Appendices

Appendix 1. Issues raised at workshops

Hamilton workshop

Three Waters (including river protection structures)

- Increased risk of flooding will have knock-on implications for all different services. Economic viability within the catchment. Insurance (or not). Knock-on effect for people who live within the region. Public health risks associated with dampness. Schools impacted by this and the implications for mental health. Property values. Depress the economy.
- We may have gone past some of the thresholds for viable land use in some regions. Rates increases becoming untenable for both councils and farmers. As soon as we say we will no longer top up the stopbanks that will be the loss of that community (and a loss for many people). Unless we have a parallel way to get out. Will be legal challenges and huge ramifications. Some of the community do not believe in climate change.
- Perceptions of safety by citizens due to having stopbanks. Loss of storytelling. Need to pay if they want to go from a 50yr to a 100 yr scheme. Gold-plated scheme $$$. If locals can't pay, the wider community or central government pay. Cost to others. Debt caps exist however.
- Loss of stopbank could knock out key roading infrastructure. In particular SH25. Would have to change to SH2.
- Loss of stopbank impacts local communities (i.e., housing).
- Loss of stopbanks impacts on agriculture and farming communities.
- Bigger pipes could lead to benefits for fish passage, etc.
- Need to ensure wastewater is dealt with to protect water supply.
- Important to maintaining commercial viability.
- Financial implications if wastewater is knocked out.
- Cows on the Hauraki plains are reliant on water schemes (treated water?).
- Citizens requiring water.
- Important for all businesses.
- Important for commercial facilities (including farms).
- Loss of stopbanks could have important improvements in terms of environmental services (assuming they are not fixed). SLR will impact the peat dome and its capability. Increased magnitude and duration of water, stripping oxygen. Increased sedimentation. Can cause more sedimentation.
- Routine failure of stopbanks may reach a point where it is untenable for this to continue in terms of cost to communities.
- Loss of airport from the pumps no longer functioning due to losing electricity.

Utilities (i.e., electricity, gas)

- Loss of power will have implications for communications systems.
- Loss of power may impact pump stations ability to function (especially with potential loss of substations).
- Loss of power will impact function of pumps for water supply.
- Loss of power, and thus pumps, may lead to the loss of the hospital.
- Loss of power makes Thames airport vulnerable to flooding inundation due to pumps no longer working.
- Citizens who require electricity for dialysis, etc., will be affected by loss of power.

- Limited high-voltage power lines in the region. Transformers around pump stations were below the ground but have been raised (before SLR was even a consideration).
- No gas lines in this region.

Commercial / financial

- Cost of impacts may be beyond the means for the communities / ratepayers.
- Risk assessment for banks in terms of infrastructure they are funding.
- Loss of jobs from loss of industries (i.e., farming communities)
- Local landowners are blaming the wetland/peat near Kuatai due to it now releasing water.
- Farmers thinking wetlands causing the flooding and koi carp are causing the sedimentation (even though this is not true).
- Commercial consequences will affect the return and money being generated in the local community.

Environmental

- Risk to human and animal health from water borne diseases. e.g., facial eczema.
- Ecosystem function of the peat may be compromised causing ramifications for other ecosystem services if it was acting the way it should as a RAMSAR site.
- Ability of the peat to deal with stormwater compromised.
- Recreational value of the peat dome affected by changes. Has gone from being a receiver of water to now being a contributor (i.e., acting like a modified sponge, which has now reached saturation). Cultural implications for Māori and others in terms of the wetland. Now very difficult to get any resource consent to build duck ponds (or any modification), so most is historical. If a level of service is withdrawn then there may be risks to the council due to having it go through the courts.
- Sedimentation and impacts on environment affecting fishing / mussel farming communities.
- Service industries will be affected by all of these.

Transport Infrastructure

- Loss of transport will impact cost of food, etc.
- Road closure will impact ability of citizens to get around. Clay at risk from drought. Coastal roads will need to be raised due to SLR.
- Communications highly reliant on the same infrastructure lines as transport (i.e., bridges and roads).
- Rivers had in the past been restricted by bridges and other infrastructure. These have been increased to improve resilience.
- Raising roads has challenges for other infrastructure (and ecosystem services).
- If the roading infrastructure is knocked out then it become untenable to maintain some of the regions industries. May change to becoming reliant on shipping (and then a part of Auckland Council?).

Governance

- A lot of non-rateable land. i.e., roads, schools, conservation land. Will be an exacerbator of the governance challenges. There are obvious deficiencies in the current funding model because the Crown does not pay rates. We will all have to pay for the costs eventually.
- Levels of service will change over time. Risk currently not put on LIMS due to it not being a requirement (because an expectation of a level of services). Amazing how little education there is about risk.Excellent illustration of disensus.
- Estimated that approximately 1/3rd of ratepayers don't live in the Coromandel region.

- Not enough ambulances in the region to move people to other regions if there is a need.

Christchurch workshop

Three Waters

- Groundwater (GW) and wastewater (WW)– as GW increases, connects to WW – as GW increases, infiltration decreases, inflow increases.
- GW to stormwater (SW) – will inundate the SW network, reduce capacity (long-term increase in GW due to SLR).
- Rising GW leads to more damp homes, asthma, and other health outcomes.
- Roads and SW – surcharge of SW leads to flooding of roads..
- GW and roading – loss of subgrade strength/capacity ('soft roads').
- GW to Commercial facilities – buildings, schools, hospitals, shops (social infrastructure).
- WW to Nature – WW spills lead to contaminated streams (human health issue), WW to Health.
- Stormwater System to many – flooding from rivers.
- Groundwater to Nature – salinity in water ways, backs up, impacts on the plants that grow on the side of streams.
- Stormwater System to Nature – discharge of contaminants.
- Integrity of pipes from saline intrusion – Flockton Basin only 13-14 m asl.
- City water supply currently sourced from 18 different bores.

Governance

- Governance (financing and infrastructure) – connects to critical lifelines: water supply, emergency services – governance at all levels, including national.
- Governance to emergency services (ES) – critical for wellbeing of city – council needs to know ES are operating and functioning:
    - There is a residual risk increase, during flood event, call outs increase, more frustrated citizens – they want to know ES are up and operational; council faces increased demands for information during an emergency/hazard event, needs to prioritise ES (additional demands, logistics, admin, etc.).
    - More the capability of sector (ES) or Civil Defence (Capability and capacity) impacts on ES link with Governance.
    - Need to establish what infrastructure strategies look like now.

Infrastructure (Electricity and grid/network)

- Electricity a driver – gets disrupted by events – business, communications, and housing.

Financial services

- Financial services and link(s) to create 'safety paradox' – goes to storm systems, water supply, wastewater, and making good decisions – strategic planning . . . what do current infrastructure strategies look like?

Iwi

- Connect governance to people – Ngāi Tahu – proactive, multigenerational, holistic, integrating mitigation and adaptation.
- Iwi have an advantage – Māori have advantages in terms of long-term perspective; coastal marae near CHC partnering with drone technologies to move marae away from the coast to meet challenges of rising sea; moving repeatedly in HB, expressed preference to continue managed retreat, and soft protection (not hard protection), deliberate wetland creation.

Other linkages

- Canterbury dependent on agriculture – if nature affected by climate change may affect job opportunities in region.
- Drought – summer restrictions on water use a consequence.
- Spatial plans – how do spatial plans get ongoing renewal and in relation to three waters?
- Planning – short-term actions and long-term planning beyond the three year cycle, shift to 100-year planning, proactive and holistic rather than reactive.

Appendix 2. A review of literature relavant to cascading climate change impacts

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Introduction

This review forms part of the Deep South Science Challenge (DSC) project: *Cascading Climate Change Impacts and Implications for Aotearoa, New Zealand.* The aim of the project is to better understand the scale and scope of cascading impacts and implications across New Zealand to inform adaptation over at least the next 100 years. Climate change will have significant impacts and implications for diverse communities, sectors, and activities. International research (Adger *et al.*, 2009; IPCC, 2014) and previous research conducted in New Zealand (Lawrence *et al*., 2016) suggest these impacts will have wider spatial and temporal effect than might otherwise be expected. Beyond the immediate location of impact, climate change will have flow-on effects for ecosystem functionality, economies, social systems, and governance. This has significant implications for adaptation planning and preparedness for future climate conditions.

The focus of the project is on the impacts for urban, infrastructure (including drinking water, storm water, and waste water ('three waters'), and the financial services sector. The type of climate change impacts considered include *Slowly emerging impacts – s*ea-level rise, and rising groundwater levels; *Widening climate variability* – drought, increased flood frequency, and coastal flood frequency; *Extremes* – coastal storm surge, intense rainfall, and wind; *Surprises* – accelerated sea-level rise; and *Combined impacts* – sea-level rise and flooding, and intense rainfall and landslip.

Particular attention is given to how the cascades interact, what and who is affected, the dependencies, inter-dependencies, external effects, the compounding effects of policy responses and how far they extend across multiple sectors. The governance implications of cascading impacts and the barriers to adaptation that flow from those implications are also examined.

Gaining insight into the scope of interconnectivity between internal and external stressors and sectors will support adaptation planning, help avoid maladaptation, and mitigate the likelihood of negative cascades across the economy (Cash *et al*., 2006; Wilbanks & Kates, 2010). This understanding will help inform how stakeholders conceptualise impacts and implications, and facilitate the development of linked-up approaches to adaptation planning that consider upstream and downstream decision implications (Eakin *et al*., 2009; Fleming *et al*., 2014). In addition, identifying and disentangling the cascade of impacts and implications will provide a qualitative basis for future quantitative systems models within the Deep South Challenge (DSC).

A consistent framing is required for examining cascades and for understanding the stressors within and between the different domains of interest. As an input to developing such a framework, this systematic review of the literature has been undertaken to examine the theoretical origins of cascades as a concept, and empirical studies undertaken that describe and analyse climate change relevant cascading impacts and implications. This enables the gap in understanding of cascades of climate change impacts to be filled within and across domains of interest to Deep South. Such understanding will inform risk and vulnerability assessment,

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the identification of trigger points for decision making, and thus build adaptive capacity amongst decision makers and advisors to shift from *post hoc* modes of decision making to anticipatory modes in a changing climate risk context.

Methods

The following review is based on a hybrid approach, combining systematic and selective review methods. Systematic reviews are well suited for synthesising large or extensive bodies of literature. Systematic reviews use reproducible, methodological strategies to select, critically appraise, synthesise, and analyse textual data, thereby reducing reviewer bias and increasing transparency (Berrang-Ford *et al.*, 2015). Given the breadth of literature on impacts of climate change, we initially thought a systematic review would be necessary to collate the existing literature, summarise and analyse the results to inform the research design. A detailed review protocol was prepared and applied (see Appendix 1). The transparent method of knowledge collection and analysis in a systematic review allows for easy data validation and replication, while the typically large scope of the review helps generate new insight across existing work.

We first followed the multi-step systematic review process, including development and documentation of the research question and research protocol, progressive literature search and refinement, data extraction, synthesis, and analysis (Khan et al., 2003; Higgins & Green, 2008). Table 1 outlines the inclusion and exclusion criteria applied during the literature search and refinement stages of the review.

However, after applying the systematic review protocol we identified several key themes and papers that had been excluded from our search results because of the narrowly defined search parameters. The iterative literature search process effectively focused with increasing detail on a smaller and smaller subset of papers. Only papers that met all search criteria were included in the initial results, which excluded some other useful literature. To address this shortfall, we conducted a selective review to supplement the initial search results. The papers included in the selective review were drawn from a broader literature base extracted from a systematic review process (Petticrew & Roberts, 2006; Higgins & Green, 2008), expert knowledge, and our own familiarity with the climate change literature.

There were three objectives for the review:

1. Develop a general understanding of how cascading impacts have been characterised, in particular for climate change impacts.
2. Show how cascading impacts have been identified and in what contexts.
3. Develop evidence of cascading effects of climate change drivers to inform future quantitative and probabilistic risk modeling activities within the DSC and the DSC *Impacts and Implications* programme of research; for example, develop a typology of cascades for urban systems, critical infrastructure – including the 'three waters' – and financial services.

Inclusion Criteria	**Exclusion Criteria**
Type of study: article, book, book chapter, working paper, report, conference paper, or thesis	Type of study: NOT article, book, book chapter, working paper, report, conference paper, or thesis
Substantial focus on dynamics and connections (cascades) of climate change impacts (drought, climate variability, extreme events, sea-level rise)	Not substantial focus on dynamics & connections of climate change effects

Substantial focus on infrastructure, financial services, and governance	Not substantial focus on sectoral climate change effects
International and New Zealand focused	Not international and New Zealand focused
English language publication	Non-English language publication
Published since a date when IPCC was set up for an initial scan and then on or after 1 January 2004 and on or before 3 November, 2017	Not published on or before 3 November, 2017, or on or after 1 January, 2004

Table 1. Inclusion and exclusion criteria used in the literature search and document selection phase.

The rationale for 2004 as our start date is the effect of the 2004 RMA Amendments in New Zealand, which require those with functions under the RMA to have particular regard to the effects of climate change.

Search terms were compiled to capture the full range of relevant research outputs associated with climate change adaptation and the relevant domains of interest (Table 1). Article screening (Table 2) enables the search returns to be fit for purpose by filtering papers and reports to match the targeted search criteria and constraints. The screening steps (Table 3) clarify the robust and repeatable process carried out to remove irrelevant and duplicate returns from the search outputs.

The application of the systematic review protocol returned a small number of focused studies relating to cascading impacts and implications. Based on the researchers' familiarity with the climate adaptation literature, we expanded our search terms for the review to include related terms such as 'teleconnections', 'multiple interacting stressors', and 'double exposure'. We manually searched the Scopus, Web of Science, Science Direct, Google Scholar, and Google Web databases and screened results for relevance on the keyword, title, abstract, and full text level according to the inclusion and exclusion criteria (Table 1, Appendix 1). Table 2 summarises the categories we used in the data extraction, organisation, and analysis stage of the literature review. If the search terms were present in any of the search fields, we included the result in the initial phase of literature collection (Table 3, Phase 1). Our literature database included the full bibliographic citation information for each search result and was cleaned up from exact duplicates (Table 3, Phase 2). After inclusion/exclusion screening was completed, our final body of literature included 162 studies (Table 3, Phase 3).

Table 2. Search strategies and terms used in ISI Web of Science, Scopus, and Google Scholar[9]

Category	Examples	Search terms
Climate Change Physical	Changes in Temperature • Temperature increase • Temperature decrease • Drought / water scarcity Changes in Rainfall • Precipitation increase • Precipitation decrease • Increased rainfall Hailstorms	climat* change*" OR "global warming" OR "change* in climate" "greenhouse effect*" AND Temperat*, Precip*, Sea level rise*, sea level chang*,glacier*, Extrem*, Drought*, Coast*, Erosion, (flash)flood*, drought, hail*, etc.

[9] Note that structure of search chains will vary to account for differences in database interfaces.

	Flood Sea-level rise/coastal inundation Glacier change	
Climate Change Socio-economic	Adaptation Vulnerability Adaptive Capacity Exposure	Adapt*, Vulnerabilit*,"adapt* capacity*", Exposur*, "Doubl* exposur*, Livelihood*, etc.
Sectors of interest	Infrastructure • Mobility/Transport • Electricity • Water • Buildings Financial Services • Insurance • Banking/Trade Government/governance • Local • Regional • National	Infrastructure, insur*, Bank*, Gov*, Tech*, transport*, electric*, primary* production, agricultur*, water, etc.
Dynamic – Connections	Linkages Tipping points Interdependencies Scale	cascad*, implication, link*, impact*, cascad*, inter*, interdepend*, nexus, tip* point, creep*, multilevel, multiscale, threshold*, turn* point*
Resilience	Social Resilience Economic Resilience Resilience of the Built Environment Resilience of the Natural Environment Cultural Capital Governance of Adaptation, Risk & Resilience	Leadership, Polic*, Strateg*, Safety, security, Infrastructure*, Building*, hous*, urban, growth, design, Engineering, "Resourc* Management", land-use plan*, adapt*, "culture* valu*, identit*, tradition*, knowledge*, practice*, "social capital", health*, education*, insuran*, etc.

Table 3. Screening Steps (iterative)

1.	All returns on international/NZ general inquiry on cascades
2.	Duplicates removed
3.	After title screen
4.	After abstract read/article scan
5.	First iteration complete & repeat cycle with specific search terms
6.	Final considered

After applying exclusion criteria, the search resulted in a total of 162 publications. The title and abstract (or executive summary) of each document was assessed according to the general objectives of this review. This further reduced the number of results to 58, which were subsequently analysed in more detail. For each result, 12 data points were collected and summarised as per Table 4.

Table 4. Coding categories

Category	Details
Bibliographic details	Author(s), title, publication data
Study context	Research question(s)
	Sector(s) examined
	Climate stressor(s) examined
	Nature of study
Responding to Cascade(s)	Did the report/paper focus on specific stakeholders?
	Did the report/paper focus on specific sectors – which ones?
	Did the report/paper focus indicate specific adaptation actions?
Other	Gaps identified
	Researcher comments

Thereafter, articles were summarised according to four criteria:

1. Was the paper of relevance to the climate stressor and domain of interest?
2. A summary of the study methods;
3. Findings; and
4. Lessons for adaptation in New Zealand.

The review

This review presents the literature relevant to cascading climate change impacts and implications for adaptation policy and practice in New Zealand, using an annotated bibliographical style.

Publications are listed alphabetically within each thematic area (by first author) with academic literature presented first, followed by any non-peer reviewed literature (e.g., conference papers, or working papers). A short overview is provided at the start of each thematic section and a summary of the key literature and its contribution to the types of climate change impacts and domains of DSC interest (urban, infrastructure, and financial sectors) is presented in the final section of the review. Each thematic section includes a summary of the research, the methodology used, the findings, and the lessons for adaptation in New Zealand.

The report is organised around the following themes:

a. Conceptual/ theoretical basis for cascades
b. Physical processes, ecosystem, and human-environment cascades
c. Multiple hazard cascades, tipping points of harm, thresholds, and surprises
d. Infrastructure cascades of floods and droughts
e. Urban systems
f. International supply chain cascades
g. Cascading impact of policy responses
h. Impact tools/network analysis
i. Governance

a. Conceptual basis for cascades

These papers provide a conceptual basis from which cascades can be placed. They include discussion of the institutional and political challenges surrounding change that moves through domains in society, the interactions between hazards and societal response and how threshold effects challenge notions of resilience in practice.

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

1. About: The authors analyse a set of institutional and political leadership challenges posed by cascading ecological crises: abrupt ecological changes that propagate into societal crises that move through systems and spatial scales.
2. Summary of methods: It integrates two, until now separate but complementary, streams of research: These are, one, crisis management studies with a strong emphasis on organisational theory and political decision making (for example, Boin et al., 2005; Smith & Elliot, 2006); and two, interdisciplinary studies of crises and change in complex and interacting social and ecological systems – henceforth social-ecological systems (for example, Folke et al., 1998; Ostrom, 2007).
3. Findings: The authors conclude their account of cascading ecological crises with three conclusions: CECs are notoriously hard to detect in advance because of their underlying complexities and poor monitoring systems; CECs challenge decision-making and coordinating capacities of actors at multiple levels of societal organisation because of their cascading and recombining capacities; CECs are prone to blame games, which hinder post-crisis learning and reform.

4. Lessons for adaptation in New Zealand: invest in innovative monitoring systems, avoid faulty crisis communication (blame games), and record instances where institutions were able to successfully manage crises across scales, sectors, and levels.

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

1. About: The paper combines research and commentary to reinforce the importance of integrating hazard interactions and interaction networks (cascades) into multi-hazard methodologies. The authors present a synthesis of the differences between multi-layer single hazard approaches and multi-hazard approaches that integrate such interactions.
2. Summary of methods: The authors, first, describe and define natural hazard, anthropogenic processes and technological hazards/disasters, second, outline three types of interaction relationships (triggering, increased probability, catalyse/impedance), third, assess the importance of networks of interactions (cascades) through case study examples, and fourth, propose two visualisation frameworks to present cascades.
3. Findings: The three groups of hazards described by the authors interact in a number of ways; three interaction relationships are discussed here. The authors also find that these interactions could potentially join together and form a network of interactions, chain, or cascade events. The visualisation of the latter specifically highlights changes in vulnerability.
4. Lessons for adaptation in New Zealand: Understanding interactions and interaction networks helps New Zealand to better, one, model the observed reality of disaster events, two, constrain potential changes in physical and social vulnerability between successive hazards, and three, prioritise resource allocation for mitigation and disaster risk reduction.

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. URL: http://www.ecologyandsociety.org/vol11/iss1/art20

1. About: The paper proposes a general model of threshold interactions in social-ecological systems (SES).
2. Summary of methods: The authors analyse four regions in the world to develop a proposed general model of threshold interactions in social-ecological systems.
3. Findings: SES have multiple threshold effects associated with a number of different controlling, slow variables that operate at different spatial and temporal scales and in different domains. The proposed model identifies patch-scale ecological thresholds, farm- or landscape-scale economic thresholds, and regional-scale socio-cultural thresholds. “Cascading thresholds,” in other words, the tendency of the crossing of one threshold to induce the crossing of other thresholds, often lead to very resilient, although often less desirable, alternative states.
4. Lessons for adaptation in New Zealand: There is not yet a systematic approach to dealing with threshold interactions. The paper gives a first indication of the domains and scales at which the most critical threshold interactions are likely to occur.

Pescaroli, G. & Alexander, D. (2015). **A definition of cascading disasters and cascading effects: Going beyond the 'toppling dominos' metaphor.** *Planet@Risk,* 3, 1, 58-67. Special Issue on the 5th IDRC Davos 2014, March 2015.

1. About: The paper offers a definition of cascading disasters that is suitable for both field and theoretical use.
2. Summary of methods: The paper presents a literature review on cascading disasters.
3. Findings: Definitions provided by the authors: *Cascading effects* are the dynamics present in disasters in which the impact of a physical event or the development of an initial technological or human failure generates a sequence of events in human subsystems that result in physical, social, or economic disruption. Thus, an initial impact can trigger other phenomena that lead to consequences with significant magnitudes. Cascading effects are complex and multi-dimensional and evolve constantly over time. They are associated more with the magnitude of vulnerability than with that of hazards. Low-level hazards can generate broad chain effects if vulnerabilities are widespread in the system or not addressed properly in sub-systems. For these reasons, it is possible to isolate the elements of the chain and see them as individual (subsystem) disasters in their own right. In particular, cascading effects can interact with the secondary or intangible effects of disasters. *Cascading disasters* are extreme events in which cascading effects increase in progression over time and generate unexpected secondary events of strong impact. These tend to be at least as serious as the original event, and to contribute significantly to the overall duration of the disaster's effect. These subsequent and unanticipated crises can be exacerbated by the failure of physical structures, and the social functions that depend on them, including critical facilities, or by the inadequacy of disaster mitigation strategies, such as evacuation procedures, land-use planning, and emergency management strategies. Cascading disasters tend to highlight unresolved vulnerabilities in human society. In cascading disasters, one or more secondary events can be identified and distinguished from the original source of disaster.
4. Lessons for adaptation in New Zealand: These definitions might help reflect on New Zealand cascading effects and disasters.

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

1. About: This paper proposes a new theoretical approach to cascading events in terms of their root causes and lack of predictability.
2. Summary of methods: Interdisciplinary theory building.
3. Findings: The authors suggest that vulnerability of critical infrastructure may orientate the progress of events in relation to society's feedback loops, rather than merely being an effect of natural triggers. In other words, cascading disasters are rooted in society's feedback loops, whereby corruption, negligence, maximisation of profit, and the structural weaknesses of the global social-economic system should be seen as causes to be studied and addressed. Subsequently, the authors suggest shifting attention from risk scenarios based on hazard to vulnerability scenarios based on potential escalation points.
4. Lessons for adaptation in New Zealand: The paradigm shift in the preparedness phase that the authors claim to identify could include escalation points and social nodes. Following their logic, clarifying what those are in the New Zealand context might enhance preparedness.

Shimizu, M. & Clark, A.L. (2015). **Interconnected risks, cascading disasters and disaster management policy: A gap analysis.** *Planet@Risk, 3*, 1. Special Issue on the 5th IDRC Davos 2014, March 2015.

1. About: The paper provides a comparative analysis of the Tohoku and Hurricane Katrina disasters, highlighting specific issues that arose, their resulting impacts, and the adequacy of the response(s) in terms of existing governance, policy, and institutional structures.
2. Summary of methods: Case study comparison.
3. Findings: The assessment focuses on interconnected issues (public policies, infrastructure, economies, production and supply chains, and risks and uncertainties). The authors find that existing disaster management policies and programmes are deficient in most areas, largely attributed to the inability to adapt to a 'new normal' of interconnected risks, cascading disasters, and unexpected consequences.
4. Lessons for adaptation in New Zealand: There is a need to define and understand interconnected risks in New Zealand, as well as the structure and impact of such disasters. Drafting policies and strategy plans on how to react to such complex problem constellations in New Zealand, and creating systemic coordination and linkages between national and local entities and among different sectors will be a step change in building capacity to respond to (future) cascading disasters.

b. Physical processes, ecosystems, and human-environment cascades

This theme examines the cascading effects of terrestrial and marine systems for other physical, ecosystems, and human-environment domains.

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

1. Ecosystem-based management (EBM) has emerged as the generally agreed strategy for managing ecosystems, with humans as integral parts of the managed system. Human activities have substantial effects on marine ecosystems through overfishing, eutrophication, toxic pollution, habitat destruction, and climate change. It is important to advance the scientific knowledge of the cumulative, integrative, and interacting effects of these diverse activities, to support effective implementation of EBM.
2. This article presents a summary and synthesis of publications, highlighting current and future challenges in the Baltic Sea ecosystem.
3. Based on contributions to a special issue of *AMBIO*, the paper presents a synthesis of scientific findings categorised into four components: pollution and legal framework; ecosystem processes; scale-dependent effects; and innovative tools and methods. The authors conclude with challenges for the future and identify the next steps needed for successful implementation of EBM in general and specifically for the Baltic Sea.
4. The paper highlights impacts that already exist in marine ecosystems across different domains and that interact to exacerbate their effect. The cumulative nature of these impacts demonstrates the importance of ecosystem-based management to better understand the systems and processes that climate change cascades will affect. This general conclusion has currency across the domains of interest to this research project.

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*, 2, 350-359. Doi: 10.1080/24694452.2016.1243039

1. This paper reviews international research on human impacts of glacier meltwater variability in mountain ranges worldwide, including the Andes, Alps, greater Himalayan region, Cascades, and Alaska. It identifies four main areas of existing research: socioeconomic impacts; hydropower; agriculture, irrigation, and food security; and cultural impacts.
2. This study uses a systematic review methodology to refocus the glacier-water problem around human societies, rather than simply around ice and climate. By systematically evaluating human impacts in different mountain regions, the paper stimulates cross-regional thinking on glaciers, hydrology, risk, adaptation, and human-environment interactions in mountain regions.
3. The article challenges a fundamental paradigm driving glacier runoff research: that shrinking glaciers lead inevitably and immediately to water scarcity for societies – an underlying assumption that hinges on environmental determinism. It reinforces the need for more social science and humanities voices in global environmental change research. The paper suggests paths forward for social sciences, humanities, and natural sciences research that could more accurately detect and attribute glacier runoff and human impacts, grapple with complex and intersecting spatial and temporal scales, and implement transdisciplinary research approaches to study glacier runoff.
4. Framing physical processes cascading from climate changes to human systems helps to demonstrate the challenge for adaptation. This enables us to visualise the wider implications of cascading impacts for societal functioning – a generic lesson for New Zealand adaptation.

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., Slotvvinski, 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*, 1-2, 17-32. Doi: 10.1016/j.jembe.2011.02.032

1. This paper presents unequivocal evidence of fundamental changes to ocean circulation and the physical parameters of waters off south-eastern Australia. However, the links to changes in species distributions, with concomitant downstream effects on community structure and dynamics, and on local economies, are unclear. These links become important given the concentration of biodiversity, very high levels of endemism, and the high economic value of recreational and commercial fisheries in south-eastern Australia in general and Tasmania in particular.
2. The study used a number of approaches to compile a synthesis, including system measurements, GIS-based assessments and surveys of genetic diversity and genetic differentiation using genetic markers and field observations across large scales under different conditions across several decades, tagging and recapture studies, and updating of data from historical records.
3. This paper demonstrates significant and cascading impacts of ocean warming off the east coast of Tasmania as a result of the intensification of the East Australian Current (EAC). This in turn leads to large changes in marine systems in eastern Tasmania. Decline in certain species as a result of range-extending sea urchins poses significant threat to rocky

reefs and key fisheries. Large-scale oceanographic change is reflected in changes in zooplankton communities and dramatic decline in giant kelp beds, precipitating cascading ecological change. The observed changes encompass range expansions and a diverse array of fish species, and changes in abundance of key species, such as giant kelp beds and pelagic species, and increased abundance of a range of coastal fishes.
4. The cascading effects of ocean warming demonstrate the complex and compounding impacts possible in ecosystems. This is of generic interest to adaptation, highlighting potential commercial implications and the inter-dependence of sectors, with changing climate.

Johnson, J. E. & Welch, D. J. (2010). **Marine fisheries management in a changing climate: A review of vulnerability and future options.** *Reviews in Fisheries Science, 18*, 1, 106-124. Doi: 10.1080/10641260903434557

1. This paper presents vulnerabilities of marine fisheries and their responses to climate change. These include exposure to increasing sea surface temperatures, ocean acidification, sea-level rise, increasing storm intensity, and altered ocean circulation and rainfall patterns. These in turn will affect target species through a range of direct and indirect mechanisms. The sensitivity of fish stocks to these changes will determine the range of potential impacts to life cycles, species distributions, community structure, productivity, connectivity, organism performance, recruitment dynamics, prevalence of invasive species, and access to marine resources by fishers.
2. Using a vulnerability assessment framework, this study examines the level of vulnerability of marine fisheries to climate change and the factors that will temper vulnerability, such as adaptive capacity. This type of approach does not rely on extensive datasets and can incorporate expert judgments and local knowledge to assess vulnerability and ultimately assist management.
3. The study found that as climate change places additional pressure on already strained fisheries productivity, consideration of social resilience can be undertaken under data-limited circumstances, managed for long-term ecological and economic stability, and set outside traditional boundaries. Although some degree of change in marine fisheries is inevitable, the extent of that change will depend not only on mitigation but on how rapidly fisheries management can respond and how flexible it can be.
4. Climate change provides an opportunity to evaluate systems management with a longer-term view. The ability of management approaches to adapt to climate change will be critical to the values at stake in any system and for the social and economic values the system provides. Consideration of these interdependencies through adaptation will require resources, responsiveness, and bold thinking both internally and external to New Zealand.

Milner, A., Khamis, K., Battin, T., Brittain, J., Barrand, N., Fuereder, L., Cauvy-Fraunie, S., Gislason, G. M., Jacobsen, D., Hannah, D., Hodson, A., Hood, E., Lencioni, V., Olafsson, J., Robinson, C., Tranter, M. & Brown, L. (2017). **Glacier shrinkage driving global changes in downstream systems.** *Proceedings of the National Academy of Sciences of the United States of America (PNAS), 114*, 37, 9770- 9778. Doi: 10.1073/pnas.1619807114

1. This research looks at the implications of shrinking glaciers globally for cascading impacts on downstream systems. Changes in river hydrology and morphology caused by climate-induced glacier loss are projected to be the greatest of any hydrological system, with major implications for riverine and near-shore marine environments. In particular, the

study identifies alterations to hydrological regimes, sediment transport, and biogeochemical and contaminant fluxes from rivers to oceans. The flow-on effects are to biodiversity and ecosystems services that glacier-fed rivers provide to humans, for example, water for agriculture, hydropower, and human consumption.

2. A new integrated conceptual model was developed of how discharge, nutrients, ecological communities, and ecosystem services respond as glacial cover decreases over time with ongoing climate warming.
3. Although the impact of melting glaciers on sea levels has received much attention to date, the authors found that other multiple downstream effects will alter riverine ecosystems with significant societal implications. There will be major changes to flow regimes in catchments fed by glaciers, with a shift to greater stochasticity as glacial runoff decreases and flow becomes more dependent on unpredictable precipitation events and snow melt. The authors conclude that adaptation measures must address all impacts across jurisdictions.
4. This is an example of a cascade narrative that can inform the consideration of other physical systems affected by changing climate. It demonstrates the wide flow-on effects across physical and social domains from a change in a physical hydrologically-relevant process.

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

1. About: The authors demonstrate the relationship between warmer winters and pest control.
2. Summary of methods: The authors use a data collection from Cromwell, Central Otago. The district is defined as rabbit-prone. The authors combined information from three climate stations. The authors defined rules for programming climate and rabbit data in relation to each other.
3. Findings: A trend towards warmer winters of the past >60 years has significantly reduced the window of time for effective control of invasive mammalian pests in temperate New Zealand. The phenomenon described is likely generalisable to the control of other vertebrate pests, particularly in temperate systems where they are seasonally food-limited. Climate change may exacerbate the unwanted impacts of invasive species by reducing our ability to manage them effectively.
4. Lessons for adaptation in New Zealand: The findings suggest that new ways of pest control are necessary already, and even more so in the future.

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.

1. About: This paper presents a resilience-based approach for assessing sustainability in a sub-catchment of the Murray-Darling Basin in south-eastern Australia.
2. Summary of methods: The paper applies a resilience framework in a case study analysis. The authors use ideas from the workbook of the Resilience Alliance.
3. Findings: The development path of the Goulburn Basin region is marked by increasing investment in infrastructure and growing reliance on agricultural processing sectors that are vulnerable to a rising water table. This has reduced the intrinsic value of biodiversity. Diversions of water for irrigation reduced the resilience and compromised the intrinsic and other values of riverine ecosystems. The authors propose that the resilience of the region

depends on: values (tipping point between market values vs. preferences for non-market, intrinsic, and option values); size of dairy and fruit processing sectors; financial viability of farms (depending on water allocation, price for irrigation, and farm area salinised); condition of irrigation and water pumping infrastructure; tree cover; water table depth and area salinised; soil acidity; and condition and functioning of riverine ecosystem. The authors state that it is necessary to devolve more resources, responsibilities, and authorities to the CMAs (catchment management authorities) and to become more effective in bridging organisations, and operating across scales and sectors.

4. Lessons for adaptation in New Zealand: New Zealand can learn from the relevant features covered here and could take those as reference points for regional adaptation and transformation ideas.

c. Multiple hazard cascades, tipping points of harm, thresholds, and surprises

Papers in this category present insights into cascading impacts in specific regional and local contexts.

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,* 10, 848-863. Doi: 10.1093/biosci/biw110

1. This paper explores a significant climatic event that affected a marine-dominated coastal system and a terrestrial polar desert ecosystem in Antarctica during the austral summer of 2001–2002. Both sites experienced winds that warmed air temperatures above the 0°C threshold, resulting in extensive snow and ice melt and triggering a series of cascading effects through the ecosystems that are continuing to play out more than a decade later. This study highlights the sensitivity of Antarctic ecosystems to warming events, which should occur more frequently in the future with global climate warming.
2. The study presents a case study analysis on the climatic setting and ecological response of two sites representative of polar ecosystems, a marine-dominated coastal system and a terrestrial polar desert, in Antarctica during a significant climatic event that affected both ecosystems.
3. Both polar sites were exposed to unusually warm winds, which had a dramatic effect for three reasons: First, the summer climate is close to the freeze or thaw threshold, and small changes in available energy (air temperature, solar radiation) create a highly nonlinear response in precipitation and hydrology between the dry, frozen state and the wet, thawed state. Ecosystems dependent on or threatened by one state or the other respond accordingly in a dramatic manner. Second, the space for terrestrial habitat in Antarctica is quite limited, conferring an island-type geography with little or no space for refuge or migration for highly adapted species in response to rapid environmental change. Consequently, a pulse event can severely alter, if not eliminate, an otherwise thriving ecosystem. Third, episodic pulse events in nutrient-poor, energy-limited environments have long legacy effects that perturb the environment and limit recovery.
4. This paper demonstrates the sensitivity of some ecosystems to threshold conditions being triggered and that such ‘events’ are likely to be triggered more frequently with climate change. The paper also demonstrated that some systems have small coping ranges as change becomes more rapid, and thus limited recovery. Understanding such concepts has significant implications for adaptive management of systems whether bio-physical or human.

Niiranen, S., Yletyinen, J., Tomczak, M., Blenckner, T., Hjerne, O., MacKenzie, B., Muller-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**. *Global Change Biology, 19*, 11, 3327-3342.

1. During the past decades many of the world´s marine ecosystems have experienced large-scale reorganisations caused by intensive exploitation of marine resources in combination with climate changes. One of the most effected ecosystems is the Baltic Sea, which has been affected by a combination of, for example, persistent eutrophication and intensive fishing, and during the last two decades of the 20th century being exposed to one of the world's fastest rates of warming. Model projections show that this region will be subject to accelerated climate changes, including atmospheric warming and changes in precipitation during the 21st century. This study addresses the question of how marine ecosystem processes and the provisioning of ecosystem services will be affected by these changes.
2. A new multi-model approach was used to project how the interaction of climate, nutrient loads, and cod fishing may affect the future of the open central Baltic Sea food web. Regionally downscaled global climate scenarios, previously developed within ECOSUPPORT, were, in combination with three nutrient load scenarios, used to drive an ensemble of three state-of-the-art regional biogeochemical models (BGMs) (including BNI-developed BALTSEM). An Ecopath with Ecosim food web model (BNI-developed BaltProWeb) was then forced with the BGM results from different nutrient-climate scenarios in combination with two different cod fishing scenarios.
3. The study showed that regional drivers could have a large impact on defining the future of the Baltic Sea, but that climate-induced changes in hydrodynamic conditions still set boundaries for food web structure and function. Regional management was shown to play an important role in determining the future of the ecosystem.
4. This study acknowledges the importance of management and the need to address the risk for ecological surprises, including the risk of non-indigenous species invasions that may lead to large changes in the ecosystem. Nonlinearities were observed in the sensitivity of different trophic groups to nutrient loads or fishing. Consequently, the risk for ecological surprises needs to be addressed, particularly when the results are discussed in the ecosystem-based management context. This has implications for ecosystems and their interaction with human systems and the interdependencies between them.

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.

1. The research presented in this paper investigated how in three subsistence agriculture dependent communities in Burkina Faso, Benin, and Ghana livestock are used to cope with losses incurred following a flood or drought. In rural West Africa, subsistence farming dependent communities are exposed to both floods and droughts. Multiple hazard events are likely to become more common. This paper presents an approach to multiple hazard risk assessment that highlights the importance of vulnerability and the cascading impacts of multiple hazards on communities.
2. A case study approach was used based on three subsistence agriculture dependent communities in Burkina Faso, Benin, and Ghana. Two hundred respondent interviews were undertaken. Starting with the single hazards, interviews were conducted with farmers across three case study areas. The interviews covered the initial impacts of floods and droughts on the crops grown in those areas and the coping strategies used to manage the

impacts and recover from the hazard events. Combining the interview data with climate change predictions, multiple hazard scenarios were developed and used as a tool to investigate how the cascading effects of multiple hazards might tip communities beyond coping and resilience, towards greater vulnerability. Using the interviews and scenarios, a comparison was undertaken of vulnerability between single and multiple hazards that better accounts for interactions and cascades and focuses on vulnerability in multiple hazard risk assessment. For the multiple hazard vulnerability assessment, a novel approach was required to overcome the limited experience that people in the area had with floods and droughts occurring in the same year – participatory group game activity followed by discussion of the multiple hazard scenarios. The game was designed to present multiple hazard situations through which the group would be required to react. Following the game play, the game pieces were used to demonstrate multiple hazard scenarios and a discussion regarding the anticipated impacts of these scenarios on the crops ensued.

3. The study found that the number and proportion of livestock needed to recover from the crop losses was critical to the resilience or vulnerability of a household. Under the single hazard vulnerability assessments, livestock could be used to raise funds to replace the damaged crops; however, under the multiple hazard scenarios, the losses were far more comprehensive. As such, most of the respondents felt that such scenarios would push them to a coping tipping point, raising the prospect of doubt in their future as a community as climate change impacts become more intense and frequent.
4. This paper uses some innovative methodologies that will be of wider relevance to adaptation in New Zealand including the use of games, vulnerability assessment for multiple hazards. It also demonstrated that different adaptation strategies can have very different consequences and, therefore, strategies for one hazard type are not necessarily suitable for multiple hazard types. As such, this research demonstrates a need for many alternative adaptation strategies that address both types of hazards rather than just one or the other. This has implications for how adaptation options are framed and assessed.

d. Infrastructure cascades

Papers in this category address infrastructure development to meet cascading impacts, with a focus on scale of impacts resulting and on urban infrastructure and tools for managing consequences.

Bollinger, L.A. & Dijkema, G.P.J. (2016). **Evaluating infrastructure resilience to extreme weather - the case of the Dutch electricity transmission network.** *European Journal of Transport and Infrastructure, 16*, 1, 214-239. URL: https://repository.tudelft.nl/islandora/object/uuid:2d9049f7-d4e1-4a42-a77b-6bbd442d1151?collection=research

1. This paper explores the resilience of the Dutch electricity transmission infrastructure to extreme weather events. Climate change is anticipated to result in an increase in the frequency and severity of extreme weather events over the coming decades. Situated in a low-lying coastal delta, the Netherlands may be particularly exposed to certain types of extreme weather-related events. The degree to which the country's electricity network may prove resilient in the face of these future events is an open question.
2. A network-based model is used to assess infrastructure resilience to two types of extreme events – floods and heat waves – and two types of adaptation measures – substation flood protections and demand-side management. The resilience of the structure and properties of the Dutch transmission infrastructure is assessed, extending previous work by

accounting for key power system characteristics such as capacity constraints and cascading failures.

3. The findings show the vulnerability of the Dutch electricity transmission infrastructure in the context of climate change. The network displays more vulnerability to floods than to heat waves, but there is some vulnerability in both. Both types of adaptation measures tested were found to enhance resilience, though substation flood protection shows greater benefits.
4. The use of the network model has relevance for assessing cascading failures in infrastructure systems and may be applicable to transport infrastructures and pipe infrastructure because of their networked structure.

Hu, X., Hall, J.W., Shi, P. & Lim, W.H. (2016). **The spatial exposure of the Chinese infrastructure system to flooding and drought hazards.** *Natural Hazards, 80*, 2, 1083-1118. Doi: 10.1007/s11069-015-2012-3

1. This paper investigates how the Chinese infrastructure system is exposed spatially to flooding and drought hazards. Recent rapid urbanisation means that China has invested in an enormous amount of infrastructure, much of which is vulnerable to natural hazards. Infrastructure exposure is considered across three different sectors: energy, transport, and waste.
2. A database from three infrastructure networks (energy, transport, and waste) is used to develop a methodology to assign the number of users to individual infrastructure assets. Hotspot analysis is imposed onto the flooding and drought hazard maps separately using the Kernel density estimator. The number of people dependent on infrastructure assets ("users") are estimated and locations are pinpointed where critical assets are concentrated in these high-risk areas. As a result, the locations of critical infrastructure that are exposed to risks of flooding and drought on a broad scale are shown and the potential number of users affected are calculated should infrastructure assets fail owing to one or a series of flooding/drought event(s) on a local scale.
3. Findings show that infrastructure assets in Anhui, Beijing, Guangdong, Hebei, Henan, Jiangsu, Liaoning, Shandong, Shanghai, Tianjin, Zhejiang (and their 66 cities) are highly exposed to flooding with impacts on rail, aviation, shipping, electricity, and wastewater. The average number of infrastructure users who could be disrupted by such impacts is 103 million. Electricity and wastewater (20 percent and 14 percent of the total, respectively) sectors are most exposed. For drought hazard, the research focused on the electricity sector, which is potentially exposed to water shortages at hydroelectric power plants and cooling water shortages at thermoelectric power plants, resulting in six million highly exposed users. Spatially, the research demonstrates that the southern border of Inner Mongolia, Shandong, Shanxi, Hebei, north Henan, Beijing, Tianjin, south west of Jiangsu (and their 99 cities) are highly exposed. The results can inform strategic infrastructure planning decisions, while the sensitivity of the sectors to hazard loading is being determined.
4. This study demonstrates the vulnerability of infrastructure if hazards and climate change effects are not adequately considered. The sheer scale of vulnerabilities has enormous flow-on effects to the economy and to people reliant on the services provided by the infrastructure. The methodology used to identify hotspots could have value to identifying infrastructure hot spots in New Zealand. Such methodologies are required in New Zealand to adequately prioritise hazard risk associated with climate change.

e. Urban systems

These papers present a range of frameworks for identifying cascades including resilience, the role of agents, and systems approaches.

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

The framework identifies cascading failures and the need for redundancy in water and energy systems to ensure greater resilience.

1. About: The article reviews concepts and theories in a range of diverse fields to illustrate how the general notion of urban climate resilience can be developed into an operational framework for planning practitioners. The framework includes characteristics of urban systems, the agents (people and organisations) that depend on and manage those systems, institutions that link systems and agents, and patterns of exposure to climate change.
2. Summary of methods: The authors extract normative characteristics of urban resilience from a diverse body of literature, grouped into three generalisable elements of urban resilience: systems, agents, and institutions.
3. Findings: Within this conceptual framework, building urban climate resilience means strengthening systems to reduce their fragility in the face of climate impacts and to reduce the risk of cascading failures; building the capacities of social agents to anticipate and develop adaptive responses to access and maintain supportive urban systems; and addressing the institutional factors that constrain effective responses to system fragility or undermine the ability of agents to take action.
4. Lessons for adaptation in New Zealand: Instead of focusing on future climate projections and defining uncertainties and climate risks, local planners can address the enabling and service provision role of core infrastructure and ecosystems, together with the capacities of agents and the structure of institutions linking systems and agents, to identify the key factors that affect resilience in their city. A fairly standard process is proposed – consistent with other community-based impact and vulnerability assessments, and including the following:
    a. Structured and facilitated multi-stakeholder deliberation to communicate knowledge, ideas, and perspectives across scales and communities, and draw conclusions to guide planning decisions;
    b. Vulnerability assessments that included analysis of fragile systems, low-capacity agents, and constraining institutions and their exposure to climate hazards;
    c. Resilience strategies that defined tangible priority interventions, based on the vulnerabilities identified in the previous step, and tied to other existing local planning processes;
    d. Implementation and learning from action; and
    e. Transmitting learning into new capacities, new knowledge, revised strategies, and action.

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. URL: https://doi.org/10.1080/19463138.2012.718279

"In the context of climate change, both of these roles are threatened by a variety of *direct* and *indirect* impacts. The *direct* impacts of climate change take the dual form of shocks, sudden impacts such as storms, typhoons and heat waves, and stresses, impacts that build gradually over time such as sea-level rise, general temperature increase, and changes in rainfall patterns. Such events will in turn generate a cascade of *indirect* effects, eroding the city's capacity to adapt as a result of significant disruptions in the socio-technical networks essential for city functioning."

1. About: this article proposes that a simplified conceptual model and resilience characteristics be used to analyse urban systems, in parallel with spatial analysis, to target action at multiple levels to reduce exposure and improve the adaptive capacity of urban populations simultaneously.
2. Summary of methods: This publication is based on evidence and experience from 10 cities that form part of the Asian Cities Climate Change Resilience Network (www.acccrn.org), as well as a literature review. A conceptualisation for urban resilience is proposed, future challenges are identified, and interventions discussed.
3. Findings: Based on a resilience framing, this article identifies future challenges cities face: direct impacts; indirect effects from disruptions of loss of essential assets and networks; and pre-existing vulnerability because of a lack of services. In a discussion of examples from the ACCCRN programme, the authors illustrate how a simple conceptual model can be used to analyse the urban system.
4. Lessons for adaptation in New Zealand: Resilience cannot be measured directly other than in terms of changing performance in response to shocks and stresses. Moreover, resilience will only be achieved through the cumulative contribution of multiple interventions and actions over time, and the ability of individuals and institutions to internalise learning and experience to inform future behaviour. It is crucial to define the desired urban resilience outcomes and start thinking about measurable network indicators that contribute to New Zealand's urban resilience.

f. Teleconnections and international supply chain cascades

These papers present insights into international supply chain cascades, focusing on primary production systems, vulnerability to environmental change, and climate impacts.

da Silva, R.F.B., Batistella, M., Dou, Y., Moran, E., Torres, S.M. & Liu, J. (2017). **The Sino-Brazilian telecoupled soybean system and cascading effects for the exporting country**. *Land, 6*, 3: 53. Doi: 10.3390/land6030053.

1. This paper analyses the cascading effects of the Brazil and China telecoupled soybean system on Brazilian maize exports and production systems, and its consequences on the domestic prices and availability of maize. The global food market means international players are connected through the flow of commodities, demand, production, and consumption. Local decisions, such as new economic policies or dietary shifts, can foster changes in coupled human-natural systems across long distances. Understanding the causes and effects of these changes is essential for agricultural-export countries, such as Brazil – which, since 2000, has expanded its soybean planted area to 19 million hectares, or 47.5% of the world's increase.
2. A telecoupling framework is used to analyse, one, the international trade dynamics between Brazil and China as the cause of the increased production of Brazilian soybean since 2000; and two, the cascading effects of the Sino-Brazilian telecoupled soybean system for Brazilian maize production and exports, consequences on domestic prices, availability, and risks associated with climatic extreme events. Census-based data at state

and county levels, policy analysis, and interviews with producers and stakeholders guided the methodological approach.

3. Findings showed that Brazilian soybean production decreased the single crop production of maize and accelerated it as a second crop to soybean. However, this practice makes farmers more vulnerable to precipitation anomalies, for example, rainfall shortage. In addition, the two-crop system of soybean/maize pressures the Brazilian maize market when unexpected events, such as extreme droughts, strike. Failed maize harvest (the second crop) can result, most of which is for domestic consumption rather than export. Cascading effects occur not only in the exporting country, but also in the importing country. For example, with more soybean going from Brazil to China, many Chinese farmers have increased planted areas for corn and rice, while reducing or even abandoning soybean production. If Brazil were to increase export taxes in response to environmental impacts of soybean trade between Brazil and China, the soybean price would likely rise and thus reduce the competitiveness of Brazil's soybean.
4. This study has particular relevance for a commodity trading country like New Zealand because cascading effects may occur years after a telecoupling system is initiated, as well as more immediately, because it is highly exposed to market changes. Consequently, there is a need for New Zealand to incorporate the telecoupling framework into land-use decision making to better understand the cascading impacts and implications of land-use changes.

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

1. About: This study presents two cases of nested, teleconnected vulnerability between peoples and places (one of the global transmission of SARS and one of coffee farmers in Vietnam and Mexico).
2. Summary of methods: This is a conceptually based case study comparison using statistical and other empirical data.
3. Findings: There are three mechanisms of interdependence: biophysical linkages and feedbacks; economic market linkages; and flows of resources, people and information. The spread of SARS as a communicable disease demonstrates the rapid geographical spread and the complex ecological causes of vulnerabilities. Likewise, the risks to livelihoods in coffee farming communities around the worlds through market and climatic factors illustrate unforeseen and unpredictable links in social-ecological vulnerabilities. In summary, differences and similarities in exposure, sensitivity, and capacity define the scope of vulnerability to social and environmental change. Vulnerability needs to be organised and understood as a phenomenon that is interdependent and interconnected.
4. Lessons for adaptation in New Zealand: This analysis shows that vulnerability cannot be assessed via place-based characteristics alone. The authors remind us to look at interconnected phenomena, synergies between actions, to be creative in the way we do research, and govern our land. Key action for research would be to identify the local actions to reduce vulnerability that have unanticipated global implications.

Moser, S.C. & Hart, J.M. (2015). The long arm of climate change: societal teleconnections and the future of climate change impact studies. *Climatic Change, 129*, 13-26.

1. About: This paper introduces a simple but systematic way to conceptualise societal teleconnections and then highlights and explores eight unique but interrelated types of societal teleconnections with selected examples:
    a. trade and economic exchange;
    b. insurance and reinsurance;
    c. energy systems;
    d. food systems;
    e. human health;
    f. population migration;
    g. communication; and
    h. strategic alliances and military interactions.
2. Summary of methods: The paper proposes a conceptual framework and conceptually explores societal teleconnections that have arisen out of societal interactions and globalisation. This includes structures, processes, substance, and actors involved.
3. Findings: Societal teleconnections link activities, trends, and disruptions across large distances, such that locations spatially separated from the locus of an event can, nevertheless, experience a variety of impacts from it. The perspective on linkages between structures, processes, substance, and actors illustrates connectedness across eight crucial teleconnections.
4. Lessons for adaptation in New Zealand: Societal teleconnections are important considerations for locally-based climate change vulnerability assessments and adaptation planning in the public and private sector. New Zealand engagement with telecoupling dynamics can highlight the complex nature-human system interactions and their effects for New Zealand and the world.

g. Cascading impact of policy responses

Papers in this category exemplify regional as well as global dynamics of climate change and the impact of policy on those.

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.** *Regional Environmental Change, 12*, 3, 523-542*.* Doi: 10.1007/s10113-011-0269-y

1. This paper discusses the interdependencies of adaptation measures across water, forestry, and nature conservation in a relatively dry region of Germany, characterised by sandy soils vulnerable to climate change impacts (e.g., summer droughts) and cascading effects on ecological systems (e.g., decreasing ground water tables, water stress, fire risk, and productivity losses) resulting in socio-economic implications. A complex interplay of unemployment, rural exodus, and an aging population challenges this structurally weak region. Multiple drivers of change are considered (e.g., climate change, unemployment), different actors (e.g., forest owners, farmers, nature conservationist, and tourists), and possible feedbacks (e.g., forest conversion provides deciduous wood to forest industry, which in turn supports further forest conversion).
2. A simple conceptual model, which focuses on land and water resources, is used to organise adaptation measures and their effects and linkages to the forestry, agriculture, and water management sectors and for nature conservation. Socio-economic and

ecological challenges and benefits are highlighted. These were assessed in subsystems embedded in a larger regional system, enabling conflicts between adaptation measures and synergies amongst the sectors to be identified.

3. The results showed that water availability and management are of concern in the forestry and agriculture sectors, and have the potential to create strong conflict. Water retention in the landscape (e.g., in wetlands or bogs for nature conservation) enables plants to satisfy their water demand in periods with low water availability. This substantially influences the discharge of rivers with benefits for transport (shipping) and other sectors (e.g., the energy sector) operating downstream. Moreover, building reservoirs for drought and flood mitigation as well as raising and relocating dikes have severe impacts on river ecology. Inducing positive effects on social and economic aspects of the water sector threatens ecological aspects of the water sector and nature conservation. Intensifying wood production (e.g., by inserting Douglas-fir in forests) under climate change may counter water-retention measures for an improvement of the regional water balance. Fields and forests connect protected areas, but, by responding to climate change, managers can raise new threats directly or indirectly to nature conservation goals (e.g., insertion of non-native, climate-resilient species or increased biomass extraction on agricultural and forest land). "Social limits" to adaptation are highlighted. Positive effects of a rewetting of wetlands and bogs for nature conservation improves the regional water balance and buffers the impact of heavy rain events and floods by easing the pressure on dikes. Building reservoirs and improved management influences the hydrograph of the whole river improving drought mitigation and flood retention. These measures in the water sector also protect infrastructure and people. An important economic co-benefit of forest conversion is that diverse forests provide a broader range of forest products and services.
4. The interdependencies, both negative and positive, shown in this paper are good examples of potential cascades from adaptation responses. The insights gained from this research highlight the need for cross-sectoral, adaptive management practices that are implemented in the knowledge of potential positive and negative effects of the adaptation action to be taken.

h. Impact assessment tools including network analysis

Papers in this category shed light on the interdependencies of climate change effects, specifically focusing on network approaches.

Espada, R.J., Apan, A. & McDougall, K. (2015). **Vulnerability assessment and interdependency analysis of critical infrastructures for climate adaptation and flood mitigation**. *International Journal of Disaster Resilience in the Built Environment, 6*, 3, 313-346.

1. This study introduces an integrated approach of analysing infrastructure risk to damage and cascade failure because of flooding. Aside from introducing the integrated approach, this study operationalised GIS-based vulnerability assessment and interdependency of critical infrastructures that had been insubstantially considered in the past analytical frameworks. The authors consider this study of high significance, considering that floodplain planning schemes often lack the consideration of critical infrastructure interdependency. The purpose of this paper is to present a novel approach that examines the vulnerability and interdependency of critical infrastructures using the network theory in a geographic information system (GIS) setting in combination with literature and government reports. Specifically, the objectives of this study were to generate the network models of critical infrastructure systems (CISs), particularly electricity, roads, and sewerage

networks; to characterise the CISs' interdependencies; and to outline the climate adaptation (CA) and flood mitigation measures of CISs.
2. An integrated approach was undertaken to assess the vulnerability and interdependencies of critical infrastructures. A single system model and system-of-systems model were operationalised to examine the vulnerability and interdependency of the identified critical infrastructures in a GIS environment. Information on existing adaptation and flood mitigation measures was elicited from government reports and integrated with findings from the modelling, to better understand implementation of natural disaster risk reduction (DRR) policies, particularly during the 2010/2011 floods in Queensland, Australia.
3. A spatially explicit framework was developed with four key operational dimensions: framing of the climate risk environment; understanding the critical infrastructures' common cause and cascade failures; modelling individual infrastructure systems and system-of-systems level within a GIS setting; and integrating the results with the government reports to increase adaptation and resilience measures for flood-affected critical infrastructures.
4. This paper provides a good example of an assessment of vulnerabilities and interdependencies amongst infrastructure with an eye on lessons from a flood event for how infrastructure can be managed and/or designed and operated in the future under a changing climate.

i. Governance

These papers discuss the implications of cascading systems for their governance, identifying gaps in research and suggesting frameworks for considering the role of governance in managing change in the environment as it affects other domains.

Galaz, V., Olsson, P., Hahn, T., Folke, C. & Svedin, U. (2008). **The problem of fit among biophysical systems, environmental and resource regimes, and broader governance systems: Insights and emerging challenges.** In O. R. Young, L. A. King, & H. Schröder (Eds.), *Institutions and Environmental Change - Principal Findings, Applications, and Research Frontiers* (pp. 147-182). Cambridge, USA: The MIT Press.

1. About: The authors propose a conceptual framework for the attributes of institutions (rights, norms, rules and decision-making procedures) that must be transformed to better match the dynamics of the biophysical systems.
2. Summary of Methods: The paper draws on the collective expertise and perspectives of a transdisciplinary group of researchers, who review, analyse, and update a previous paper on the 'problem of fit' between ecosystems and institutions (Folke *et al*., 1998).
3. Findings: The authors suggest that institutions and policy prescriptions must acknowledge the interdependencies between social and ecological systems. Failure to do so may result in poor advice to policy and decision makers and fail to adequately address emerging global problems (e.g., loss of biological diversity, climate change). The authors also describe a mis-match between biophysical systems and institutions. In resilience terminology, there is a need to focus on the capacity of institutions and broader governance mechanisms to deal with environmental change as linked to societal dynamics and to reorganise after unforeseen impacts.
4. Lessons for adaptation in New Zealand: There is a demonstrated need to refocus adaptation attention on the interaction between coupled human and natural systems in an integrated fashion. While there are efforts at integrated climate change impacts and

vulnerability assessment these often emphasise either social (values, norms, decisions, and actions) or biophysical impacts. The authors cite Folke *et al*. (2005) to highlight the following four interacting aspects of importance in adaptive governance of complex social-ecological systems:

a. Build knowledge and understanding of resource and ecosystem dynamics to be able to respond to environmental feedbacks;
b. Feed ecological knowledge into adaptive management practices to create conditions for learning;
c. Support flexible institutions and multilevel governance systems that allow for adaptive management; and
d. Deal with external perturbations, uncertainty and surprise.

These can be used in the New Zealand planning context as a constructive guide to a reconceptualisation of adaptive governing systems.

Birkmann, J., Garschagen, M., Kraas, F. & Quang, N. (2010). **Adaptive urban governance: new challenges for the second generation of urban adaptation strategies to climate change.** *Sustainability Science, 5*, 185–206. Doi:10.1007/s11625-010-0111-3.

1. About: This paper reviews the recent climate change adaptation strategies of nine selected cities and analyses them in terms of overall vision and goals, baseline information used, direct and indirect impacts, proposed structural and non-structural measures, and involvement of formal and informal actors.
2. Summary of methods: The paper presents a combination of formalised city-scale adaptation strategies with an empirical analysis of actual adaptation measures and constraints at household level. Cases compared are a climate change impacts study for Ho Chi Minh City and Can Tho City (in the Mekong Delta).
3. Findings: Responding to the notion of state failure to provide appropriate responses to disaster, the authors discuss adaptive governance mechanisms in their concluding section. Key aspects of adaptive governance resulting from their study are considering and linking different spatial and temporal scales; integration of, and mediation between, different types (sources) of knowledge; and consideration and combination of different measures, tools and norms. With this they underscore the importance of integrating adaptation assessments, planning, implementation, and evaluation. The paper stresses the need for a stronger consideration of the inter-linkages between formal and informal action in adaptation; the integration of different knowledge types; assessments of cross-scale secondary effects of specific measures; the identification of potential conflicts between given adaptation strategies; the integration of urban climate change adaptation endeavours with initiatives in the wider field of sustainable urban development; and limits and tipping points with respect to adaptation options.
4. Lessons for adaptation in New Zealand: The authors point to gaps in research as well as planning with regard to adaptive governance for urban contexts. Based on the stressors named above, New Zealand could explore these themes in the context of urban planning for climate change. The involvement of different disciplines is crucial in this endeavour (for example, the authors indicate the need to overcome the strong prevalence of engineering in the field). Research gaps exist in relation to tools and procedures for monitoring and evaluation, which could be addressed in New Zealand.

Duit, A. & Galaz, V. (2008). **Governance and complexity – Emerging issues for governance theory.** *Governance: An International Journal of Policy, Administration, and Institutions, 21*, 311–335.

1. About: This paper presents different hypotheses on how different governance types can be expected to handle processes of change characterised by nonlinear dynamics, threshold effects, cascades, and limited predictability.
2. Summary of methods: This paper is a theoretical-argumentative exercise that leads to a typology of governance systems based on their adaptive capacities as well as a reflection on combinations of governance systems across levels.
3. Findings: The likelihood of cascades is related to the degree of coupling between systems. Furthermore, the authors argue that adaptive capacity of a governance system can be understood as a function of the trade-off between exploration and exploitation. In their view, (the ideal) robust governance type combines a high capacity for exploration and an equally high level of exploitation, providing both steady state governance and long-term transformation processes. The authors differentiate between fragile, flexible, robust, and rigid governance types and propose that a combination of types allows for buffering reactions, which allows buffering for slow as well as rapid change.
4. Lessons for adaptation in New Zealand: In a world of non-linear change, complex adaptive systems are necessary to both explore new ways and provide stability. New Zealand could explore the possibilities that come with multi-level governance systems.

Conclusions

The conceptual origins of cascade thinking have particular relevance for urban systems, the three waters, and other connected network infrastructure. Similarly, adaptation actions flow on to wider domains of interest, such as the financial services sector (insurance, banking, and financial investment).

The literature reviewed for this project about cascade thinking traverses many domains including ecosystems dynamics and their intersection with human-environment systems; multiple hazard cascades; tipping points of harm, thresholds, and surprise; infrastructure cascades; urban systems, teleconnections, and international supply chain cascades; cascading impact of policy responses; and tools for assessing and governing these dynamic and changing systems. Based on this review of the literature and our empirical work, we identified a number of key issues that characterise cascading climate change impacts and their implications for adaptation in New Zealand.

Conceptual basis

A number of different fields of study and diverse theoretical approaches have been used to develop conceptual frameworks for characterising and assessing cascading impacts and implications of climate change. Many of these – including ecology, social-ecological resilience, natural hazards research, systems, and organisational theory – have learned from one other, evidenced by the shared emphasis on 'linked-up' systems or network thinking; a focus on critical thresholds in natural, built, and human systems, and interactions and feedback loops.

For New Zealand – which is exposed to a range of geo-climatic hazards – there is an opportunity to better consider the interconnections and interactions between climate change and other stressors, as well as their effects on each other. Considering climate change impacts within a broader risk-management or resilience framing may enable closer consideration of the way in which impacts cascade across spatial and temporal scales, and provide a catalyst for innovative management and response options that consider the whole system.

Physical processes, ecosystem and human-environment cascades

Examination of marine ecosystems and how environmental change cascades within and between species, demonstrates how climate change impacts affect systems where a stressor exacerbates existing stressors leading to cascades. The complex, compounding and cumulative nature of these impacts demonstrates how a better understanding of a system illuminates potential climate change effects. This general conclusion has currency for adapting across domains of interest. Framing physical processes cascading from climate changes to human systems helps to demonstrate the challenge for adaptation. This enables us to visualise the wider implications of cascading impacts for societal functioning – a generic lesson for New Zealand adaptation.

Climate change provides an opportunity to evaluate systems management with a longer-term view. The ability of management approaches to adapt to climate change will be critical to the values at stake in any system and for the social and economic values the system provides. Consideration of these interdependencies through adaptation will require resources, responsiveness, and bold thinking both internally and external to New Zealand.

Multiple hazard cascades, tipping points of harm, thresholds and surprises

Examples of the sensitivity of some ecosystems to threshold conditions being triggered, demonstrate that such 'events' are likely to be triggered more frequently with climate change, and that some systems have small coping ranges as change becomes more rapid, thus limiting recovery time between events. Understanding such concepts has significant implications for adaptive management of systems, whether bio-physical or human. The cascading impacts of ecological surprises show the importance of management and the need to address the risk of surprises. The literature demonstrates how nonlinearities stress particular sensitivities at different levels across bio-physical and human systems that depend on each other. This has implications for ecosystems and their interaction with human systems and the interdependencies between them. Different adaptation strategies can have very different consequences and, therefore, strategies for one hazard type are not necessarily suitable for multiple hazard types. As such, many alternative adaptation strategies that address both types of hazards, rather than just one or the other, will need to be assessed. This has implications for how adaptation options are framed and assessed.

Infrastructure cascades

The research also demonstrates the vulnerability of infrastructure if hazards and climate change effects are not adequately considered. The sheer scale of vulnerabilities in network systems has enormous flow-on effects to the economy and to people reliant on the services provided by the infrastructure. The inter relationships, particularly between infrastructure and the land uses it serves, are critical for adaptation to the changing climate and development risks going forward.

Urban systems

Cascades in urban systems are typically framed using resilience and systems science, with emphasis on interconnected systems, stability, and thresholds, for analysing and managing risk to urban systems. Identifying places to intervene can reduce vulnerability and enhance the urban systems' institutions and agents.

The combined effects of climate change and increasing urbanisation in New Zealand will require greater emphasis on understanding the dynamic climate systems and the changing impacts for urban design and planning. Infrastructure design that can perform over a range of futures will be more robust if underpinned by civic engagement, resulting in more healthy urban-ecosystems that can develop into more climate-aware and flexible urban futures.

Teleconnections and international supply chain cascades

International supply chains are critical for the New Zealand economy. Changing climate conditions can precipitate decisions in exporting countries that can have large flow-in effects in importing countries and vice versa. Decisions taken in response to climatic conditions or the impact of climate change on production systems, can fundamentally impact industry structure. This can have social and economic consequences for countries – even if they are geographically distant from one another – through imports, exports, and other forms of exchange. Furthermore, cascading effects may occur years after a telecoupling system is initiated or, in New Zealand's case, more immediately because of our significant exposure to market changes. Consequently, there is a need for New Zealand to incorporate the telecoupling framework into land-use decision making to better understand the cascading impacts and implications of land-use changes.

Cascading impact of policy responses

Interdependencies, both negative and positive, point to potential cascades from adaptation actions. Insights highlight the need for cross-sectoral, adaptive management practices that are implemented in the knowledge of potential positive and negative effects of the adaptation action to be taken. In addition, emissions mitigation policy responses can propagate cascades that affect the ability to adapt under a changing climate if those responses are generally inflexible to adaptation.

Impact tools and network analysis

The use of network models has relevance for assessing cascading failures in infrastructure systems across water, transport, and network utilities. Collection of flood analogues of failure can provide lessons for assessment of vulnerabilities and interdependencies for how infrastructure can be managed and/or designed and operated in the future under a changing climate. Some innovative methodologies were found that will be of wider relevance to adaptation in New Zealand, including the use of serious games and adaptive pathways planning for vulnerability assessment of multiple hazards and hotspots assessment for infrastructure design, planning, and implementation. Such methodologies are necessary in New Zealand to adequately frame issues, assess vulnerabilities, to prioritise hazard risk associated with climate change, and to develop ongoing sustainable pathways that are fit for dealing with changing risk profiles over time.

Governance

Governance is central to reducing exposures and costly consequences. Governance includes the agents, systems, rules, norms, and processes that influence decision-making choices within communities. Adaptive governance is one framing of governance that has evolved for analysing how exposures and uncertainties can be managed ahead of harm occurring from climate change impacts – that is, anticipatory planning that is flexible over time and does not lock-in unsustainable pathways.

For New Zealand to be able to respond effectively to the cascading risks of climate change, it will require the capability and capacity to reorganise within desired states ahead of changing conditions and surprises. This will also require innovation and novelty to transform social-ecological systems – such as the provisioning of flood protection infrastructure – into a new regime (e.g., nature-based and room for the river), rather than falling back into pre-existing exposures, institutions, and processes. Understanding the linkages, feedbacks, and connections between climate risk management and governance is central to reducing exposures of people in urban areas and their infrastructure services, and thus reducing costly consequences.

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Appendix 3. Systems maps outlining the cascading impacts of climate change

Deliberate
Discuss.Understand.Act.

National Institute of Water & Atmospheric Research (NIWA)

'Deep South' National Science Challenge

System maps outlining the cascading impacts of climate change

May 2018

Report by:
Justin Connolly — Director, Deliberate
Paula Blackett — Senior Social Scientist, NIWA

Discuss. Understand. Act.

Table of contents

1 Introduction

The purpose of this report is to present and discuss several system maps that have been informed by stakeholder interactions in the "Cascading Impacts and Implications for Aotearoa-New Zealand (A-NZ)" project funded by the Deep South National Science Challenge.

A primary research aim of the cascades project is to better understand the scale and scope of cascading climate change impacts and implications across A-NZ through complex socio-ecological systems with a focus on infrastructure and the financial sector. In particular, how they interact, who is affected, where interdependencies, feedbacks and co-dependencies occur, and how far impacts and implications might extend across multiple sectors.

Cascades have been framed as implications which arise from an impact and move across time, space and organisations effecting ecological, social, and economic domains. Recognising that implications and effects may move through a connected socio-ecological system potentially recombining or exacerbating through external policy decisions or concurrent impacts and events.

Types of climate change impacts considered as starting cascades for the purposes of this work

- *Slowly emerging impacts* – for example sea level rise
- *Widening climate variability* – for example increased drought, flood, coastal storm frequency
- *Extremes* – for example coastal storm surge, intense rainfall, wind
- *Surprises and combined impacts* for example

Systems thinking methodologies were identified as an approach which facilitated the elucidation of cascades and provided a foundation for the exploration of their relevance and significance to decisions makers.

2 Contributing data and methodology

The information that underpins the system maps has been generated from multiple sources, using mixed methods and on-going interactions with stakeholders.

The primary data collection stage involved three workshops, one each in Wellington, Hamilton and Christchurch. These involved different combinations of stakeholders and linked to different scales. Each workshop sought to provide alternative perspectives on potential cascades by focusing a group of participants on a defined geographical area: Wellington city; Hamilton-Hauraki plains; Christchurch-low lying city suburbs.

Each workshop identified critical infrastructure within the geographical area of interest and considered both how climate change (i.e. slowing emerging impacts, widening climate variability and extremes) might affect that infrastructure and how the different infrastructure types were connected with each other, and with other social and economic components of the system. This information was used to inform the building blocks of potential cascades and a system map through describing how parts of the system were understood to be connected. Individual cascades relating to particular infrastructure was aggregated into a single system map because it was evident that strong commonality existed between how the individual systems operated. As a result, the diagram represents all types of infrastructure for all the climate impacts considered.

Once constructed, the system map was tested with a sub-set of key informants in a small workshop and one on one meetings. Participants were talked through the diagram to confirm that it represented their perspective of how the system functioned.

The system map is also known as a causal loop diagram, but the term 'system map' is used here for ease of reference.

3 What is systems thinking?

The world that we live in is a highly interconnected place of causality and effect. The work of policy development often seeks to respond to undesirable behaviour or patterns being experienced in our natural environment and therefore seeks to influence these causes, to alter or improve the desired behaviour.

Systems thinking is a conceptual framework and set of tools that have been developed to help make these patterns of interconnectedness clearer (Senge, 1990)[1]. They help us understand the structure of a set of various interacting factors that present in behaviour we are trying to understand. This helps us better understand which parts of a system are having the most influence on a certain behaviour and allow us to identify areas of leverage to influence this.

'Systems Thinking' is a name often applied or interchanged to the academic discipline of 'System Dynamics'. System Dynamics originated from the Sloan School of Management at the Massachusetts Institute of Technology, Cambridge, Massachusetts in the late 1960's. The term systems thinking as it is used in this report refers to the concepts articulated by the discipline of System Dynamics (Sterman, 2000).

4 Balancing and reinforcing loops.

Systems thinking is especially interested in systems where loops of causality are identified – these are called *feedback loops*. There are two types of feedback loops, *balancing* and *reinforcing* (Senge, 1990).

In a *balancing feedback loop*, the direction of influence (i.e. same or opposite) provided by one factor to another will transfer around the loop through that one factor (or series of factors) and influence back on the originating factor in the *opposite* direction. This has the effect of *balancing out* the direction of the original influence.

In a *reinforcing feedback loop*, the direction of influence (i.e. same or opposite) provided by one factor to another will transfer around the loop and influence back on the originating factor in the *same* direction. This has the effect of *reinforcing* the direction of the original influence, and any change will build on itself and amplify.

The two types of feedback loop are described in Figure 1.

[1] For a detailed introduction to the concepts of Systems Thinking, the reader is referred to *The Fifth Discipline – the art and practice of the learning organisation* by Peter Senge (1990) as an accessible introduction.

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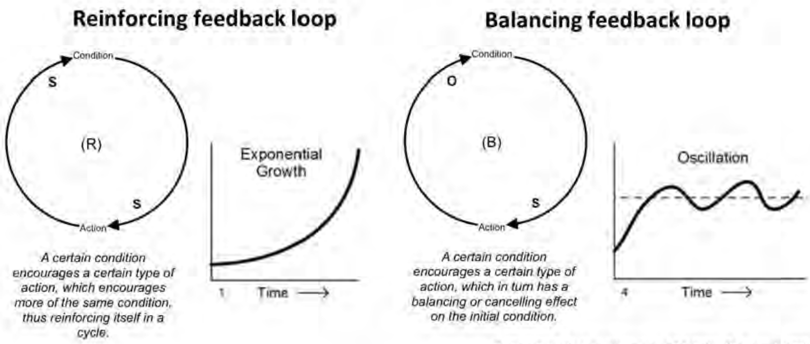
Figure 1. The two types of feedback loops



Adapted from Senge (1990) & Ford (2010)

Feedback loops can be made up of more than two variables and can be mapped together to form a system map, or a causal loop diagram. The way that these interact in a wider system helps provide insight into the consequential impacts on systems.

3

5 Preface to the descriptions of the system maps

The system map has been developed to two scales of detail. The first system map (summary) provides a summary outline of the overall system and factors driving the expectations from, and investment in, core infrastructure. Consistent with the systems thinking approach, the factors within this system are highly aggregated so as to highlight the way the system operates as a whole, rather than any one particular part in general.

The second system map (detailed) expands some of the detail within these same feedback loops, yet in greater detail. This allows for a more sophisticated view of the interactions within each part of the system, while still maintaining a focus on the aggregated nature of the variables and their interaction with each other.

Both levels of detail of this system will be described in this section.

While the cascading impacts of climate change on infrastructure are the interest of this system map, climate change itself will be a factor that influences an existing system where infrastructure investment decisions are made. The current level of infrastructure provided by or for a community, and their corresponding levels of service, are the result of multitude decisions made over recent decades. These decisions will be both a collection of small and large decisions about infrastructure investment and maintenance. They will also be the result of a social process that balanced the desire for and expectation of infrastructure services with varying abilities and decisions to provide such infrastructure.

As noted, these processes have been operating for many decades, and some parts operate more quickly than others. Yet it is important to note that there are multiple delays in this system, many of which are significant. The system maps herein are qualitative in nature and it is difficult to note the exact level any delay in any great detail. It is therefore considered suffice to note that many of the delays, where noted, may be of the nature of several to many years. Where possible this has been described in the supporting narrative.

The names of variables described in the system map are noted in *italics*.

6 Summary system map

At its most fundamental level a collection of infrastructure performs a variety of functions for society. Infrastructure in this instance describes a range of services that are provided to the public, often without them even realising, that enable society to operate to an expected level. The services provided include the provision of: stormwater drainage and flood protection; the collection, treatment and supply of fresh drinking water; the removal, treatment and disposal of wastewater from households and businesses; roads, railways and other transport infrastructure; electricity generation and supply via a public network; and internet/telephone connectivity via a public or private network.

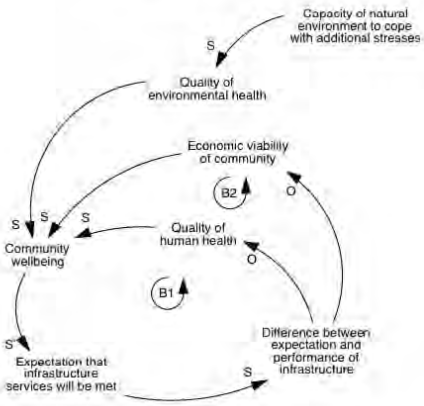
While it is acknowledged that the provision of electricity is a core service required for the provision of most of the other services, for the purposes of the system map, the term infrastructure refers to all of these services.

6.1 Feedback loops B1 and B2

The core of the system map is based around two balancing loops – B1 and B2 (Figure 2). Both of these loops show that there is a relationship and ongoing balance between the performance of infrastructure in line with community expectations. This tension is captured by the factor called *Difference between expectation and performance of infrastructure*, which is the gap between expectation and reality. Any change in the difference in this gap will have an opposite effect on *Community wellbeing* via either of the factors of *Economic viability of the community* or *Quality of human health*. That is, if the performance gap was to *decrease* – meaning that performance was *closer* to expectations – then *Community wellbeing* would increase.

While note part of these two feedback loops themselves, the *Quality of environmental health* also impacts *Community wellbeing*.

Figure 2. Feedback loops B1 & B2 (summary)



Feedback loop B1 shows that if there is little difference between the expectation and performance of the services of infrastructure (i.e. they are performing in line with expectations), then the *Quality of human health* will improve which in turn will increase

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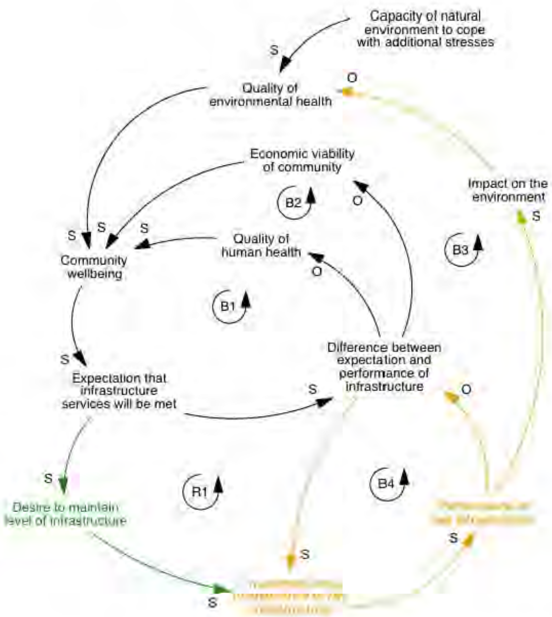
Community wellbeing. This will be through the direct benefits provided to the community such as flood protection, the provision of water, or functioning transportation networks. In turn, an increase in community vitality will increase a community's *Expectation that infrastructure services will be met*. This may, in turn, prompt an *increased target level of service*, which would have the effect of *increasing* the gap between target and actual infrastructure performance (the performance gap). If the performance gap was to increase, over time this would be expected to have a negative impact on community vitality. These balancing forces between infrastructure performance levels and community vitality would keep both in balance at a level acceptable to the community.

Feedback loop B2 is based on the same fundamental interaction between expectations and reality. The difference though, is that this loop enables infrastructure to contribute to *Community wellbeing* indirectly via the factor of *Economic viability of the community*. This acknowledges the part that financial vitality and employment play in wider community vitality and, in turn, the part that infrastructure plays in supporting this. It is also noted that there is a wide range of private infrastructure that supports the economic vitality of a community. In some instances, this will be supported by wider community infrastructure (for example, a reliable power supply may be required to run milking sheds or a de-watering pump). The lower the gap between the expectations and performance of infrastructure, the greater the potential for economic vitality and community wellbeing. Similarly, if the gap was to increase through an unnecessarily large rise in expectations, or a drop in service provision, this will have a detrimental impact on economic and community vitality.

6.2 Feedback loops R1, B3 & B4

While loops B1 & B2 are at the core of the system, they only deal with the impacts that the performance of infrastructure has on community wellbeing and its expectations of infrastructure. To better account for the actual decision process for *investing in or maintaining infrastructure*, we need to add feedback loops R1, B3 and B4.

Figure 3. Feedback loops R1, B3 and B4 (summary)



Feedback loop R1 extends B1 & B2 from the *expectation* node and captures the actual desire and decisions to invest and maintain infrastructure. A higher expectation that infrastructure services will be met does not immediately translate into a decision to continue investing in infrastructure. Firstly, a higher expectation will drive a higher *Desire to maintain levels of infrastructure*. In turn, this will have a same influence on decisions to invest in new or maintain existing infrastructure (*Investment and maintenance of key infrastructure*). As investment in infrastructure increases it follows that the *Performance of key infrastructure* would also increase.

Note at this point that the factor *Difference between expectation and performance of key infrastructure* is influenced by <u>both</u> the *expectation*, and the *performance* of that infrastructure. This is an example of the various ways that multiple feedback loops can influence the same factors within a system.

Within feedback loop R1, as the performance of infrastructure increases then the difference between expectation and performance will continue to narrow, this will in turn improve community and economic vitality, increasing both the expectations that service levels will be met and the desire to continue investing in infrastructure. Feedback loop R1 is a <u>reinforcing loop</u> which will continue to drive in the same direction unless moderated by other balancing loops such as B1 and B2.

Feedback loop B3 is a new balancing loop that is formed from the influence that *Performance of Key Infrastructure* has on the *Impact of the environment* which, in turn, affects the *Quality of environmental health*. As a decrease in this would have an opposite impact on *Community*

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wellbeing, then so this would flow through to the loop back to the investment in and then the performance of infrastructure, hence balancing this out.

Feedback loop B4 is a further balancing loop that will moderate the reinforcing behaviour of R1. This is a small loop within R1. This holds that *Increased investment and maintenance of key infrastructure* will continue to improve the *Performance of key infrastructure* and lower the *Difference between expectation and performance of infrastructure* (performance gap). In turn, this reduced performance gap will reduce the decision relating to the *Investment and maintenance of key infrastructure*.

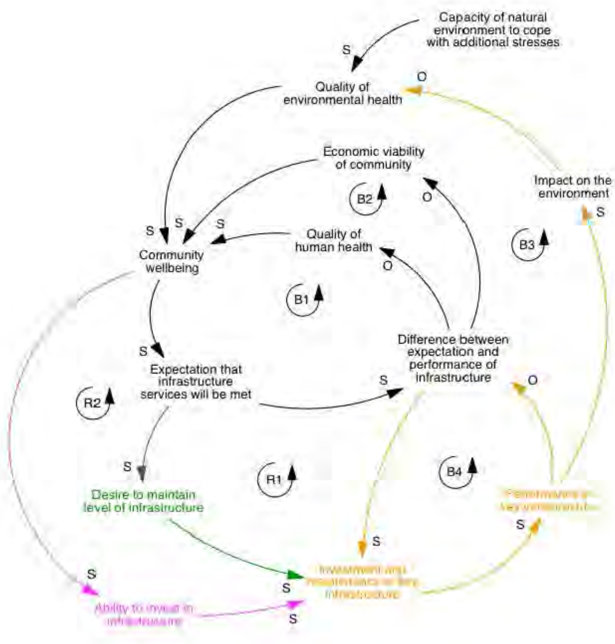
This means that decisions to investment in or maintain infrastructure are influenced by both the *desire* to invest, as well as the current *actual performance* of infrastructure.

6.3 Feedback loop R2

Extending this further, decisions to invest in infrastructure are not only influenced by the desire to invest and the current performance of infrastructure. They are also influenced by a community's *ability to invest*.

Feedback loop R2 incorporates a community's *Ability to invest in infrastructure* into the decision to invest in and maintain infrastructure, the performance gap of that infrastructure and economic and community vitality. It holds that generally, if the economic and community vitality of a community increase, then the *ability* of that community to invest in infrastructure is also increased. In turn this will influence actual infrastructure investment decisions.

Figure 4. Feedback loop R2 (summary)



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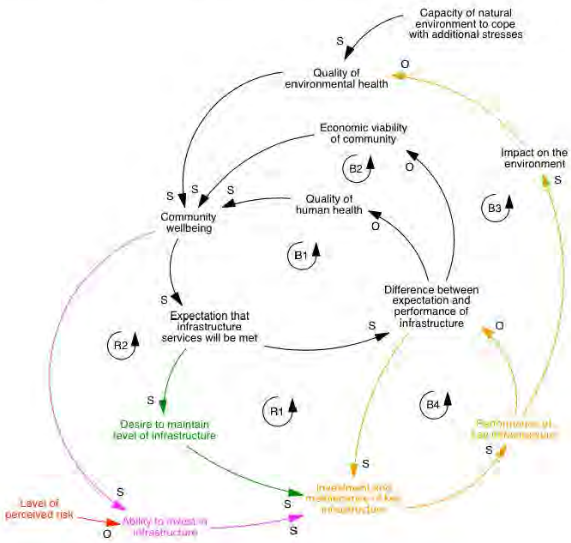
Note here that decisions to invest in or maintain infrastructure (Investment and maintenance of key infrastructure) are now influenced by three factors: the *desire* to invest, the *actual performance* of infrastructure, as well as a community's *ability* to invest. The level to which each of these various factors dominate at any one time will have a dynamic impact the level of infrastructure investment and maintenance.

6.4 Influence of perceived level of risk

The ability to invest is an important input into investment decisions. Like many of the other factors, it is influenced by multiple factors. While economic and community vitality will have a *same* influence on a community's ability to invest, the *Level of perceived risk* will have an *opposite* influence on ability. This is shown in Figure 5 and captures the risk associated with infrastructure investment as perceived by the finance and insurance industries, which are important contributors to and enablers of investment and maintenance decisions. Any significant increase in risk would be expected to limit both the ability to finance investment decisions as well as the ability to secure insurance cover over infrastructure in the event of adverse weather events.

Figure 5. Influence of received risk (summary)

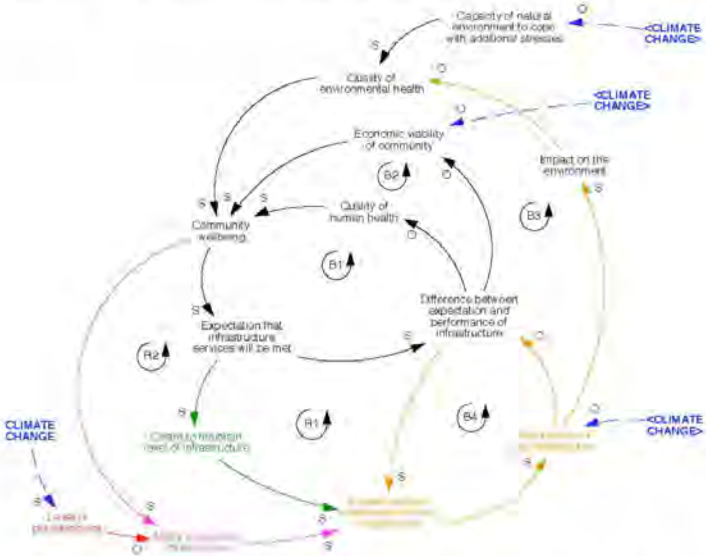


6.5 Where climate change will impact the system

The summary system map described above outlines the high level, yet fundamental, dynamics of the system that drives decisions on investment and maintenance of infrastructure. It now follows to map out the places in this system that climate change will have an impact.

Climate change is expected to directly impact the system in four main areas. It will directly impact the performance of key infrastructure; the level of perceived risk relating to the financing and insuring of key infrastructure; the economic viability of a community through its impacts on the *private infrastructure* that supports economic activity; and the *Capacity of the natural environment to cope with additional stresses* (see Figure 6).

Figure 6. Where climate change impacts the system (summary)



As noted earlier, the broad impacts of climate change will be sea level rise (SLR); more extreme weather events; greater climate variability; and possible changes in ecosystem dynamics. The main impacts considered here are sea level rise and an increase in the number and severity of extreme events.

6.5.1 Performance of key infrastructure

The most obvious impact of climate change will be on the ***Performance of key infrastructure*** itself through both SLR and more extreme weather events. Rising sea levels will increase the water table and put greater pressure on existing infrastructure to perform. This may be by the impact that rising water tables and sea levels will have on gravity-based infrastructure systems like stormwater drainage and sewerage systems, as well as infrastructure buried in the ground such as water supply and electricity/telecommunication networks. Infrastructure specifically built for low-lying or flood prone areas may also come under greater pressure. For example, SLR may impact the ability of flood protection infrastructure such as stop banks to perform adequately. Further, some ground water pumping infrastructure may be relied upon to maintain the water table at a level where pasture can be maintained as productive. The ability of both of these to operate well would come under pressure with rising sea levels which would place an increasing pressure on maintenance and renewal regimes from the asset owners.

The other way that key infrastructure is affected is by more extreme weather events. Rather than an increasing continuous pressure on infrastructure, extreme events may directly damage or destroy key infrastructure, resulting in the need for significant repairs or replacement of infrastructure. The impact of this would be the need for significant funds to re-invest in infrastructure, in order to return them to their previous performing levels of service. This would have a significant impact on a community's ability to invest in infrastructure and is

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likely to have a medium-term impact on the performance gap of key infrastructure, thus affecting the economic viability and community vitality of an area. Financial impacts of repairs may be significant and affect performance in the longer-term through a persistently large performance gap. In this case the impact of an ongoing large performance gap would be a decrease in economic activity and community vitality, in turn lowering expectations of infrastructure, which may in turn decrease the level of service expected from infrastructure.

These are examples of the balancing nature of the feedback loops in action and may result in the system returning to a period of balance, yet at a lower level of service.

6.5.2 Level of perceived risk

Another significant impact of climate change will be on the ***Level of perceived risk***. Rising sea levels and the increased frequency and severity of storm events will impact the level of perceived risk associated with decisions to build or maintain infrastructure. This factor has an influence on a community's *ability* to invest in and maintain infrastructure, mostly through the provision of financing and insurance services, as the providers of these services will find it increasingly risky to both insure or lend for such investments.

In turn this will decrease a community's ability to invest unless they are able to increasingly – or even wholly – self-fund and self-insure such initiatives. As climate change will have an impact on the economic vibrancy of a community through its impact on infrastructure performance, this is likely to be the case.

This means that a community's ability to invest in infrastructure will be impacted by the influence through the pathway of decreased infrastructure performance impacting the ability to invest, as well as the increase perceived risk impacting that ability.

6.5.3 Economic viability of a community

Climate change will also have a direct impact on the ***Economic viability of a community*** via its impact on a range of private infrastructure. This will occur both directly and through its impact on supporting key infrastructure.

Direct costs will be incurred where impacts on private infrastructure will require major repairs or replacements. While this will not incur direct costs from the community, it will have an impact an individual's ability to contribute to the community funds for the damage to other key infrastructure. The loss of private infrastructure will also directly impact the ability of farms and businesses to continue to operate, and therefore their economic viability.

Any potential impacts on private infrastructure may be exacerbated by flow-on effects from damage to key infrastructure. For example, where private infrastructure is supported by key infrastructure such as roads or power to run factories or milking sheds, for example.

6.5.4 Capacity of the natural environment to cope with additional stresses

Further to the above, climate change will also have an impact on the ***Capacity of the natural environment to cope with additional stresses***. The natural environment will effectively have a certain amount of latent capacity to absorb the impacts of additional stresses. However, if this ambient level within the environment was to change majorly, then the environments ability to absorb changes or stresses will be impacted.

For example, if climate change resulted in a higher level of naturally retained water in soils and waterways, then this would likely reduce the capacity of that receiving environment to absorb and moderate the impacts of additional wet events. Similarly, if the ambient environment became much drier as a result of climate change, this may also result in drier soils with less ability to absorb wet weather events.

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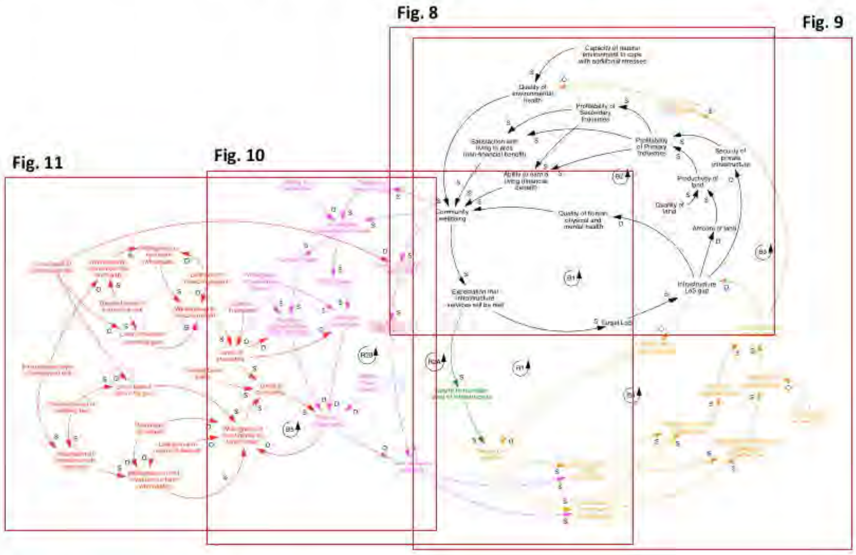
7 Detailed system map

Having described the system map at a summary level, this section will describe it at a more detailed level. This is still based around the six main feedback loops (B1-4 & R1-2) and the influence of perceived risk (where a small feedback loop B5 is added). Each area is expanded to describe the relationships in greater detail yet are still at an aggregated level to reinforce the interconnected nature of the overall system, rather than the content of any one area in detail.

An overview of the detailed system is shown below in Figure 7. Sub-areas detailed in subsequent figures are highlighted by the boxes.

Figure 7. Detailed system map with detailed figures highlighted



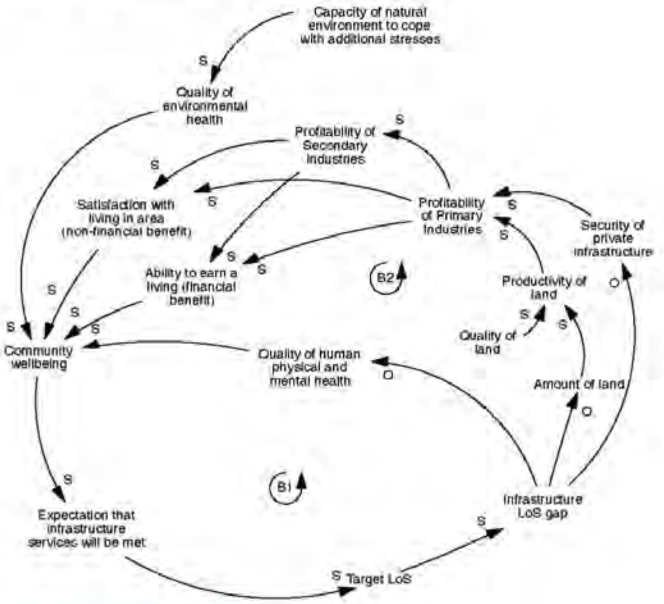
7.1 Feedback loop B1

The primary feedback loop of B1 is the least changed feedback loop in the detailed system. The factor of *Community wellbeing* is retained. This still has a same influence on the *Expectation that infrastructure services will be met*, which in turn has a same influence on a new factor called *Target Levels of Service (LoS)*.

This new factor has been separated from the previous *Difference between expectation and performance of infrastructure* to reflect the very definite step that a community takes to choose the level of service that they wish their infrastructure to provide. In turn, this has a same influence on the revised 'difference' factor, now called *Infrastructure LoS gap*. This more specifically reflects the specific gap between the *target* level of service sought, and the *actual* level of service delivered.

There remains an opposite relationship between the *Infrastructure LoS gap* and the slightly expanded factor - *Quality of human physical and mental health*. This in turn continues to have a same influence on *Community wellbeing*. That is, if this gap decreases (i.e. the closer actual performance is to target) this is likely to produce and increase in *Community wellbeing*, and vice versa.

Figure 8. Feedback loops B1 & B2 (detail)



7.2 Feedback loop B2

The detail within feedback loop B2 has been expanded considerably, with the single factor of *Economic viability of community* being broken into eight factors.

Most directly, the Infrastructure LoS gap will have an opposite influence on the *Amount of land*. This reflects the direct service key infrastructure provides by maintaining a stock of productive land in some low-lying areas, through the provision of land drainage, pumping stations and flood protection. The *Amount of land* will have a same influence on the *Productivity of land* which, it is noted, is also influenced by the *Quality of land*. In turn the *Productivity of the land* will have a same influence on the *Profitability of primary industries*, which is an aggregation of the primary productive industries in many low-lying areas of the country.

For the purposes of this narrative, primary industries include all types of agriculture (including dairying and pastoral meat farming), horticulture and forestry.

As described earlier, key infrastructure – through the Infrastructure LoS gap – will also have an opposite influence on the *Security of private infrastructure* through the provision of roads (access) and power to maintain private pumping stations. This will also have a same influence on the *Profitability of primary industries*.

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The *Profitability of primary industries* will in turn have a same influence on the *Profitability of secondary industries*, which are summarised as the collection of processing and service industries that support the primary industries. This might be processing plants, machinery sales, livestock service providers (vets, herd testing etc) and so on.

The profitability of primary and secondary sectors will in turn both have a same influence on two factors that contribute to *Community wellbeing*. These are *Satisfaction with living in area* and *Ability to earn a living*. These two factors reflect an aggregation of both the *non-financial* (satisfaction) and *financial* (earning a living) contributions to community vibrancy.

7.3 Feedback loops R1, B3 & B4

Moving into other parts of the system, feedback loops R1, B3 and B4 are all expanded significantly, due to the expansion of the area around investment and performance of infrastructure.

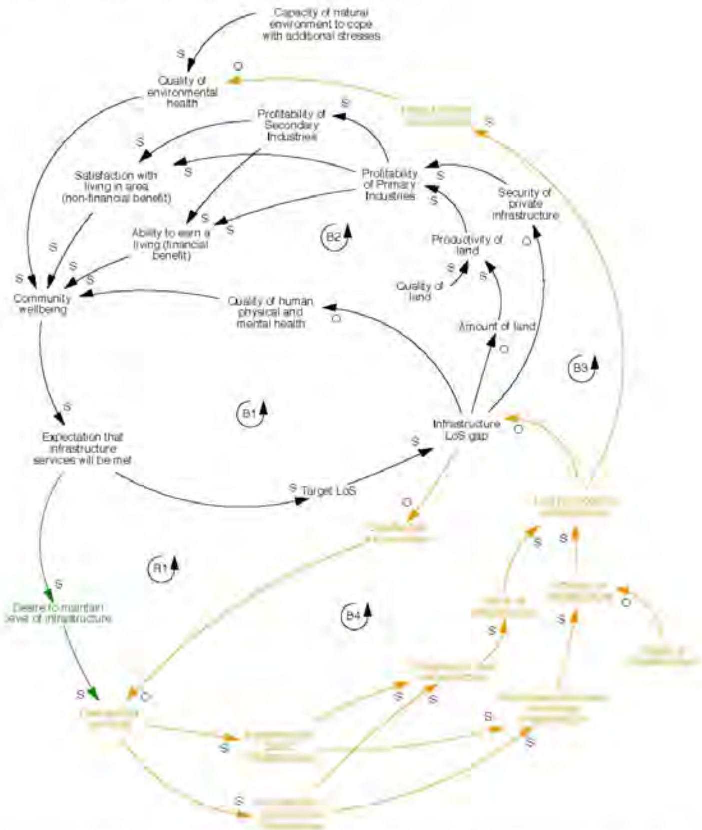
Feedback loop R1 retains the same initial factor, *Desire to maintain level of infrastructure*. As previously noted this reflects that fact that an *expectation* of a service level from infrastructure does not automatically translate into a *desire* for more infrastructure. In this detailed system this notion is extended further, and an additional factor is added (with a same influence), called *Demand for services*. This reflects the fact that a desire is different to a demand, which in turn informs a decision to actually invest in infrastructure.

It is noted here that two types of key infrastructure are prevalent in these systems – public infrastructure (drainage, water supply, wastewater, flood protection and transport) and commercial infrastructure (power and telecommunications networks). The point where a decision is made to invest in either of these infrastructures has been split into separate factors. This reflects the different ownership structures of the two infrastructure types. These are both influenced by a same influence from the *Demand for services*.

In turn, these factors both have same influences on either the *Provision of new infrastructure*, or the *Maintenance/renewal of existing infrastructure*. These factors have been separated out to highlight the difference that a decision to invest in *new* infrastructure will increase the overall *Stock of infrastructure*; while a decision to invest in *maintenance or renewal* of infrastructure will not impact the overall stock but will improve the *Efficacy of infrastructure* (performance) in the existing stock. A factor describing the natural *Decay of infrastructure* will also influence the *Efficacy of infrastructure* in an opposite way – that is the greater the decay, the lower the efficacy.

Both the *stock* and *efficacy* of infrastructure factors have a same influence on the actual *Levels of service (LoS) provided by infrastructure*. This in turn will provide the measure for the actual performance of infrastructure to the factor capturing the *Infrastructure LoS gap*. From this factor R1 continues on the same path as B1 and B2 round to the *Expectation that infrastructure services will be met*.

Figure 9. Feedback loops R1, B3 & B4 (detail)



The additional connection that created **feedback loop B3** in the simple system map remains the same. With the exception it now starts from the revised factor of *LoS provided by infrastructure*. Otherwise this feedback loop is expanded in the same way as feedback loop R1.

As in the summary system, the smaller balancing **feedback loop B4** is made by connecting the actual provision of services back to the demand for them. In this details system map, the factor *Infrastructure LoS gap* has an opposite influence on *Satisfaction with services*, which in turn has an opposite influence on the *Demand for services*. In other words, the better the performance of the infrastructure, the better the satisfaction, therefore the lower the demand for additional services.

This expansion of detail shows that an *increase* in the Level of service gap does not directly result in demand for more services: first it presents as a *decrease* in *Satisfaction with services*, which then is one of the contributing factors to an increased *Demand for services*.

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7.4 Feedback loop R2 (R2A & R2B)

The other feedback loop in the summary system was the **R2 feedback loop**, which influenced a communities *Ability to invest in infrastructure*. Previously there was a direct influence between *Community wellbeing* and *Ability to invest in infrastructure*, which has now been expanded substantially to include 11 other factors. It is also important to note that this loop has been further divided into two slightly different pathways (R2A and R2B).

The *Ability to invest in infrastructure* factor from the summary system has been re-labelled as the *Debt to equity ratio gap* in this detailed system. That is, the difference between the *Target debt to equity ratio* versus the actual *Debt to equity ratio*. This better reflects the main driver of investment decisions for an organisation, which is the level of equity that an organisation has in relation to the level of debt that it holds, and its comfort with such a level of debt.

Feedback loop R2A describes the pathway to the *Target debt to income ratio* which is a reflection of an organisations appetite for risk. *Community wellbeing* has a same influence on the *Level of comfort with debt* that a community will have (most directly in a public organisation like a council, but also indirectly in commercial organisations delivering public goods, like electricity networks). The *Level of comfort with debt* has a same influence on the *Target debt to equity ratio*, which in turn is an input to the *Debt to equity ratio gap*.

Feedback loop R2B describes a pathway to the actual *Debt to equity ratio*. *Community wellbeing* will influence the *Number of people/households in an area*, both directly and via the mediating factor of a *Desire to remain in situ*. This is describing both the ability of a vibrant area to attract new residents, as well as reinforcing the desire of existing residents to remain.

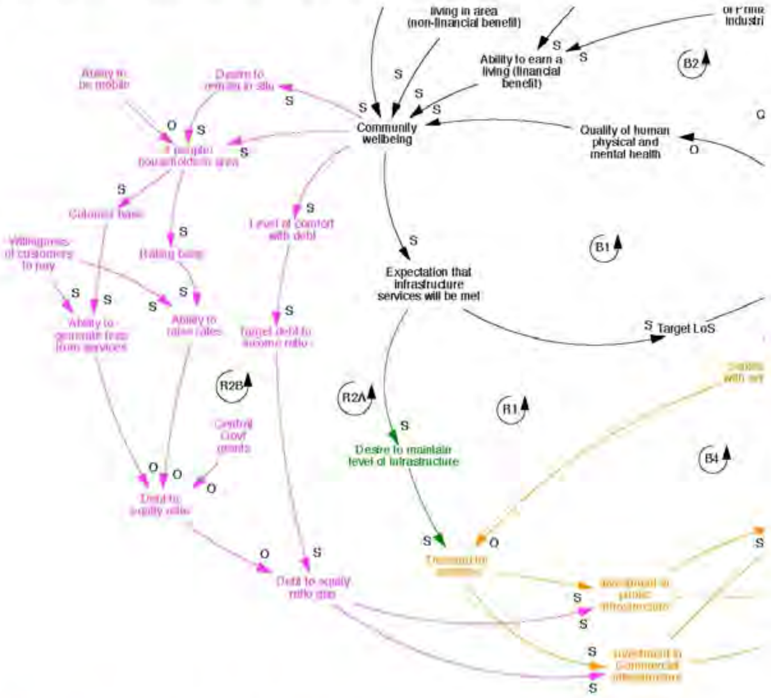
It is important to note that a family or individuals *Ability to be mobile* will also have an *opposite* influence on the *Number of people/household in an area*. This reflects the fact that some households may have difficulty moving from a location, for example due to having all of their assets locked up in their house with very little opportunity to leverage this. While this is a less dominant influence when community vitality is buoyant, it become a more dominant influence when community vitality decreases. This would become especially relevant if this occurred due to the impact of climate change.

The *Number of people/households in the area* then have a same influence on an organisations ability to generate income. For a council this would increase their *Rating base*, which would increase their *Ability to raise rates*, which would decrease their *Debt to equity ratio* (by increasing the 'income' component). Similarly, for a commercial organisation a similar pathway exists through an increase in the *Customer base*, which then increases the *Ability to generate fees from services*, which in turn would lower their *Debt to equity ratio*.

A council's *Ability to raise rates* and a commercial organisation's *Ability to generate fees from services* are also both influenced by the *Willingness of customers to pay*. That is, simply having more people does not mean that more income will be generated, as this will also be influenced by the willingness of customers to pay.

The *Debt to equity ratio gap* will then have a same influence on decisions to invest in either key public or commercial infrastructure.

Figure 10. ***Feedback loop R2 (R2A & R2B – detail)***



7.5 Level of perceived risk

The final area described in the summary system is that of the *Level of perceived risk*. In the detailed system map this is expanded from one factor to 18 factors. These are best described as two pathways representing insurance and finance providers, that each incorporate two levels of perceived risk – local and international.

Unlike the previous factors and influences, this sub-section will be described in reverse order, as it does not form a feedback loop.

Beginning with the range of **factors that influence borrowing**, the *Willingness of local banks to lend (retail)* represents the retail arm of institutional finance organisations that lend to councils or utilities in New Zealand. This factor will have a same influence on the actual *Level of borrowing* that may occur to these organisations. In turn, this will also have a same influence on the resulting *Debt to equity ratio*, which consequently will have an *opposite* influence on the willingness of local banks to lend. This results in the addition of a small **balancing feedback loop (B5)**.

This is important to note, as this means that all of the influences on the *Level of borrowing* described below are driving factors in this small, but important, balancing loop. These influences will directly impact this feedback loop (B5) as well as indirectly influencing the other feedback loops described above.

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The *Level of borrowing* is also directly influenced by the independent variable of *Central Government Loans*. This acknowledges that local government infrastructure is a special case that sometimes can benefit from central government loans.

The *Willingness of local banks to lend (retail)* is influenced by four factors. The *Probability of default* and the *Likely loss in event of default* both have an opposite effect on willingness to lend. The *Willingness of International investor to lend (wholesale)* has a same impact on retail banks willingness to lend. This also acknowledges that the banking industry has both retail and wholesale layers and that the retail bank that lends money to an organisation must in turn borrow that money from a wholesale provider. Finally, the *Local banks risk level gap*, which is the difference between their *Desired level of lending risk* and their *Perceived level of risk*. The higher the gap between a lenders *Desired level of lending* risk and the actual *Local level of perceived risk*, the more likely that a lender will be to lend.

The *Local level of perceived risk* will also have an opposite effect on a community's *Level of comfort with debt*.

Continuing back up the chain of influence, the *Willingness of international investors to lend (wholesale)* is influenced by the *International investors risk level gap*. This is the difference between their *Desired level of lending risk* and the *International level of perceived risk*. Having separate international and local factors for perceived levels of risk acknowledges that locals are more invested in their area, and therefore may perceive risk more acutely. It also acknowledges that the International level of perceived risk will be a more aggregated and balanced view of risk from around the world. This takes into account how risk in New Zealand is part of an aggregated assessment of risk for wholesale institutions.

The other pathway of influence within this risk section are the **factors that influence insurance provision**. The *Level of insurance* provided influences several things: The *Level of borrowing* (same influence), as lending arrangements will often require insurance to cover loan repayments; the *Ability to raise rates* for a council (opposite influence); and the *Ability to generate fees from services* (opposite influence). These last two opposite influences acknowledge that if the *Level of insurance* is low there will be a consequential pressure to counter the lack of insurance by generating income through rates or fees to balance that risk.

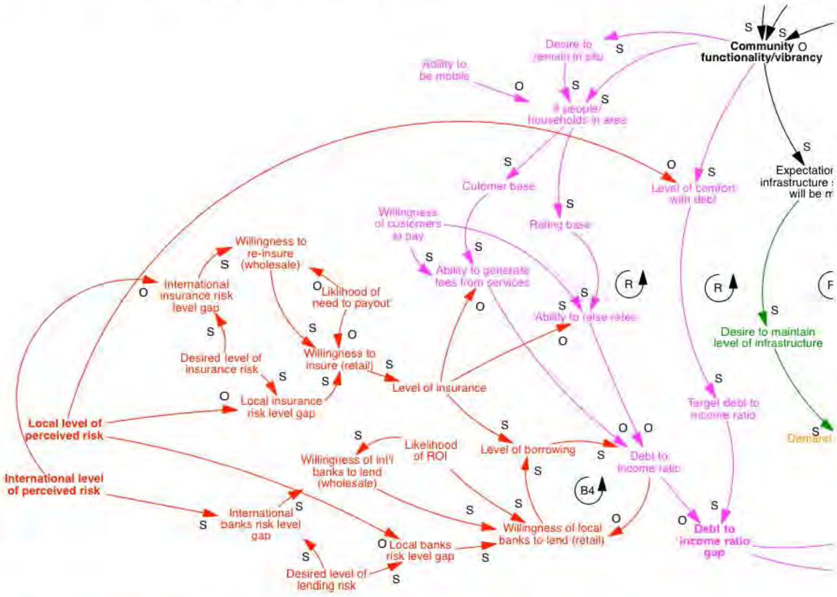
The *Level of insurance* is influenced by the *Cost of insurance* to the buyer, as well as an insurance providers *Willingness to insure (retail)*. Like borrowing, this recognises the local willingness within the New Zealand market to provide insurance.

The local *Willingness to insure (retail)* is in turn influenced by the *Willingness to re-insure (wholesale)*, which recognises that the services of retail insurers themselves are influenced by a wholesale market. The willingness of both retail and wholesale levels to insure is influenced (with an opposite) by the *Likelihood of the need to payout*.

The willingness of both retail and wholesale insurance providers are influenced by a *Local insurance risk level gap* and an *International insurance risk level gap, respectively*. While the *Desired level of insurance risk* will influence the upper part of this gap, the *Local level of perceived risk* and the *International level of perceived risk* will influence the lower part of both the local and international insurance gap calculations, respectively.

While the influence of perceived risk into feedback loops R2A and R2B is predominantly linear, it is important to note that it influences in several places. The *Local level of perceived risk* influences R2A directly by influencing a community's *Level of comfort with deb*. While feedback loop R2B is influenced via the insurance and borrowing pathways, which are ultimately heavily influenced by both the *International level of perceived risk* and the *Local level of perceived risk*.

Figure 11. Influence of perceived risk (detail)



7.6 Where climate change will impact the system

Having described above the expanded and detailed system map, the places within this system where climate change will have an impact are now considered. Climate change is still expected to directly impact the system in the same four main areas. However, given the expanded detail, these areas are described with greater clarity.

7.6.1 Performance of key infrastructure – efficacy and decay

The performance of key infrastructure remains the main area affected. This will just occur more specifically through the impact climate chance will have on the *Efficacy of Infrastructure* and the *Decay of infrastructure*. Climate chance impacts may limit the ability of infrastructure to operate effectively, thus impacting its *efficacy*; and it may speed up the decay of rate for that piece of infrastructure, meaning that infrastructure *does not last as long* as originally intended. The immediate consequential impact of this is that the performance of infrastructure will drop leading to an increased gap between target and actual performance of infrastructure . This is likely to impact business profitability, human health and community wellbeing.

It is likely that longer term impacts of this will be that the expectations of infrastructure performance may lower or need to be lowered; or that more investment than anticipated will be required to maintain the expected level of service from infrastructure.

7.6.2 Economic viability of a community – productivity of land

There will be a direct impact on the *Productivity of land* through rising sea levels and water-tables, as well as the disruptive impact that extreme events will have on primary production.

This recognises the direct impact that climate change will have on productive land through loss of animals or crops and/or the impact on farm infrastructure.

The *Security of private infrastructure* provided by key infrastructure (e.g. the provision of power etc) will be eroded by the lower performance of infrastructure.

7.6.3 Capacity of the natural environment to cope with additional stresses

It remains likely that climate change will also have an impact on the ***Capacity of the natural environment to cope with additional stresses***. This impact remains the same as in the simple system map. Where the natural environment will effectively have a certain amount of latent capacity to absorb the impacts of additional stresses. If this ambient level within the environment was to be impacted, then the environments ability to absorb changes or stresses will be impacted.

For example, if climate change resulted in a higher level of naturally retained water in soils and waterways, then this would likely reduce the capacity of that receiving environment to absorb and moderate the impacts of additional wet events. Similarly, if the ambient environment became much drier as a result of climate change, this may also result in drier soils with less ability to absorb wet weather events.

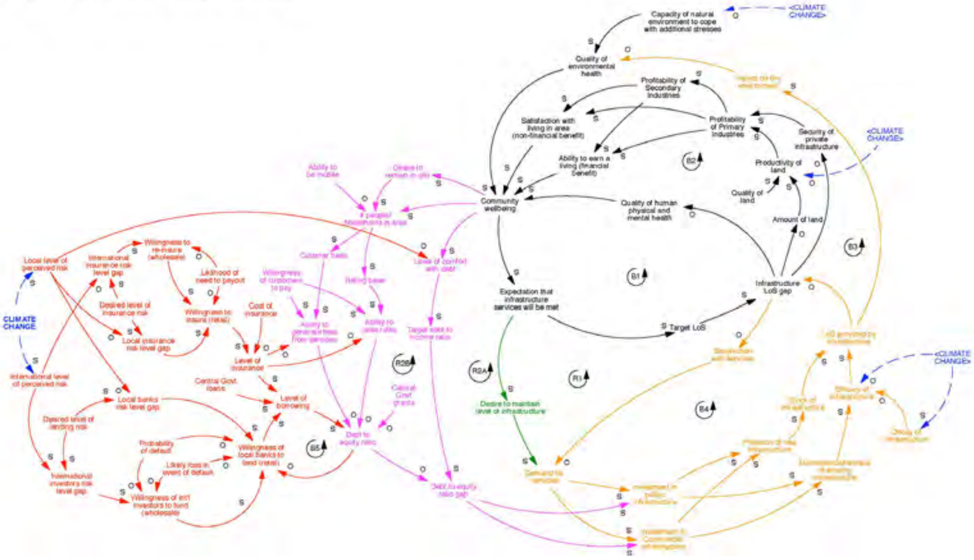
7.6.4 Level of perceived risk – International and local

An expanded chain of influence from perceived risk to the provision of insurance and borrowing has been described above. The key areas where climate change will impact this area remains the perceived level of risk, yet it has been separated into the *Local level of perceived risk* and the *International level of perceived risk*. It is these two factors that climate change will directly impact.

It will however, impact them in different ways. The *Local level of perceived risk* is expected to be more dramatically impacted by climate change in the short-term. As sea level rise occurs and extreme events become more frequent, there is likely to be a more immediate adjustment to the perceived level of risk.

The *International level of perceived risk* will also be directly impacted, yet because this is an aggregated level of perceived risk across the entire world, this may change more slowly in response to the effects of climate change within New Zealand. However, because this aggregation takes into account climate change impacts all around the world, it is likely that this measure is likely already trending in an upward direction, due to the impacts of climate change already beginning to be realised in other parts of the world. Whereas the impacts of climate change in New Zealand are yet to begin manifesting themselves in a non-controversial or agreed way.

Figure 12. Where climate change impacts the system (detailed)



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8 Summary and conclusion

This report has described an aggregated system that represents the everyday provision and operation of major community infrastructure and how the impacts of climate change may cascade through this system.

Using data collected in three major workshops as well as one on one interviews with stakeholders, both a simple and a detailed system map have been described. Both contain five main components, most of which are circular.

Firstly, the circular influences of the performance of infrastructure on community wellbeing via economic and human health benefits were described. Environmental health was also noted as a contributing factor to community wellbeing. Secondly, the factors that contributed to the provision and performance of infrastructure that stemmed from a demand for infrastructure provision were described. Thirdly, the small but important influence that the *demand* for maintaining a certain infrastructure of infrastructure was described – a key link that translates expectations into demand. Fourthly, several pathways that influenced a community's *ability* to pay for infrastructure were described. They focused on the level of comfort with debt and the means by which revenue to fund infrastructure were generated. Finally, a range of insurance and financing influences – themselves in turn influenced by perceived risk – were described, as was their influence on a community's ability to pay.

The system described some linear influences but mostly circular feedback loops. These influenced both themselves and flowed into other feedback loops. While this may appear difficult to comprehend at a glance – and it is likely to be – it provides an excellent summary of a highly complex and *dynamic* system of interconnected influences. Most factors within the system are not simply influenced by a single linear influence, most are multiple and many feedback around on themselves in a circular fashion.

When the likely impacts of climate change are mapped onto these system maps, consequential and cascading impacts can be traced through most factors of the system, being described narratively and anecdotally.

It is expected that this system mapping will be of interest and use to anyone with an interest or need to understand the cascading impacts of climate change. It will be of particular interest to practitioners and decision-makers within the industries described, as it helps to makes the interconnectedness and inter-relatedness of the many complex factors involved in the system more explicit. While still at an aggregated and synthesised level, the ability of these system maps as a tool for increasing understanding should not be underestimated. It is presented as a complimentary tool for use with more detailed analysis of specific areas of the systems described within.

9 References

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Appendix 4. Participant organisations

Wellington Water

Greater Wellington Regional Council

Hutt City Council

Kapiti Coast District Council

Victoria University of Wellington

Christchurch City Council

Waimakariri District Council

Ministry for the Environment

Ngāi Tahu

Environment Canterbury

Waikato Regional Council

Thames-Coromandel District Council

Hamilton City Council

Waikato District Council

Infrastructure Alliance (Hamilton City and Downer Ltd)

NZTA (NZ Transport Authority)

Representatives of insurance and banking companies