim, W.H. (2016). The spatial exposure of the Chinese infrastructure system to flooding and drought hazards. *Nat Hazards, 80*, 1083-1118. https://doi.org/10.1007/s11069-015-2012-3

Inam, A., Adamowski, J., Halbe, J. & Prasher, S. (2015). Using causal loop diagrams for the initialization of stakeholder engagement in soil salinity management in agricultural watersheds in developing countries: A case study in the Rechna Doab watershed, Pakistan. *Journal of Environmental Management, 152*, 251-267.

Johnson, C.R., Banks, S.C., Barrett, N.S., Cazassus, F., Dunstan, P.K., Edgar, G.J., Frusher, S.D., Gardner, C., Haddon, M., Helidoniotis, F., Hill, K.L., Holbrook, N.J., Hosie, G.W., Last, P.R., Ling, S.D., Melbourne-Thomas, J., Miller, K., Pecl, G.T., Richardson, A.J., Ridgway, K.R., Rintoul, S.R., Ritz, D.A., Ross, D.J., Sanderson, J.C., Shepherd, S.A., Slotwinski, A., Swadling, K.M. & Taw, N. (2011). Climate change cascades: Shifts in oceanography, species' ranges and subtidal marine community dynamics in eastern Tasmania. *Journal of Experimental Marine Biology and Ecology*, *400*, 17-32. https://doi.org/10.1016/j.jembe.2011.02.032

Kinzig, A., Ryan, P., Etienne, M., Allison, H., Elmqvist, T. & Walker, B. (2006). Resilience and regime shifts: assessing cascading effects. *Ecology and Society, 11*, 1: 20.

Knox, J., Hess, T., Daccache, A. & Wheeler, T. (2012). Climate change impacts on crop productivity in Africa and South Asia. *Environ. Res. Lett., 7*, 3: 034032. https://doi.org/10.1088/1748-9326/7/3/034032

Koks, E. (2018). Moving flood risk modelling forwards. *Nature Climate Change, 8*, 561-562.

Kruse, J., White, R., Epstein, H., Archie, B., Berman, M., Braund, S., Chapin, F., Charlie, J., Daniel, C., Eamer, J., Flanders, N., Griffith, B., Haley, S., Huskey, L., Joseph, B., Klein, D., Kofinas, G., Martin, S., Murphy, S., Nebesky, W., Nicolson, C., Russell, D., Tetlichi, J., Tussing, A., Walker, M. & Young, O. (2004). Modeling sustainability of Arctic communities: An interdisciplinary collaboration of researchers and local knowledge holders. *Ecosystems, 7*, 815-828.

Latham, A.D.M., Latham, M.C., Cieraad, E., Tompkins, D.M. & Warburton, B. (2015). Climate change turns up the heat on vertebrate pest control. *Biol Invasions, 17*, 2821-2829. https://doi.org/10.1007/s10530-015-0931-2

Lawrence, J., Blackett, P., Cradock-Henry, N., Flood, S., Greenaway, A. & Dunningham, A. (2016). Synthesis Report RA4: *Enhancing capacity and increasing coordination to support decision making*. Climate Change Impacts and Implications (CCII) for New Zealand to 2100. MBIE contract C01X1225. Wellington: NZCCRI, Victoria University of Wellington; NIWA; Landcare Research.

Lawrence, J. & Haasnoot, M. (2017). What it took to catalyse uptake of dynamic adaptive pathways planning to address climate change uncertainty. *Environmental Science & Policy, 68*, 47-57. https://doi.org/10.1016/j.envsci.2016.12.003

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T., Izaurralde, R.C., Lambin, E., Li, S., Martinelli, L., McConnell, W., Moran, E., Naylor, R., Ouyang, Z., Polenske, K., Reenberg, A., de Miranda Rocha, G., Simmons, C., Verburg, P., Vitousek, P., Zhang, F. & Zhu, C. (2013). Framing sustainability in a telecoupled world. *Ecology and Society, 18*, 2: 26. https://doi.org/10.5751/ES-05873-180226

Li, J., Liu, T., Hashim, M. & Yao, L. (2019). System dynamics modeling: The impact of climate change on China's ecological water forecast evaluation. In Xu, J., Cooke, F., Gen, M. & Ahmed, S. (Eds.), Proceedings of the Twelfth International Conference on Management Science and Engineering Management (pp. 1341-1351). ICMSEM 2018. Lecture Notes on Multidisciplinary Industrial Engineering. Cham: Springer International Publishing, Cham, pp. 1341-1351.

Moser, S.C., Hart, J.A.F., 2015. The long arm of climate change: societal teleconnections and the future of climate change impacts studies. Climatic Change 129, 13–26. https://doi.org/10.1007/s10584-015-1328-z

Moxey, A., White, B. (1998). NELUP: Some reflections on undertaking and reporting interdisciplinary river catchment modelling. *Journal of Environmental Planning and Management, 41*, 397-402.

Nicolson, C.R., Starfield, A.M., Kofinas, G.P. & Kruse, J.A. (2002). Ten heuristics for interdisciplinary modeling projects. *Ecosystems, 5*, 4, 376-384.

Niiranen, S., Yletyinen, J., Tomczak, M.T., Blenckner, T., Hjerne, O., Mackenzie, B.R., Müller-Karulis, B., Neumann, T. & Meier, H.E.M. (2013). Combined effects of global climate change and regional ecosystem drivers on an exploited marine food web. *Glob Chang Biol, 19*, 3327-3342. https://doi.org/10.1111/gcb.12309

Ostrom, E. (2007). A diagnostic approach for going beyond panaceas. *PNAS, 104*, 15181-15187. https://doi.org/10.1073/pnas.0702288104

Pachauri, R. K. , Allen, M. R. , Barros, V. R. , Broome, J. , Cramer, W. , Christ, R. , Church, J. A. , Clarke, L. , Dahe, Q. , Dasgupta, P. , Dubash, N. K. , Edenhofer, O. , Elgizouli, I. , Field, C. B. , Forster, P. , Friedlingstein, P. , Fuglestvedt, J. , Gomez-Echeverri, L. , Hallegatte, S. , Hegerl, G. , Howden, M. , Jiang, K. , Jimenez Cisneroz, B. , Kattsov, V. , Lee, H. , Mach, K. J. , Marotzke, J. , Mastrandrea, M. D. , Meyer, L. , Minx, J. , Mulugetta, Y. , O'Brien, K. , Oppenheimer, M. , Pereira, J. J. , Pichs-Madruga, R. , Plattner, G. K. , Pörtner, H. O. , Power, S. B. , Preston, B. , Ravindranath, N. H. , Reisinger, A. , Riahi, K. , Rusticucci, M. , Scholes, R. , Seyboth, K. , Sokona, Y. , Stavins, R. , Stocker, T. F. , Tschakert, P. , van Vuuren, D. & van Ypserle, J. P. (2014). *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. R. Pachauri and L. Meyer (Eds). Geneva: IPCC, 151 p., ISBN: 978-92-9169-143-2

Pardoe, J. & Birkmann, J. (2014). Vulnerability cascades in multiple hazard risk assessment**.** In *Proceedings of the 5th International Disaster and Risk Conference: Integrative Risk Management - The Role of Science, Technology and Practice* (pp 552-555). Davos: IDRC Davos 2014.

Parliamentary Commissioner for the Environment. (2015). *Preparing New Zealand for rising seas: Certainty and uncertainty*. Wellington: Office of the Parialimentary Commissioner for the Environment.

Paterson Guma, I., Semwanga Rwashana, A. & Oyo, B. (2018). Food Security Policy Analysis Using System Dynamics: The Case of Uganda. *International Journal of Information Technologies and Systems Approach (IJITSA), 11*, 1, 72-90. doi:10.4018/IJITSA.2018010104

Pescaroli, G. & Alexander, D. (2016). Critical infrastructure, panarchies and the vulnerability paths of cascading disasters. *Nat Hazards, 82*, 175-192. https://doi.org/10.1007/s11069-016-2186-3

Räsänen, A., Juhola, S., Nygren, A., Käkönen, M., Kallio, M., Monge, A.M. & Kanninen, M. (2016). Climate change, multiple stressors and human vulnerability: a systematic review. *Reg Environ Change, 16*, 2291-2302. https://doi.org/10.1007/s10113-016-0974-7

Rocha, J.C., Peterson, G.D., Bodin, O. & Levin, S.A. (2018). Cascading regime shifts within and across scales. *bioRxiv*, 364620. Preprint. https://doi.org/10.1101/364620

Reyer, C., Bachinger, J., Bloch, R., Hattermann, F.F., Ibisch, P.L., Kreft, S., Lasch, P., Lucht, W., Nowicki, C., Spathelf, P., Stock, M. & Welp, M. (2012). Climate change adaptation and sustainable regional development: a case study for the Federal State of Brandenburg, Germany. *Reg Environ Change, 12*, 523-542. https://doi.org/10.1007/s10113-011-0269-y

Shimizu, M. & Clark, A.L. (2015). Interconnected risks, cascading disasters and disaster management policy: A gap analysis. *Planet@Risk, 3*, 2.

Smith, D. & Elliot, D. (Eds). (2006). *Key Readings in Crisis Management – Systems and Structures for Prevention and Recovery*. London: Routledge.

Stave, K.A. (2002). Using system dynamics to improve public participation in environmental social-ecologicaldecisions. *System Dynamics Review 18*, 139-167.

Sterman, J. D. (1994). Learning in and about complex systems. *System Dynamics Review, 10*, 2-3, 291-330.

Tidwell, V.C., Passell, H.D., Conrad, S.H., & Thomas, R.P. (2004). System dynamics modeling for community-based water planning: Application to the Middle Rio Grande. *Aquatic Sciences, 66*, 4, 357-372.

Tidwell, V.C., & Van Den Brink, C. (2008). Cooperative modeling: Linking science, communication, and ground water planning. *Groundwater, 46*, 174-182. doi:10.1111/j.1745-6584.2007.00394.x

Turner II, B., Esler, K.J., Bridgewater, P., Tewksbury, J., Sitas, N., Abrahams, B., Chapin III, F.S., Chowdhury, R.R., Christie, P., Diaz, S., Firth, P., Knapp, C.N., Kramer, J., Leemans, R., Palmer, M., Pietri, D., Pittman, J., Sarukhán, J., Shackleton, R., Seidler, R., van Wilgen, B. & Mooney, H. (2016). Socio-Environmental Systems (SES) research: what have we learned and how can we use this information in future research programs. *Current Opinion in Environmental Sustainability, 19*, 160-168. https://doi.org/10.1016/j.cosust.2016.04.001

Tyler, S. & Moench, M. (2012). A framework for urban climate resilience. *Climate and Development, 4*, 311-326. https://doi.org/10.1080/17565529.2012.745389

van den Belt, M. (2004). *Mediated Modelling: A systems dynamics approach to environmental decision making*. Washington: Island Press.

van Eeten, M.J.G., Loucks, D.P. & Roe, E.M. (2002). Bringing actors together around large-scale water systems: Participatory modeling and other innovations. *Knowledge, Technology and Policy, 14*, 94-108.

Vennix, J.A.M., Akkermans, H.A. & Rouwette, E.A.J.A. (1996). Group model-building to facilitate organizational change: an exploratory study. *System Dynamics Review, 12*, 39-58.

Walker, B., Holling, C.S., Carpenter, S. & Kinzig, A. (2004). Resilience, adaptability and transformability in social-ecological systems. *Ecology and society, 9*, 2: 5.

Walker, B.H., Abel, N., Anderies, J.M. & Ryan, P. (2009). Resilience, adaptability, and transformability in the Goulburn-Broken Catchment, Australia. *Ecology and Society, 14*, 1: 12.

Weisz, C. (2018). Resilient design: 'Systems Thinking' as a response to climate change. *Architectural Design, 88*, 24-31.

Wilbanks, T.J. & Kates, R.W. (2010). Beyond adapting to climate change: Embedding adaptation in responses to multiple threats and stresses. *Annals of the Association of American Geographers, 100*, 719-728. https://doi.org/10.1080/00045608.2010.500200

Williams, A., Kennedy, S., Philipp, F. & Whiteman, G. (2017). Systems thinking: A review of sustainability management research. *Journal of Cleaner Production, 148*, 866-881. doi:https://doi.org/10.1016/j.jclepro.2017.02.002

Willner, S., Otto, C. & Levermann, A. (2018). Global economic response to river floods. *Nat. Clim. Change* 8, 594-598. https://doi.org/10.1038/s41558-018-0173-2.

Winz, I., Brierley, G. & Trowsdale, S. (2009). The use of system dynamics simulation in water resources management. *Water Resources Management, 23*, 1301-1323.

Zevenbergen, C., Fu, D. & Pathirana, A. (2018). Transitioning to sponge cities: Challenges and opportunities to address urban water problems in China. *Water, 10*, 1230. https://doi.org/10.3390/w10091230