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Turbulent Times – Development of an Accessible Decision-Support Methodology to Aid Uncertain Flood-Based Decision-Making

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A thesis submitted in fulfilment of the requirements for the degree of Master of Science in Environmental Science, School of Environment, The University of Auckland, 2019.
Abstract

Assessing the possible future behaviour of river systems is complicated by deep climatic and socio-environmental uncertainties. However, traditional flood protection strategies have generally ignored such uncertainties, preferring to implement extreme “hard engineering” solutions. The perceived inadequacy of these strategies has resulted in the development of decision-support methods which seek to quantitatively investigate the suitability of different interventions using flood impact assessments that take into account different uncertainty scenarios. The success of decision-support methods overseas and in New Zealand has led to the Ministry for the Environment recommending the Dynamic Adaptive Policy Pathways approach for national implementation in coastal hazard management. A similar recommendation for the widespread use of Dynamic Adaptive Policy Pathways to address river management problems is expected in the coming years. However, it is unclear whether widespread uptake of decision-support methods is feasible for New Zealand local government given the national models and software currently available to councils. In addition, communicating the outcomes of such modelling can be difficult. Serious games based on water management have proved successful in engaging stakeholders with deep uncertainty problems, but have been so far underutilised in the New Zealand context, possibly due to difficulties in calibrating them to specific management problems.

This thesis therefore seeks to develop a Dynamic Adaptive Policy Pathways implementation methodology for the Lower Whanganui River flood management problem using only limited resources and readily available software. In particular, the methodology addresses how climate uncertainties might be accounted for in flood impact assessments, how asset databases might be constructed to assess vulnerability and how possible interventions might be compared within a developed impact model. A serious game session based on the impact model is then carried out to gain insights into the model and its utility for local government stakeholders. This thesis finds that carrying out decision-support investigations and creating serious games for New Zealand flood management problems is possible, but can be complex, time consuming and provide limited accuracy. It therefore concludes that widespread implementation of these methods is unlikely until national models have been improved and the process streamlined.
I would first like to thank my supervisors Dr Susan Owen and Associate Professor Giovanni Coco for their contributions to this thesis. Your insights and expertise were invaluable and have left clear impressions on both my work and my passion for research.

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Whether you helped provide data or expertise, participated in a focus group or just gave up your time to listen to my troubles, I am truly thankful for your assistance.

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<td>CBD</td>
<td>Central Business District</td>
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<tr>
<td>CF</td>
<td>Consent Form</td>
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<td>DAPP</td>
<td>Dynamic Adaptive Policy Pathways</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
</tr>
<tr>
<td>FEMA</td>
<td>Federal Emergency Management Agency</td>
</tr>
<tr>
<td>GCM</td>
<td>Global Climate Model</td>
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<tr>
<td>GIS</td>
<td>Geographic Information Systems</td>
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<td>GNS Science</td>
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<td>HAZUS FIT</td>
<td>HAZUS Flood Information Tool</td>
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<td>HIRDS</td>
<td>High Intensity Rainfall Design System Version 3</td>
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<td>Land Information New Zealand</td>
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<td>LWR</td>
<td>Lower Whanganui River</td>
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<td>MCDEM</td>
<td>Ministry of Civil Defence and Emergency Management</td>
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<td>MFE</td>
<td>Ministry for the Environment</td>
</tr>
<tr>
<td>NIWA</td>
<td>National Institute of Water and Atmospheric Research</td>
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<tr>
<td>NZTA</td>
<td>New Zealand Transport Agency</td>
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<tr>
<td>ONRC</td>
<td>One Network Road Classification</td>
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<td>Whanganui District Council</td>
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Chapter 1

INTRODUCTION

1.1 Context
River flooding is one of the world’s most destructive natural hazards, responsible for over 220,000 fatalities and NZ$1.2 trillion of damage between 1980 and 2013 (Winsemius et al., 2016). With climate change set to worsen these statistics, river management plans must meet both current and future generations’ needs (Brundtland, 1987; Intergovernmental Panel on Climate Change (IPCC), 2014). However, inter-generational planning is complex and the science is often fragmented (Sigel, Klauer, and Pahl-Wostl, 2010). Yet decision-makers must make rational and socially responsible decisions despite these uncertainties (Reichert et al., 2015; Walker et al., 2003).

Decision-support methods supported by flood impact assessment modelling allow the damages associated with different flooding scenarios to be assessed, offering invaluable information to planners and decision-makers (Alfieri et al., 2018). However, concerns around uncertainty have led to many disregarding the outputs of these models (Slawinski et al., 2017). The result has been decision-maker inaction or, in-keeping with traditional flood defence strategies, reliance on engineering-based solutions that cannot adapt over time and are instead tailored to a single “best-guess” at the future, with no back-up plan if that guess is wrong (Butler and Pidgeon, 2011; Haasnoot et al., 2013; Kwakkel, Haasnoot, and Walker, 2015). Neither approach appropriately accounts for the uncertainties inherent in projecting future flood events; the former treats uncertainties as an impassable barrier and the latter pretends they do not exist (Campbell, 1985; Voinov et al., 2016).

Yet accounting for uncertainty in river flood management is vital, given the complexities inherent in many socio-environmental issues (Kunreuther et al., 2013). And it is imperative that we begin immediately. Long-term changes in the magnitudes and frequencies of flooding events now seem inevitable for much of the world (Arnell and Gosling, 2016; Dankers et al., 2014). Current practice has thus far failed to sustainably manage such hazards, resulting in an “adaptation deficit” (MFE, 2017; Burton and May, 2004) and further delay in implementing effective responses will only leave more people and property exposed (Knutti et al., 2016).

Planning for adaptation must therefore begin to embrace uncertainties and start the transition from traditional flood defence towards more dynamic flood risk management (Butler and Pidgeon, 2011). However, for this to be achieved, decision-support methods used to inform management plans must also be capable of implementation using only the limited resources available to local bodies.

1.2 Thesis Rationale and Objectives
The problems discussed above are particularly acute in New Zealand. Approximately two thirds of the country’s population live in flood-prone areas (Rouse, 2012) and this will likely increase with population growth. Given the possible effects of climate change, it is critical that flood management decisions are made and implemented with due consideration of uncertainties.
Decision-support methods integrate uncertainty issues into traditional flood impact modelling. By exploring a range of scenarios for possible uncertainties, rather than a single “best-guess” future, they allow informed decisions regarding the appropriateness of interventions over time (Ranger, Reeder, and Lowe, 2013; Stephens, Bell, and Lawrence, 2017). Framing flood impact and intervention assessments as part of these wider decision-support methods can engender trust by providing transparent decision-making processes (Hall, Lazarus, and Swannack, 2014), while the modelling processes behind decision-support methods also offer unique engagement opportunities (e.g. serious games – Valering et al., 2013) to explore adaptation concepts in a range of future scenarios.

Whilst there is increasing application of decision-support methods to river flood management worldwide (e.g. Haasnoot, 2013; Lempert et al., 2013), uptake in New Zealand has been limited (see Lawrence and Haasnoot, 2017 in regards to the Hutt River; Tonkin and Taylor, 2017 in regards to the Waiho River). Instead, academics have focussed on applying decision-support methods to coastal hazards, especially sea level rise (e.g. Lawrence, Bell, and Stroombergen, 2019; Stephens et al., 2017). However, with new guidelines from the Ministry for the Environment (MFE) encouraging local governments to use a Dynamic Adaptive Policy Pathways (DAPP) decision-support method to aid decision-making in a coastal setting (MFE, 2017; Lawrence et al., 2018), it seems likely that similar guidance for river flood hazards will follow.

But is widespread implementation of DAPP for river flood management problems feasible? The current lack of uptake in New Zealand means that key questions, including whether existing national models and databases are capable of accommodating DAPP and whether local councils have sufficient resources to implement decision-support methods, have yet to be addressed. In addition, there has been little consideration around how the outcomes may be conveyed to communities effectively.

This thesis seeks to develop usable models for inclusion in a DAPP decision-support method based on a flood-prone New Zealand river, specifically the Whanganui River. It considers both the practicalities of developing such models using widely available software (focussing on Geographic Information Systems (GIS) and Microsoft Excel) and how they might be used to develop serious games to encourage stakeholder engagement with management uncertainties. As such, this thesis answers the following question:

What can be learned from applying an accessible (involving minimum cost, expertise and time) Dynamic Adaptive Policy Pathways approach to aid uncertain flood-based decision-making processes in relation to a New Zealand river?
To answer this question, the following objectives must be achieved:

Objective 1 - To develop an accessible methodology (the DAPP implementation methodology) to facilitate a model-based DAPP investigation of possible interventions for the Lower Whanganui River using three modules (climate and inundation; assets; and management and assessment) based on flood impact assessments.

Objective 2 – To analyse how the final modelling suite can be used to encourage stakeholder engagement with deep uncertainty through developing a serious game.

1.3 Case Study: The Lower Whanganui River

The Whanganui River is New Zealand’s longest navigable river and is located on the lower west coast of the North Island (Hsiao, 2012). The river is significant both to local Māori and wider governing institutions, being granted legal personhood status as part of a Treaty of Waitangi settlement process and accompanying legislation in March 2017 (Hutchison, 2014; Te Awa Tupua Act, 2017). Its extensive catchment stretching from headwaters on Mount Tongariro to the Tasman Sea includes various settlements, the largest of these being the city of Whanganui (over 40,000 people – Statistics New Zealand, 2013) in the Lower Whanganui River (LWR), defined here as the area immediately adjacent to the river’s channel over its last 22km before the river mouth (Figure 1.1) (Hsiao, 2012).

![Figure 1.1](image-url) – Location of the Whanganui River catchment in New Zealand (left) and the LWR sub-catchment (right).

Storm events eroding and transporting large quantities of loose sediment within the Whanganui catchment have noticeably elevated much of the river’s lower channel (Brierley et al., 2018; Horizons Regional Council (HRC), 2014). Combined with bedrock valley confinement in the intermediate and upper catchment, this has
resulted in significant flood risk for the LWR (Brierley et al., 2018) and indeed, there have been several destructive flood events since European colonisation (Figure 1.2).

**Figure 1.2** – LWR discharges from 1858-2015 including extrapolated historical extremes (blue) and annual maxima recordings post-1957 at the upstream Paetawa and Te Rewa gauge sites (orange). Destructive flood events greater than 4000m³/s are highlighted (discharges taken from Blackwood and Bell, 2016; photographs taken from Whanganui Chronicle, 2006; Whanganui Regional Museum, 2018).

Flood management in the LWR is currently undertaken by HRC. Since taking over management responsibilities from Whanganui District Council (WDC) in 2007, HRC has investigated several flood protection options, primarily involving traditional structural defence (Blackwood, 2007a). Initially, four stopbank areas were proposed for the river’s north and south banks to protect the priority areas of Taupo Quay, Balgownie Avenue, Upper Putiki and Anzac Parade to 1 in 200-year design levels (Figure 1.3 - HRC, 2008). However, public opposition meant only two stopbanks were ultimately built, giving 1 in 200-year protection (with 0.5m freeboard) and 1 in 50-year protection (with no freeboard) to Balgownie Avenue and Anzac Parade respectively (Ice Geo and Civil, 2012; Wilson, 2015).
This traditional flood defence strategy was widely accepted until the flooding of 19-21 June 2015, which resulted in a 5150 m³/s discharge being recorded at the City Bridge, devastating exposed areas of the LWR (Blackwood and Bell, 2016). More than 100 households were evacuated in what was the second largest river flood in New Zealand’s recorded history (Blackwood and Bell, 2016; Wilson and McDonald, 2015). Anzac Parade in particular suffered extensive damage, as its stopbank was not designed to cope with inundation at this level and consequently failed (Cooke and Galuszka, 2015).

Since the June 2015 flood, HRC has sought to incorporate new intervention options, including increased floor heights and staged managed retreat, into its flood management of the LWR. In particular, $50,000 annually has been set aside for interventions along Anzac Parade (Stowell, 2018). A new 1 in 200-year stopbank has also been proposed for the Upper Putiki area at a possible cost of $1.2m to ratepayers (Stowell, 2018). However, community concern over the efficacy and cost of the proposed measures means they may never be implemented (Stowell, 2018).

The LWR is an ideal case study to investigate accessible decision-support methods for several reasons. Scoping conversations with regional and district planners revealed that the landscape of the area has changed little in recent decades due to Whanganui’s stable population generating limited new development. In addition, current primary development zones in the Otamatea and Westmere suburbs are situated far from the main channel (Westcott, 2017). Therefore, distributions of assets and people can justifiably be kept static throughout.
the investigated planning horizon, unlike in the majority of DAPP-based studies (e.g. Lawrence and Haasnoot, 2017; Ramm, Watson, and White, 2018a; Ramm, Watson, and White, 2018b; Ranger et al., 2013), allowing model simplification that would not be possible elsewhere. This allows greater scope to focus on the sub-catchment’s existing complexities in terms of people, assets and flood protection schemes. In addition, as HRC’s management strategy remains in flux, any information gained from modelling in this thesis may be of use to HRC going forwards.

The LWR also clearly demonstrates the current resource constraints placed on local government in regards to river management. Since 2004, when large flood events caused extensive damage to the region, HRC has invested heavily in new measures throughout its Whanganui, Rangitikei and Manawatū protection schemes. Such spending has contributed to a cumulative debt of approximately $35 million to be paid over the next 18 years through targeted rate increases (HRC, 2019). HRC is therefore under increased pressure to reduce costs where possible, including the expense of flood plain mapping necessary for hazard analysis. Indeed, with the exception of some additional spending in the wake of the devastating June 2015 floods, spending on floodplain mapping has been in decline for over a decade (Figure 1.4). As such, there is a clear need for HRC to use cost-effective strategies to evaluate possible flood intervention strategies in order to prevent community alienation.

![Figure 1.4 – Recent HRC expenditure on flood plain mapping recorded in annual plans (adapted from HRC, 2007-2016).](image-url)
1.4 Research Framework and Thesis Structure

This thesis follows a modular structure. First, Chapter Two reviews three key areas of the literature, specifically deep uncertainty’s role in modern river management, the ability of decision-support methods to account for deep uncertainty through flood impact assessments and how serious games based on resulting models can enhance stakeholder engagement with management concepts. Chapters Three, Four and Five then set out the relevant method and results associated with the three model-based modules of the DAPP implementation methodology (Figure 1.5) which together generate a working flood impact model to assess LWR flood interventions. These three modules: integrate climate uncertainties into modelled flood hazards to establish scenarios (Chapter Three – module 1); use these scenarios to assess asset vulnerabilities against a developed database (Chapter Four – module 2); and identify interventions whose efficacy can be assessed (Chapter Five – module 3). Chapter Six then presents the method for, and results that emerged from, a serious game session used to encourage stakeholder engagement in uncertain water management problems.

![Diagram showing the DAPP implementation methodology and corresponding thesis structure.](image)

**Figure 1.5** – The DAPP implementation methodology and corresponding thesis structure.

Finally, overall discussions and conclusions for the thesis in relation to the research question and two overarching objectives are provided in Chapter Seven.
Chapter 2
LITERATURE REVIEW

2.1 Introduction
Literature regarding decision-support methods in river flood management contexts has developed over recent decades to address three key topics, specifically: the characteristics of deep uncertainty; the ability of decision-support methods to account for deep uncertainty using flood impact assessments; and the use of serious gaming to understand water management problems. In considering each of these topics, this chapter examines the place of flood impact models within decision-support methods and how they might provide useful information for decision-makers by incorporating uncertainties into damage calculations. It then identifies various gaps in the literature, which the remainder of this thesis then seeks to address.

2.2 Deep Uncertainty in River Flood Management
Identifying and addressing flood management uncertainties in complex river systems is exceptionally difficult due to the interplay between different environmental, social and economic parameters (Lempert et al., 2000). Simple models can be useful tools to analyse the interactions between these parameters (Warmink et al., 2010). However, attempting to downscale global climate models (GCMs) combined with difficulties predicting local population trends means that local government modellers and decision-makers face an “uncertainty cascade” when trying to establish climate change effects on river floods (e.g. Figure 2.1) (Walker et al., 2003; Wilby and Dessai, 2010).

The irreducible and often unidentifiable uncertainties represented in uncertainty cascades combine to produce “deep uncertainty” (Haasnoot et al., 2013; Kwakkel, Auping, and Pruyt, 2013; Lawrence et al., 2018; Lempert, 2003) Deep uncertainty is formally defined as circumstances in which (Lempert et al., 2003, p3.):

“...analysts do not know, or the parties to a decision cannot agree on, (1) the appropriate models to describe the interactions among a system’s variables, (2) the probability distributions to represent uncertainty about key variables and parameters in the models, and/or (3) how to value the desirability of alternative outcomes”.

The deep uncertainty associated with river flood management problems means that they are difficult to resolve into any single climate or flood impact model (Haasnoo and Middelkoop, 2012; Haasnoo et al., 2013; Ranger et al., 2013). Thus, there is a growing demand for methodologies that transform models addressing individual aspects of a deep uncertainty problem into more holistic assessment tools. In particular, planners seek methodologies able to incorporate and explore multiple uncertainties and inform decisions which will have long-lasting effects. Recent efforts have revolved around the developing field of decision-support methods which attempt to use the scientific data from risk assessments and impact modelling to evaluate possible management options over a series of identified uncertainty scenarios (Gibson et al., 2017; Reichert et
al., 2015). Traditionally, scenarios include downscaled versions of the IPCC’s global Representative Concentration Pathways (RCPs) to account for possible climate change uncertainties whilst representations of other land-use and policy uncertainties are tailored specifically to case studies (Maier et al., 2016; Ray and Brown, 2015).

![Figure 2.1](image-url) – An uncertainty cascade for future-based flood impact modelling of local river systems (adapted from Refsgaard et al., 2013).

### 2.3 Decision-Support Methods

Decision-support methods promote management plans that can successfully operate under a wide range of future scenarios, placing uncertainty at the centre of decision-making (Walker, Haasnoot, and Kwakkel, 2013). To accomplish this, decision-support methods follow three guiding principles (MFE, 2017; Walker et al., 2013):

- not all uncertainties can be reduced/eliminated;
- not accounting for uncertainties could result in management strategies which cannot adapt to change (lock-in effects); and
- ignoring uncertainties may lead to missed opportunities resulting in previously workable plans becoming unsustainable (path dependencies).
Recent uptake of decision-support methods reflects a move towards decision-making being supported by modelling. This approach allows objective consideration of new and previously unpopular interventions (e.g. managed retreat) alongside traditional protection (such as stopbanks for the LWR) (Nye, Tapsell, and Twigger-Ross, 2011). By considering flood impacts over extended timeframes, decision-support methods also encourage a transition from one-stop “flood defence” towards dynamic “flood risk management”, enabling more nuanced aspects of risk to be investigated (Butler and Pidgeon, 2011).

Decision-support methods for deep uncertainty problems typically promote one or more of the following (Van Drunen, Leusink, and Lasage, 2009; Walker et al., 2013):

- resistance – enabling systems to withstand greater external pressures;
- resilience – promoting faster system recovery;
- static robustness – reducing vulnerability across as many conditions as possible; and/or
- dynamic robustness – encouraging flexibility so that plans can change to suit the conditions, using signposts and triggers to identify when contingency plans need to be enacted

However, methods focussed on resistance often recommend interventions which are expensive and difficult to adapt to changing conditions (Millar, Stephenson, and Stephens, 2007). By contrast, resilience methods focus on sustainability and the capacity of communities to “bounce forward”, allowing faster recovery from the impacts of hazard events (Manyena et al., 2011; Seager, 2008) but at the expense of taking the politically unpopular view that certain levels of damage are inevitable.

Both resistance and resilience methods also assume that the projections they are based on are accurate (Walker et al., 2013). However, the deep uncertainty surrounding river management suggests such assumptions are invalid. If projections of the future are inaccurate, strategies based upon them will likely fail (Haasnoot et al., 2013; Kwakkel et al., 2013). Furthermore, there is no guarantee that a "best-guess" projection of the future, even if ultimately accurate, will prompt the adoption of a strategy that optimises outcomes for all stakeholders and assets (Lempert et al., 2006; Maier et al., 2016).

To minimise problems associated with resistance and resilience-based strategies, newer methods promote plans which are less dependent on the accuracy of projections by trying to meet one of two objectives (Walker et al., 2013):

- plans are robust to many different realisations of the future (static robustness e.g. Robust Decision-Making); or
- plans can adapt to many different realisations of the future (dynamic robustness e.g. DAPP).

Decision-support methods based on static and dynamic robustness try to protect management plans from failure by determining whether objectives are still achieved in chosen scenarios despite underlying assumptions
about uncertainties proving false (Bloemen et al., 2017; Walker et al., 2013). Each method is designed to advance a certain set of decision priorities and can be made more or less complex depending on the time and resources available to run models. An overview of current robust and dynamic focussed decision-support methods used to aid flood-based decision-making is given in Table 2.1.

Table 2.1 – Overview of available decision-support methods used to aid flood management (adapted from MFE, 2017 and Watkiss et al., 2014).

<table>
<thead>
<tr>
<th>Decision- Support Method</th>
<th>Objective</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
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</table>
| Cost-Benefit Analysis (CBA) | Short-term assessments specifically looking at market sectors | • Well known and frequently applied to river and coastal hazard problems.  
• Most useful when climate risk probabilities are known.  
• Operates best for market sectors.  
• Frequently used in combination with other methods. | • Reliant on good data for major cost-benefit components.  
• Uncertainty incorporation limited to probabilistic risk.  
• Equal treatment of high probability–low risk and low probability–high risk so under high uncertainty potentially good options for the future may fail. |
| Cost Effectiveness Analysis (CEA) | Short-term assessments in non-monetary terms. Comparative assessment method. | • Most useful when climate risk probabilities are known but for non-monetary assets (e.g. ecosystem health) and a single dominant impact is investigated.  
• Shows which strategy achieves a required risk level for the lowest cost. Can be used in combination with other methods. | • Requires agreement on sectoral social objective (e.g. tolerable risk of flooding). Also need clear establishment of cost-risk reduction relationship.  
• Evaluates options with only one outcome (reducing flood risk).  
• Equal treatment of high probability–low risk and low probability–high risk.  
• Uses single metric for multiple impacts.  
• Little uptake in research. |
| Multi-Criteria Analysis (MCA) – suite of methods with potential combinations | Simple framework for evaluating options over varying timeframes in accordance with set criteria | • Integrates qualitative and quantitative information.  
• Presents possible options as a simple weighted hierarchy.  
• Highly adaptable and increasingly popular. | • Should be clearly adapted to specific case studies.  
• Researchers should also consider potential uncertainties associated with decision-maker interpretations of weighted hierarchies. |
| Iterative Risk Assessment or Adaptive Management (IRM) | Framework for assessment and planning associated with complex risks/long timeframes. | • Iterative analysis that uses monitoring, research, evaluation and learning to adjust plans as information becomes available.  
• High flexibility.  
• Can incorporate monetary and non-monetary components. | • Difficult to use for complex problems with multiple risks – problems identifying thresholds.  
• Questions remain over practical application. |
<table>
<thead>
<tr>
<th>Decision-Support Method</th>
<th>Objective</th>
<th>Strengths</th>
<th>Weaknesses</th>
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<tbody>
<tr>
<td>Real Options Analysis (ROA)</td>
<td>Quantifies the value of particular interventions based on the amount of risk transferred under uncertain future conditions.</td>
<td>• Useful for comparing flexible and inflexible interventions.</td>
<td>• Issues incorporating non-market assets.</td>
</tr>
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<td></td>
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<td>• Encourages learning by stipulating whether more information is required before interventions are applied.</td>
<td>• Requires known probabilities and decision points.</td>
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<td></td>
<td></td>
<td>• Frequently used in combination with other methods.</td>
<td>• Highly complex.</td>
</tr>
<tr>
<td>Robust Decision-Making (RDM)</td>
<td>Attempts to find robust strategies for deep uncertainty problems – strategies whose performance is unaffected by a range of plausible futures</td>
<td>• Values static robustness rather than optimisation for given scenarios.</td>
<td>• Can become computationally complex depending on the problem.</td>
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<tr>
<td></td>
<td></td>
<td>• Uses scenario discovery algorithms to provide insights to combinations of uncertainties that result in system failures.</td>
<td>• Requires a large number of impact simulations over different future scenarios to develop a case database that can be searched.</td>
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<td></td>
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<td>• Approach can be targeted in by the adaptation options considered resulting in faster computation times than other approaches (e.g. multi-objective optimization).</td>
<td>• Time intensive.</td>
</tr>
<tr>
<td>Portfolio Analysis (PA)</td>
<td>Focus on the tradeoffs between investment and given levels of risk for asset portfolios.</td>
<td>• Emphasis on spreading asset investments to spread risk – Investments with high variance on potential returns are judged as high risk.</td>
<td>• Currently few applications of PA in flood risk management.</td>
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<td>• Can use economic or physical metrics to quantify expected returns from each portfolio.</td>
<td>• Requires key data regarding the variance of options over the range of climate scenarios investigated.</td>
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<td>• Encourages going beyond standard one stop shop solutions to combat uncertainties.</td>
<td>• May have interdependency issues between considered options.</td>
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<tr>
<td>Dynamic Adaptive Policy Pathways or Dynamic Adaptive Pathways Planning (DAPP)</td>
<td>Develops a dynamic adaptive plan to combat long-term uncertainty based on component pathways.</td>
<td>• Encourages flexibility in allowing plans to change as more information about future conditions becomes available.</td>
<td>• Fundamentally static responses but dynamic elements could be introduced with other methods (e.g. ROA)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Also draws on PA strengths by using pathways made up of multiple interventions.</td>
<td>• Evaluation of pathways is traditionally done through scorecard analysis which can be highly subjective.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Simple conceptual framework.</td>
<td>• Usually used in conjunction with other model-based tools (e.g. MCA, ROA)</td>
</tr>
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</table>

Some of these methods have proven so successful that they have been adapted into policy to support national adaptation projects (Lawrence et al., 2019). In New Zealand, MFE has recommended DAPP as a preferred mechanism for generating adaptive coastal hazard plans based on the work of the Resilience National Science Challenge “Living at the Edge” project (funded by the Ministry of Business, Innovation and Employment), particularly in devising coastal management plans for the Hawkes Bay (MFE, 2017; Lawrence et al., 2019).
Unlike other decision-support methods (e.g. CBA, IRM and traditional RDM), DAPP is not reliant on high levels of computational complexity to be applied and can be used across a large range of problem types (Lawrence et al., 2018). It also provides a simple conceptual framework that can be easily communicated to stakeholders. As such, DAPP is a logical choice for implementation on a national scale.

2.3.1 Dynamic Adaptive Policy Pathways

DAPP (Figure 2.2) is a decision-support method that seeks to create flood management plans based on acceptable levels of hazard impact and has been applied to sections of the Rhine Delta (Haasnoot et al., 2013) and the Thames2100 project (McGahey and Sayers, 2008; Ranger et al., 2013). The method integrates the stepwise approach to basic policy development and contingency planning found in adaptive policymaking with the sequencing of interventions found in adaptive pathways (Haasnoot et al., 2013; Stephens et al., 2017). The result, Haasnoot et al (2013) claim, is an accessible conceptual framework which can be applied across different management problems while also allowing customisation to take into account changing circumstances. This increased flexibility drastically reduces risks of maladaptation as any problems can be corrected over time by decision-makers (Bloemen et al., 2017).

DAPP assumes that policies/decisions have a fixed shelf-life and will lose efficacy if wider system conditions change significantly (Kwadijk et al., 2010). Situations where the hazard impact becomes so great that current management strategies cannot meet their societal objectives are called adaptation tipping points; when these are reached, a new management pathway is required (Haasnoot et al., 2012; Kwadijk et al., 2010; Werners et al., 2013). Using appropriate models, the nature and possible timing of tipping points can be analysed under different uncertainty scenarios to inform an adaptive plan comprising short and long-term actions over an

Figure 2.2 – Components of the DAPP decision-support method (MFE, 2017 and adapted from Haasnoot et al., 2013).
extended timeframe (Kwakkel, Walker, and Haasnoot, 2016; Lawrence et al., 2018). Different action pathways can then be put in place if pre-determined tipping points are reached. Signpost and trigger scenarios are also used to pre-empt main tipping point events, allowing necessary strategy changes to be made earlier and thus avoiding unnecessary damage (Kwakkel et al., 2016; Stephens et al., 2017).

The cyclical nature of DAPP means that management agencies must revisit each step of the method throughout the life of an adaptive plan, incorporating new information as it becomes available. This revisiting may include re-examining societal objectives as communities evolve or the updating of RCPs with more accurate data (Sanford et al., 2014), resulting in intervention pathways being re-evaluated. This ability to continually add and update information exists because DAPP does not try to find single immediate solutions to deep uncertainty problems. Instead, it establishes a management system that is equal parts proactive and reactive, seeking to maintain societal objectives over time.

Plans resulting from DAPP can inform both management practices and wider community understandings about adaptation and underlying modelling of flood impacts, highlighting the effects of climate change uncertainties and the need for adaptive long-term management strategies to address them (Barnett et al., 2014; Bloemen et al., 2017). Additionally, communities can help to define societal objectives and impact modelling evaluation strategies used to establish adaptation tipping points (e.g. Barnett et al., 2014). In doing so, valuable information can be provided for the generation of DAPP whilst encouraging community buy-in to the process.

2.3.2 Flood Impact Assessments

Traditionally, flood impact assessments have supported decision-making for disaster relief and resource allocation and, in the longer term, been used to determine appropriate insurance policies (Hammond et al., 2015). Now they are an essential part of decision-support methods, including DAPP, because they can generate damage approximations associated with hypothetical flood events (Ramm et al., 2018a; 2018b). However, historical impact assessment approaches, like the policies they have informed, have tended to focus on one-off flood events, with the aim of reducing the economic costs associated with that single flood (Merz, Hall et al., 2010). By contrast, contemporary impact assessments use computer models to assess impacts associated with a large number of possible events and whether a specific level of damage will occur or be exceeded within a given timeframe (e.g. annual exceedance probabilities) (Merz, Kreibich et al., 2010., 2014; Zhou et al., 2012). Such assessments frequently use economic impacts as part of a common denominator approach, presenting hazard impacts in a consistent format (i.e. as a dollar figure) that can be readily explained to communities and other stakeholders (Merz, Kreibich et al., 2010).

Flood impact assessment modelling uses hazard and vulnerability assessments to determine likely flood effects (Olsen et al., 2015). First, appropriate hazard layers are generated to approximate expected flood characteristics (Merz and Thieken, 2004). These can be based on observational inundation data (e.g. satellite imagery – Schumann and Di Baldassarre, 2010) or, more commonly, hydrological and hydraulic simulation models which represent flood generation processes and can be calibrated using historical flooding events (de
Moel et al., 2015; Hammond et al., 2015). A spatially accurate population and asset vulnerability layer is then superimposed on the hazard layer to derive location-specific flood information (Schmidt et al., 2011). The probability of expected damage to assets is then calculated based on the overlap between the hazard and vulnerability layers and presented using various metrics (e.g. replacement and repair costs, casualties, societal disruption etc.) (Crawford et al., 2018; de Moel et al., 2015). Figure 2.3 provides an overview of this process.

![Figure 2.3](image)

**Figure 2.3** – Basic steps for a flood impact assessment with illustrations specific to this thesis. Hazard assessment steps are in blue, vulnerability assessment in yellow, identification of exposed assets in green and corresponding impact damages in orange (DEM provided by HRC and damage functions taken from Reese and Ramsay, 2010).

However, the deep uncertainty associated with river management problems and the limited resources of local government mean that accurately determining the probabilities required for standard flood impact assessments is not always possible (MFE, 2017; Eaves and Doscher, 2015; Olsen et al., 2015). In these circumstances, decision-support methods like DAPP remove the need to calculate fixed probabilities by using uncertainty scenarios to evaluate intervention effectiveness (Haasnoot et al., 2015). These uncertainty scenarios can be modelled by adjusting the hazard (e.g. increased flood magnitudes) and vulnerability (e.g. increased population density) layers of models. Simple scenario approaches can therefore give valuable
insights into uncertainty combinations that may lead to adaptation tipping points and be used to suggest corresponding intervention pathways.

_Flood Hazard_

Hazard layers for flood impact assessments are typically based on the results of flood simulation models calibrated using historical observations (de Moel et al., 2015). Such models vary in complexity, ranging from an overlay of areas subjected to inundation on a DEM to three-dimensional solutions for a matrix of geomorphic and fluvial equations (Sanders et al., 2005). The complexity required will be determined by the purpose of the model.

For flood impact assessments forming part of a decision-support method, the goal is to approximate the characteristics of potential flooding at asset locations in order to calculate possible damages over a range of scenarios (Zhou et al., 2012). One way of accomplishing this is through combining local-scale simulation models with global and national climate models which incorporate climate change effects. The resulting model suite is then used to investigate hydrological discharge, flood attributes and flood impacts (Figure 2.4) (Ward et al., 2014). However, the process of combining models is very complicated due to the range of possible flooding effects (e.g. water depth, flow velocity, debris effects, etc.) and location-specific factors including geomorphology and the presence of flood defence structures.

_Figure 2.4_ – Illustrating a basic model suite used to derive local scale flood attributes from changes in global/regional climate.

Because of the complexity and resources involved in developing, calibrating and running the relevant software, flood simulation models have generally been used to project only a small number of isolated flood events (King and Bell, 2005). However, DAPP requires impact assessments based on large numbers of different uncertainty scenarios. As such, streamlining must be achieved through improved model efficiency and technology; use of simple conceptual models; or using surrogate/emulation models (Teng et al., 2017). However, such streamlining introduces possible uncertainties of which decision-makers should be made aware (Brath, Montanari, and Moretti, 2006, Walker et al., 2003; Warmink et al., 2010).

_Flood Vulnerability_

Flood vulnerability assessments to support impact modelling investigate asset attributes to determine how they might be impacted by different flood events and to calculate possible damages based on those impacts (de Moel et al., 2015; Merz, Kreibich et al., 2010). Modelled damage to assets can be categorised based on
whether or not damages are quantifiable in monetary terms (tangible versus intangible) and whether they are the result of direct contact with floodwaters or an associated effect outside the flooded area (direct versus indirect) (Figure 2.3) (Hammond et al., 2015; Olsen et al., 2015). Within the literature, flood vulnerability assessments based around direct tangible damage calculations are generally preferred, as they are the most straightforward to model and their outcomes are easily understood (Merz, Kreibich et al., 2010).

Damage Functions

Damage functions (or damage curves) are used in flood vulnerability assessments to link hazard characteristics to an expected level of impact for particular assets (e.g. Figure 2.5) (Merz, Kreibich et al., 2010; Olesen, Löwe, and Arnbjerg-Nielsen, 2016). The international standard for flood-based functions has historically been depth-damage functions (Seifert et al., 2010; Smith, 1994). While damage functions based on other parameters (e.g. flow velocity, duration of inundation) are becoming increasingly prominent (Merz, Kreibich et al., 2010), whether such functions accurately reflect the interactions between the relevant parameters in the real world is unclear (Wagenaar et al., 2016). However, in each case, the damage function uses flood hazard data for the location of a particular asset to calculate a corresponding percentage of damage or a damage ratio (de Moel et al., 2015; Olesen et al., 2016). For direct tangible damages, this ratio can be multiplied by the asset’s full or depreciated replacement cost to estimate loss (de Moel et al., 2015). Direct intangible damages, by contrast, usually require further calculations to translate hazard characteristics into a continuous variable (e.g. displacement time, disrupted business time) that might then be converted into a tangible cost (e.g. temporary accommodation cost, loss of business costs) or else are based on a fixed percentage of tangible damages (Hammond et al., 2015). Because of the difficulty in translating specific hazard characteristics into estimates of indirect damage, such damages cannot usually be assessed using damage curves.
Damage functions for direct tangible damages can be characterised by their development (e.g. empirically derived functions versus synthetic) and the range of possible assets to which they can be applied (e.g. relative functions which can be widely applied versus absolute functions which cannot). Each has unique advantages and disadvantages, making them suitable for different purposes. Table 2.1 gives an overview of the four main function types and their possible applications.

While damage functions have been used globally since the 1970s (Grigg and Helweg, 1975), and there have been efforts to refine existing functions and develop new ones in line with available pre- and post-event data (Pistrika, 2010), there remain few damage functions calibrated for New Zealand assets. Due to community concerns around damage to residential properties, most New Zealand depth-damage functions have focused exclusively on suburban homes (e.g. Reese and Ramsay, 2010). This has led to other important asset types, including three waters and electrical infrastructure, being neglected (Hammond et al., 2015; Merz, Kreibich et al., 2010). Since the assets used to derive damage functions should be as similar as possible to those to which the function is applied (Reese and Ramsay, 2010), this lack of calibrated damage functions for key asset types is a significant issue for holistic flood impact assessments to overcome.

**Figure 2.5** – Example of relative depth-damage functions for different building use categories (adapted from Reese and Ramsay, 2010).
Table 2.2 – Damage function classifications (adapted from Merz, Kreibich et al., 2010).

<table>
<thead>
<tr>
<th>Damage Function</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Empirical functions | Developed from historically observed data | • Based on real data so greater accuracy than synthetic functions  
• Can apply damage mitigation measures  
• Can quantify associated uncertainties | • Requires detailed post-event surveying which is rarely available  
• Based on events of a particular magnitude meaning extrapolation is unreliable  
• Curves are based on particular asset types and cannot easily be applied to different assets |
| Synthetic functions | Developed based on expert judgement independent of observed damages | • Can be developed for individual assets  
• As actual flood hazard data is not required, can be readily developed for any area  
• High level of standardisation | • Substantial effort required to establish necessary databases or undertake large surveys for different asset types  
• What-if analyses are subjective and can therefore incorporate additional uncertainties  
• Mitigation measures cannot be taken into account |
| Relative functions | Use damage ratios to establish monetary damages associated with a spectrum of flood events | • Simple to use  
• Good transferability in time and space  
• Applicable for different purposes  
• Widely used across national level hazard loss estimation software (e.g. RiskScape, HAZUS-MH) | • Are based on asset values which may be difficult to obtain across large datasets |
| Absolute functions | Absolute monetary amounts of damage per at-risk asset | • Asset values are not required as damages are calculated directly | • Functions need to be regularly recalibrated  
• Cannot be readily applied to other areas |

National Models to Inform Flood Impact Assessments

National models that can provide the hazard and vulnerability components of flood impact modelling theoretically offer a mechanism for developing decision-support methods cheaply and consistently. A national approach would also relieve resource-constrained local governments of the responsibility of maintaining impact models and datasets, allowing them to focus on adapting these decision-support methods to specific case studies. However, for a national model to be applied at the local scale, it must allow calibration to specific case study parameters or be able to focus on a geographically defined area.
In theory, there are several New Zealand national models and datasets that meet this requirement and could provide the flood hazard and vulnerability components for a DAPP investigation. For example, the TopNet national hydrological model (Figure 2.6) developed by New Zealand’s National Institute of Water and Atmospheric Research (NIWA), could be used to develop river discharges affected by climate change for component impact assessments (Lawrence et al., 2013). Currently, TopNet has only been calibrated for New Zealand’s major river networks (Collins et al., 2018) and has rarely been used to inform flood impact assessments (e.g. the Hutt River Lawrence et al., 2013). However, expanding the program’s scope could offer opportunities for streamlining localised DAPP investigations by linking RCP-based climate change scenarios to a particular river’s discharges, providing the flood hazard component for flood impact assessments. TopNet’s potential application to the DAPP implementation methodology developed in this thesis is considered in Chapter Three.

![Figure 2.6](image_url) – Schematic diagram showing the main components of the New Zealand TopNet semi-distributed hydrological model (taken from Bandaragoda, Tarboton, and Woods, 2004).

Where TopNet may provide flood hazard information, the national RiskScape program can offer insights into asset vulnerability for impact assessments. RiskScape is a freely available software tool developed by NIWA and Institute of Geological and Nuclear Sciences (GNS Science). The tool estimates tangible damages from a variety of flooding, volcanic, seismic and meteorological hazard case studies by assessing input hazard and vulnerability information as part of an impact assessment process (Figure 2.7) (Deligne et al., 2017; King and Bell, 2005; King and Bell, 2009; Reese and Ramsay, 2010; Schmidt et al., 2011). RiskScape’s strength is that it seeks to develop damage outputs for given hazards quickly with few user inputs and thus is an obvious choice.
for use in decision-support methods applied nationally (GNS Science/NIWA, 2017). RiskScape’s possible applications to the DAPP implementation methodology are explored in Chapter Four.

![Figure 2.7](image.png)

**Figure 2.7** – Illustrating the impact assessment process used in RiskScape (taken from GNS Science/NIWA 2017).

### 2.3.3 Dynamic Adaptive Policy Pathways Evaluation Strategies

Decision-support methods usually culminate in some form of evaluation of possible management interventions (Haasnoot et al., 2013). For DAPP, evaluation of possible damage reductions resulting from interventions can be conducted qualitatively using scorecards based on professional judgement (e.g. Figure 2.8) or quantitatively, using additional computation-based support tools and flood impact assessments (e.g. scenario discovery based on Robust Decision-Making – Kwakkel et al., 2016). Whilst qualitative analyses can suggest at a high-level which approach may be preferable, relying on subjective experiences rather than reassuringly definite numbers may reduce their perceived efficacy and thereby prevent long-term community investment in DAPP (Ramm et al., 2018b). In contrast, quantitative investigations evaluating options over all possible uncertainty values are resource-intensive (Kwakkel et al., 2016), but offer an unbiased and evidence-based recommendation that can be taken to communities.

The range of options available when evaluating DAPP outputs is a well-recognised strength of the approach (e.g. Lawrence and Haasnoot, 2017; Lin et al., 2017; Stephens et al., 2017). However, this flexibility may also result in a lack of consistency. National implementation of DAPP would therefore require a standard evaluation approach to be used by all local governments. This thesis investigates the use of a new computation-based decision-support code to evaluate LWR interventions in Chapter Five.
2.4 Serious Games to Inform River Flood Management

There are few opportunities to study how decision-support methods might assist flood-based decision-making processes outside of actually implementing them. Serious simulation games, in which the primary purpose is something other than pure entertainment (den Haan and van der Voort, 2018), allow rapid feedback on long-term management strategies by forcing players to make decisions which would usually be taken over years or decades over the course of a few rounds. These games also seek to educate participants about deep uncertainty problems (Lawrence and Haasnoot, 2017) while simultaneously demonstrating how present-day decisions might affect future flood impacts. Finally, game sessions can provide valuable information about what decision-makers perceive to be the key considerations in flood management (Bots and Van Daalen, 2007; Lawrence and Haasnoot, 2017), allowing researchers to better reflect these considerations in future impact models and intervention evaluation techniques.

Typically taking the form of role-play simulation exercises, serious games require participants to make decisions based on provided information whilst being forced to comply with an underlying set of constraints (Schenk and Susskind, 2014). The game then translates these decisions into downstream effects in line with overarching game objectives; for example, in decision-support method inspired games, outputs may highlight the benefits of specific management approaches. On an individual level, the illustration of deep uncertainty using interactive models increases the likelihood of the concept resonating with decision-makers (Haug, Huitema,
and Wenzler, 2011). Furthermore, human participants can put their own constraints (e.g. prioritising protection of heritage buildings) on deep uncertainty problems which would not otherwise be considered by an objective model (Bots and Van Daalen, 2007). As such, serious games offer a novel way to bridge the science-policy interface (Van Pelt et al., 2015).

Serious games have been applied to better understand and support water management decision-making throughout Europe (e.g. Haug et al., 2011; Hoekstra, 2012; Valkering et al., 2013). Whilst they have shown great promise in New Zealand (e.g. Lawrence and Haasnoot, 2017), uptake has been limited. Considering the potential benefits of serious games highlighted above, methods to develop new games for the New Zealand context warrant further investigation.

**Evaluating Serious Gaming Outcomes**

Alongside developments in software, recent decades have seen the establishment of new conceptual frameworks for evaluating serious game outcomes. These frameworks seek to provide a standard against which to assess game performance, with most focussing explicitly on how and how well a game facilitates learning opportunities. For example, the three part framework proposed by Baird et al. (2014), which distinguishes between three learning types, cognitive (new learning or changes in existing understanding), normative (changes in viewpoints) and relational (improved understanding of others’ perspectives), has frequently been used to evaluate serious game outcomes (e.g. den Haan and van der Voort, 2018; Flood et al., 2018; Lawrence and Haasnoot, 2017). Similarly, Bots and van Daalen (2007) established a six-part framework to measure how well serious games act as impartial mediators within complex policy scenarios. Such frameworks assume game models to only be capable of calculating damages, with evaluations focussed on assessing high level learning opportunities. This assumption has arguably resulted in games where the inner workings of models are hidden, preventing participants from providing feedback on the component parts (Mechler et al., 2019). By contrast, increasing the transparency of gaming software and related impact models may allow players to explore their component modelling processes and thereby provide feedback that can be used to improve future versions (Jean et al., 2018).

**The “Sustainable Delta Game” (SDG)**

The SDG is one of the most widely used serious games available for flood management problems (e.g. Lawrence and Haasnoot, 2017; Valkering et al., 2013; Van Pelt et al., 2015; Van der Wal et al., 2016). It is freely accessible from the Deltares institute and has three game worlds to choose from comprising river and coastal management problems (Deltares, 2016). The game combines a computational simulation model used to generate annual discharges (from Haasnoot et al., 2012) with various visual elements to allow players to make flood-based decisions and see their consequences over extended time frames (Figure 2.9) (Van Pelt et al., 2015). These visual elements include a map of the area on which chosen interventions can be displayed, as well
as fictional newspaper articles which set out information regarding community opinions and global economic trends which may affect decision-making (Valkering et al., 2013).

![Figure 2.9 – Overview of the Sustainable Delta Game model components (taken from Valkering et al., 2013). Note STEEP refers to Social, Technological, Economic, Environmental and Political.]

One shortcoming of the SDG is that, whilst teams can view their scores across different metrics (e.g. economic flood damage, casualties, drought impacts and biodiversity loss) (Deltares, 2016), they cannot directly see the methods used to calculate those scores and so cannot learn about core modelling processes. Allowing participants to better engage with the models behind the game could lead to valuable insights, including into how flood damages and community priorities can be more accurately represented for asset protection. By enabling players to directly judge the impact models’ accuracy and identify areas for improvement, players may also become more willing to trust management recommendations based on those models. The SDG also lacks a visual display of the extent of simulated flood events; however, current literature suggests that using 3D mapping techniques to display flood inundation can improve risk hazard visualisation and communication and, by extension, the decision-making process (Chen et al., 2018; Macchione et al., 2019). A new accessible method to create transparent serious games and evaluate their outcomes is therefore needed to generate stakeholder buy-in for broader decision-support methods that are based on the same models. An examination of one possible approach is conducted in Chapter Six.
2.5 Areas for Further Research

It is clear that quantitative decision-support methods supported by flood impact modelling have great potential to aid decision-making in river flooding contexts. In New Zealand, several national models may also provide useful inputs into both hazard and vulnerability components of the DAPP implementation methodology if they can be adapted to particular case studies. However, whilst these isolated models provide a useful starting point, they are not a complete methodology and it is unclear what additional components will be required to produce a model which is effective at a local scale. In addition, serious games based on flood management problems have also been under-utilised and there is a need to better understand how calibrated, transparent game complexes and 3D flood visualisations could aid in communicating local flood impacts and improving stakeholder buy-in to DAPP and other decision-support method investigations. This thesis therefore seeks to fill some of these gaps using a custom-made DAPP implementation methodology.
Chapter 3

MODULE 1: CLIMATE AND INUNDATION

3.1 Introduction
This thesis seeks to develop flood impact assessment modelling for use in a DAPP implementation methodology using limited time and resources (Thesis Objective 1). A necessary first step to developing such modelling is to create usable flood hazard inputs based on climate change influenced RCP scenarios.

Using a 64-bit version of Microsoft Excel to carry out calculations, this chapter sought to develop flood hazard inputs through:

- analysing the capacity for TopNet model outputs to provide a viable benchmark for management authorities to test potential interventions against;
- infilling the annual LWR historical annual maxima record;
- establishing a hypothetical time series based on the distribution of the new annual maxima record;
- incorporating RCP-derived effects into the time series using the NIWA High Intensity Rainfall Design System (HIRDS) model; and
- developing flood depth grids for hypothetical time series discharges using the freely available HAZUS Flood Information Tool (FIT).

Resulting flood depth grids are then used as the flood hazard component of flood impact modelling (module 2).

3.2 TopNet Analysis
The TopNet hydrological model integrates the results of six downscaled GCMs from the IPCC to assess potential future discharges for New Zealand’s major river systems, including the Whanganui River (Collins, Montgomery, and Zammit, 2018; McMillan, Booker, and Cattoën, 2016). Each GCM is driven by climate forcings associated with one of the four established IPCC RCP scenarios (2.6, 4.5, 6.0 and 8.5) but is otherwise run continuously for 128 model years (1971 to 2099) (Collins et al., 2018). However, the fact that TopNet runs continuously means that its outputs are not calibrated against historical records (McMillan, Jackson, and Poyck, 2010). This lack of calibration can potentially produce implausibly extreme discharges that would not only reduce accuracy but also slow down processing times for the broader DAPP implementation methodology model suite. It was therefore necessary to screen the TopNet data before use.

To establish TopNet’s capacity to provide relevant RCP-derived LWR discharges, 128 years of modelled annual maximum discharges for the upstream Te Rewa gauge site were sourced from NIWA. This included a 34 year calibration period (1972-2005) and a 93-year climate change-influenced period (2007-2099) for each of the six GCMs operating under the four IPCC RCP scenarios. As the Te Rewa gauge only began recording in 2006, historical readings had to be derived from the Paetawa gauge (in operation from 1957 to 2013). However,
because Paetawa’s proximity to the newer Te Rewa gauge site means that it has the same catchment area (6643 km²), the two sites are used interchangeably by HRC and for this project (Blackwood and Bell, 2016).

TopNet data for the 1972-2005 calibration period was screened for accuracy against historical discharges for the Paetawa/Te Rewa gauge sites to identify any statistically significant differences between the datasets. The comparison between the TopNet outputs for the least extreme RCP (2.6) and the historical record for the Paetawa /Te Rewa gauge sites is shown in Table 3.1. For this comparison and subsequent analyses, a discharge of 5150 m³/s recorded at the City Bridge was associated with the June 2015 annual maxima as the Te Rewa gauge record of 4755 m³/s did not account for extensive rainfall in the lower catchment that specifically contributed to this event (Blackwood and Bell, 2016).

Table 3.1 – Direct comparison of historical annual maxima and annual maxima outputs for the Te Rewa gauge from TopNet. This includes results of two-tailed two sample t-tests for the mean annual maxima historical record and the mean annual maxima during the TopNet calibration period (1972-2005) for each of the six GCMs with statistically significant differences indicated by p-values <0.05 (red).

<table>
<thead>
<tr>
<th>Model</th>
<th>Annual Maxima Discharge (m³/s) – Statistics for Calibration Period (1972 – 2005)</th>
<th>Annual Maxima Discharge (m³/s) – Statistics for climate change-influenced period (2007-2099) under RCP 2.6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>p-Values</td>
</tr>
<tr>
<td>Historical Record (1957-2015)</td>
<td>2359 ± 822</td>
<td>-</td>
</tr>
<tr>
<td>GCM 1</td>
<td>1289 ± 737</td>
<td>1.58x10^{-11}</td>
</tr>
<tr>
<td>GCM 2</td>
<td>1339 ± 612</td>
<td>1.04x10^{-12}</td>
</tr>
<tr>
<td>GCM 3</td>
<td>1270 ± 764</td>
<td>2.17x10^{-11}</td>
</tr>
<tr>
<td>GCM 4</td>
<td>1642 ± 919</td>
<td>3.21x10^{-6}</td>
</tr>
<tr>
<td>GCM 5</td>
<td>1803 ± 1972</td>
<td>0.02</td>
</tr>
<tr>
<td>GCM 6</td>
<td>1720 ± 1536</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The comparison shows large disparities between annual maximum extremes for all TopNet GCMs over the calibration period and the extremes observed in the historical record, resulting in statistically significant differences. These differences (in particular for high magnitude annual maxima), observed even when using the least extreme RCP scenario were deemed too great for the TopNet generated data to be used to test plausible management interventions in module 3. The decision not to use TopNet data was further supported by the fact
that maximum discharges for three of the GCMs over the climate change influenced period (2007-2099) were three times higher than the largest annual maxima from the LWR historical record (Blackwood and Bell, 2016), again suggesting that the TopNet projections were unrealistic.

### 3.3 An Alternative to TopNet

A new hypothetical time series of future LWR flood events from 2016 to 2100 was therefore needed to replace the TopNet data. This was created using:

- a new time series for possible future flood events based on the discharge distribution of an infilled LWR historical record;
- likely changes in LWR temperatures with different RCPs;
- baseline precipitation for the hypothetical time series based on relationships from the NIWA High Intensity Rainfall Design System Version 3 model (HIRDS), using average LWR storm duration for annual maxima events in the historical record;
- new precipitation values for RCP temperature projections based on HIRDS outputs; and
- converting differences between baseline and new precipitation values into changes in LWR discharges.

#### 3.3.1 Infilled Historical Annual Maxima

To generate a hypothetical time series for future flood discharges in the LWR, it was first necessary to establish the distribution of annual maxima across the historical record for the Paetawa and Te Rewa gauges. The historical record for these gauge sites (1957-2015) was supplemented with information from 12 other extreme flows recorded in pre-1957 documentary evidence (including written accounts, photographs, etc.) (Blackwood and Bell, 2016). HRC and NIWA have previously used information regarding the extent of inundation caused by these floods to extrapolate plausible corresponding discharges. Although less accurate than the formal annual maxima discharge recordings post-1957, these estimates of historical floods should be considered part of the historical record as they provide useful insights into the characteristics of rare extreme events (Blackwood and Bell, 2016). However, to avoid exaggerating their rate of incidence when amalgamating these extremes with the 1957-2015 annual maxima series, it was necessary to fill in the years of missing annual maxima data between the first historical extreme (in 1858) and the first year of formal annual maxima recording (1957). This was done through extrapolating the post-1957 flood distribution for the missing years.
In particular, the missing years in the pre-1957 historical record were assumed to have smaller annual maxima than the smallest of the historical extreme events (3700m³/s – 1935) since otherwise there would likely be documentary evidence of them too. Thus, extreme events from the post-1957 annual maxima record needed to be removed before extrapolation. The distribution of the remaining post-1957 discharges was then used to statistically extrapolate values for the 89 missing years of the pre-1957 record. This was done by establishing what proportion of the available historical record fell into each of five 500m³/s bins (ranging from 1000m³/s to 3500m³/s) then allocating a similar proportion of the hypothetical time series to each bin using random number generation. The resulting infilled time series hydrograph for historical annual maximum LWR discharges is shown in Figure 3.1. Overall, this infilling process was relatively straightforward and could be carried out quickly with limited knowledge of Excel.

![Figure 3.1](image)

**Figure 3.1** – Infilled historical time series of annual maximum discharges for the LWR (2016-2100). Error bars show the extent of 500m³/s discharge bins for statistically extrapolated data points.

### 3.3.2 Hypothetical Time Series for Future Years

Having assigned discharge bins to a “complete” historical record for the period 1858-2015, it was then necessary to derive a hypothetical time series for the years 2016-2100. Using a similar method to that described above, each year from 2016-2100 was assigned a 500m³/s discharge bin (ranging from 1000m³/s to 5500m³/s) such that each bin held the same proportion of annual maxima as for the complete historical record. A random number for each year was then generated in Excel to give an exact discharge within the relevant bin. Whilst this approach does not explicitly account for relevant climate phenomena (such as El Niño Southern Oscillation), if these effects influenced historical floods, they should have a corresponding influence on the hypothetical time series (although the time series would not predict the extent of that influence in a particular year).
Although many different combinations of flood events were possible for the 85-year period, a single hypothetical time series (Figure 3.2) was selected to illustrate how the remainder of the DAPP implementation methodology can be applied. This decision was taken because resource constraints mean that local councils are unlikely to wish to generate multiple time series; however, it does risk undermining the DAPP process by relying on one possible version of the future, the exact problem that DAPP is trying to avoid. Finding a mechanism to carry out analyses for multiple time series simultaneously should therefore be a high priority for future research.

![Figure 3.2 – Hypothetical time series of possible LWR annual maximum discharges for 2016-2100.](image)

### 3.3.3 Representative Concentration Pathway-Derived Climate Effects

Having generated a time series of possible LWR annual maximum discharges, that time series needed to be adjusted to account for climate change. However, because RCP scenarios are defined in terms of temperature increases, some mechanism to relate these increases to increased river discharges was needed.

First, it was necessary to assign expected temperature increases associated with different RCP scenarios to each year in the hypothetical discharge time series. Recent investigations have sought to use NIWA’s regional climate models to investigate potential temperature changes for HRC-managed areas for four statistically downscaled RCP scenarios (Pearce et al., 2016). However, those investigations produced projections only for certain periods (specifically 2031-2050, 2081-2100 and 2101-2120) rather than a continuous timeline of possible temperature changes (MFE, 2018). As such, these outputs could not be directly incorporated into the DAPP implementation methodology, which requires a continuous time series for the investigated planning horizon.
Instead, continuous global warming projections from the IPCC AR5 report were used to estimate the extent of warming associated with the different RCP scenarios for each year (IPCC, 2014). Although based on global scale climate models, values for each RCP were found to be within the 90% confidence interval established by the regional studies based on NIWA’s models (Pearce et al., 2016), suggesting that they could be applied to the LWR without alteration. In addition to the four IPCC RCP scenarios and a baseline assuming no climate change, a sixth RCP scenario comprising RCP 8.5 values with an additional 20% temperature increase was also included (Figure 3.3). This additional scenario was added in light of recent literature which indicates that the current global warming trajectory is tracking above the RCP 8.5 scenario (e.g. Sanford et al., 2014). Annual values were then extracted and used as inputs for temperature-precipitation relationships to calculate expected precipitation increases for each year of the hypothetical discharge time series under different RCPs.

![Graph](image)

**Figure 3.3** – Time series of expected changes in Te Rewa catchment area temperatures until 2100 associated with five RCP scenarios (adapted from IPCC, 2014).

To convert the increased temperatures associated with the different RCP scenarios to corresponding increases in precipitation first meant establishing a baseline series of precipitation estimates associated with the hypothetical time series discharges. To do this, the return periods of discharges in the time series were calculated using an HRC Gumbel plot from Blackwood and Bell (2016). It was then assumed that discharges of a certain return period under the average storm duration at Te Rewa would have resulted from precipitation events of a similar return period (i.e. a 1 in 200-year discharge event would have resulted from a 1 in 200-year precipitation event).

Functional relationships for the established precipitation return periods could then be developed using the web-based application of NIWA’s HIRDS model. HIRDS is recommended by MFE as a tool for investigating
extreme rainfall projections under climate change projections (Hunter, Burkitt, and Trangmar, 2010) and utilises more than three decades of national and local New Zealand precipitation gauge data to statistically extrapolate precipitation return periods for sites across the country (see Carey-Smith, Henderson, and Singh, 2018 and Thompson, 2011 for relevant equations). Using regionalisation principles (primarily Dalrymple’s index-flood method) and records from surrounding gauge sites, the system derives averages for annual precipitation maxima associated with specific design-storms (ranging from 10 minutes to 72 hours duration, 1.58 to 100-year return period events) for a particular location (Griffiths, McKerchar, and Pearson, 2014). Critically for this project, HIRDS can also modify those design-storms to account for changes in national temperatures (in single degree increments from 1°C to 6°C) by applying MFE-validated percentage adjustments in rainfall depths and intensities (Semadeni-Davies, 2010). To investigate potential RCP effects on precipitation using HIRDS, a baseline design-storm duration needed to be established. This was calculated by taking the average of the number of days in which rain fell continuously (average >0.5mm for each day) immediately prior to annual maximum events at Te Rewa for the period 2007-2015 (Table 3.2).

Table 3.2 – Storm durations for 2007-2015 annual maximum discharges at the Te Rewa gauging site based on HRC data.

<table>
<thead>
<tr>
<th>Year</th>
<th>15 Minute Discharge Annual Maxima at Te Rewa Gauge (m³/s)</th>
<th>Approximate Storm Duration (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>4965</td>
<td>72</td>
</tr>
<tr>
<td>2014</td>
<td>1871</td>
<td>72</td>
</tr>
<tr>
<td>2013</td>
<td>3923</td>
<td>72</td>
</tr>
<tr>
<td>2012</td>
<td>2523</td>
<td>48</td>
</tr>
<tr>
<td>2011</td>
<td>2636</td>
<td>72</td>
</tr>
<tr>
<td>2010</td>
<td>2024</td>
<td>48</td>
</tr>
<tr>
<td>2009</td>
<td>1364</td>
<td>72</td>
</tr>
<tr>
<td>2008</td>
<td>2231</td>
<td>96</td>
</tr>
<tr>
<td>2007</td>
<td>1474</td>
<td>48</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>67</td>
</tr>
</tbody>
</table>

This analysis of revealed an average storm duration at Te Rewa of approximately 67 hours. As HIRDS does not produce summary statistics for this storm duration, an alternative baseline design-storm duration of 72 hours was selected for subsequent analysis. While the use of this longer duration could exaggerate potential effects of climate change on precipitation, this option was preferable to the next closest option of a 48-hour design-storm duration which would have significantly underestimated these effects.
Effects associated with RCP scenarios could then be applied to precipitation return periods associated with hypothetical time series discharges based on HIRDS relationships between temperature change and precipitation for a 72 hour design-storm duration at Te Rewa (Figure 3.4). However, the relationship will differ depending on the precipitation return period under consideration. Because HIRDS only generates results for specific precipitation return periods, a new relationship was needed to connect temperature and precipitation for other return periods not considered by HIRDS. This was done by plotting the gradient and y-intercept of the trend lines for HIRDS generated return periods (i.e. the trend lines shown in Figure 3.4) and deriving logarithmic relationships to connect those points (Figure 3.5). These relationships could then be used to identify the gradient and y-intercept for trend lines corresponding to other return periods.

Figure 3.4 – Augmentation relationships for HIRDS 72 hour design-storm precipitation return periods under incremental warming scenarios at the Te Rewa gauge.

Figure 3.5 – Relationships used to produce linear trend line equations for non-HIRDS 72 hour design-storm precipitation return periods under non-incremental warming scenarios at the Te Rewa gauge.
Next, increases in precipitation to represent the effects of climate change associated with RCPs had to be calculated. First, the return periods of precipitation events associated with baseline discharges of the hypothetical time series were entered into the gradient and y-intercept relationships described above (Figure 3.5). This produced the components of a linear trend line for each return period to characterise a specific temperature-precipitation relationship. The change in temperature anticipated under different RCPs for each year could then be entered into these specific temperature-precipitation relationships to calculate climate change-affected precipitation for each return period. The climate change-affected precipitation could then be compared to the precipitation associated with baseline discharge return periods (calculated using Figure 3.6) to establish a percentage change.

![Figure 3.6](image)

**Figure 3.6** – HIRDS 72 hour design-storm precipitation return period relationships for the Te Rewa gauge.

Percentage changes in precipitation for each year in the hypothetical time series under different RCPs were then converted into corresponding changes in discharges using a percentage relationship derived from a rainfall-to-flow model calibrated for the Hutt River (Figure 3.7) (MFE, 2010). The Hutt River model was selected as there was no model available for the Whanganui River or any other river in the HRC area. Furthermore, the Hutt River model was considered an appropriate substitute given the rivers have similar characteristics in their lower catchments. However, since the Hutt River catchment has a greater proportion of urban, impervious surfaces (Martin, 2017), the model likely overestimates the proportion of precipitation being converted to flow for the LWR, so discharges would similarly be overestimated. From a conservative management perspective, slight overestimations of possible climate change effects are likely more useful for testing the effectiveness of interventions than underestimations (Merz, Hall et al., 2010). It is also possible that future population growth along the LWR could increase the impervious surfaces near the river, meaning that the Hutt River relationship would become more representative over time. However, future research may need to consider how else precipitation-flow relationships could be established where full modelling is not possible.
Figure 3.7 – Rainfall-to-flow relationship established for the Hutt River based on a spatially distributed model (adapted from MFE, 2010). This relationship was used in this study to relate percentage changes in precipitation to corresponding changes in discharge for the LWR at Te Rewa.

Finally, percentage changes in discharges for each year in the time series under different RCP scenarios were added to baseline values to establish final discharge projections. Figure 3.8 summarises the key steps involved in incorporating RCP-based climate effects into the hypothetical LWR time series.

Figure 3.8 – Overview of the steps involved in incorporating RCP-derived effects into selected discharge time series. Colours represent the different information sources. Yellow = HRC data. Grey = HIRDS model outputs. Green = author.

The final discharges for the selected time series under the six RCP scenarios are shown in Figure 3.9. These could then be used to represent physical flood hazards as part of the impact modelling component of the DAPP implementation methodology.
Figure 3.9 – Final hypothetical annual maximum discharges at Te Rewa gauge associated with different RCP warming scenarios for the 2016-2100 planning horizon.

An overview of the processes used to create the final hypothetical time series is shown in Figure 3.10.

Figure 3.10 – Overview of processes used to create the LWR hypothetical time series from 2016-2100.
It should be noted that this method required several assumptions. In particular, it assumed that only one high magnitude flooding event occurs each year. While this assumption is supported by the historical record, this may change under different climate projections. It also assumes that climate change has not affected the historical record, which can therefore provide an objective baseline.

3.4 Developing Flood Depth Grids

The RCP-derived discharge outputs for Te Rewa were then used to develop flood depth grids for the LWR. This was achieved by:

- establishing relationships between Te Rewa gauge discharges and corresponding inundation depths at downstream cross-sections using relationships from a HRC hydraulic model; and
- inputting inundation depths into the freely available HAZUS FIT depth grid simulator.

These depth grids could then be used to investigate the viability of different flooding interventions for the LWR (module 3).

HRC Cross-Section Relationships

HRC currently uses a hydrodynamic MIKE 11 model as part of wider MIKEFLOOD complex to assess past and future flood inundation for the LWR (Blackwood and Bell, 2016). Developed by Hydro Tasmania in 2007, MIKE 11 evaluates single direction flows using differential equations (Teng et al., 2017) to create cross-section data (including peak river height and discharge) based on multiple hydrologic, hydraulic and geomorphological input parameters (Blackwood and Bell, 2016; DHI, 2017). MIKE 11 is also capable of using advanced modelling techniques to account for flow obstructions (e.g. bridges, dams, etc. – DHI, 2017), making it a useful planning support tool.

Historically, the HRC MIKE 11 model has been used to analyse individual floods of particular return periods (focussing on 50, 100 and 200-year) to assess the protection afforded by specific interventions (e.g. Blackwood, 2007a). Scoping discussions with HRC modellers revealed that MIKE 11 has not been used for more extensive modelling due to long computation times (over two hours per model run) coupled with limited awareness of how such models might be used strategically to inform responses to deep uncertainty problems.

The MIKE 11 calibration for the LWR covers the main river channel from the original Paetawa gauge site (2km upstream of the Te Rewa gauge site) to the river’s estuary with the Tasman Sea (Blackwood and Bell, 2016). It processes and extrapolates physical data for 50 cross-sections along the river channel. Critically, it has been tested against observed water levels from the 2015 LWR flood and found to produce results within 0.3m of the actual values (Figure 3.11) (Blackwood and Bell, 2016). HRC therefore considers MIKE 11 to provide accurate representations of LWR flood characteristics (Blackwood and Bell, 2016).
Figure 3.11 – HRC MIKE 11 flood model calibration against physical inundation data collected from the 2015 LWR flood (taken from Blackwood and Bell, 2016).

As cross-section peak depth data needed to be generated for all hypothetical time series discharges (a total of 510 annual maxima), it was not feasible to directly model all discharges using MIKE 11. Instead, a series of linear regression relationships between discharges at the Te Rewa gauge and inundation height at 32 relevant downstream cross-sections (Figure 3.12) was developed (Figure 3.13). These relationships were based on six MIKE 11 outputs associated with different return periods (1, 5, 30, 50, 100 and 200-year events) and run using HRC’s established set of baseline flood parameters.

Figure 3.12 – HRC MIKE 11 cross-section locations for the LWR.
These surrogate relationships allowed equivalent cross-section peak depths to be calculated for return periods other than those modelled by HRC without requiring extensive computation time. These peak depths could then be further processed to produce depth grids for the LWR.

**HAZUS Flood Information Tool (FIT) Depth Grid Simulator**

The HAZUS FIT extension to the ArcGIS software (part of the freely available HAZUS 4.2 package) was used to produce necessary flood depth grids for each discharge in the hypothetical time series (Federal Emergency Management Agency (FEMA), 2018). The tool was developed to improve the quality of physical inundation information (assuming static geomorphology) supplied to the main HAZUS software which, like New Zealand’s RiskScape program, seeks to quantify the potential social, financial, human and property impacts associated with natural hazards (Scawthorn et al., 2006). While HAZUS is specific to the United States and Canada, the FIT riverine extension can be used to develop flood depth grids for any river, although this requires local knowledge and flood data, including peak inundation depths at cross-section locations (Schneider and Schauer, 2006). The FIT tool has been in development since 1997 (Scawthorn et al., 2006), but few studies have analysed its outputs independently from the wider HAZUS loss estimation software and methodology. However, case study comparisons of final HAZUS losses with validated federal loss estimates indicate FIT depth grids offer plausible representations of real world floods (e.g. Ding et al., 2008). As such, the FIT software should offer reasonable accuracy for the DAPP implementation methodology, whilst also being accessible for local councils with limited resources.
In order to use FIT to generate flood depth grids for a specific case study, three key pieces of data are needed, as set out in Table 3.3.

Table 3.3 – Input requirements for the riverine version of the HAZUS FIT and their purpose (adapted from FEMA, 2018).

<table>
<thead>
<tr>
<th>Input</th>
<th>Purpose</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood Elevation Lines (Cross-Sections) with peak inundation data</td>
<td>Primary flood surface to determine inundation</td>
<td>ArcGIS polyline feature class – must be same datum as DEM</td>
</tr>
<tr>
<td>Digital Elevation Model (DEM)</td>
<td>Provides a terrain surface that can be subtracted from a flood surface to give inundation depths</td>
<td>Esri grid – must be same datum as flood elevation lines</td>
</tr>
<tr>
<td>Floodplain Boundary Outline</td>
<td>Used to define the floodplain centreline</td>
<td>ArcGIS shapefile feature class</td>
</tr>
</tbody>
</table>

For this thesis, flood elevation lines were generated using the HRC MIKE 11 relationships discussed above. As to the other required inputs, a 10m resolution DEM and a floodplain boundary outline for a 200-year LWR return period flood were provided by HRC. Whilst more detailed DEMs were available, the 10m resolution significantly reduced computation time (~20 minutes compared to over three hours for 1m resolution) whilst maintaining sufficient accuracy to produce useful damage outputs.

Once these three components had been incorporated into the FIT, the area of analysis was defined by manually inputting the upstream and downstream limits and the floodplain buffer zone (Figure 3.14) (FEMA, 2018). The FIT could then expand out the peak depth data from the flood elevation lines to all areas within the buffer zone using corresponding flood elevation points merged with DEM grid cells to create a flood surface layer (FEMA, 2018). The software then subtracts the terrain heights supplied by the DEM from the flood surface layer (FEMA, 2018). This produced depth grids (e.g. Fig 3.15) which could be used to determine the level of inundation associated with modelled discharges at a particular point, providing the flood hazard component for impact modelling.
Figure 3.14 – Components of the HAZUS FIT analysis (black) and key data inputs (red).

Figure 3.15 – Example of a HAZUS FIT output for the LWR generated from a peak hypothetical Te Rewa gauge discharge of 8762.73m³/s. Scale bar indicates inundation depths in meters.

A summary of the methods used to create the HAZUS flood depth grids is shown in Figure 3.16.
3.5 Summary

This chapter developed a straightforward, low-cost method for generating RCP-influenced LWR discharges for the period 2016 to 2100 and converting these into flood depth grids suitable for the flood hazard component of impact modelling. However, these processes were found to be time consuming. For example, to transform cross-section data into flood depth grids took over 170 hours alone using HAZUS FIT (approximately 20 minutes per depth grid multiplied by 85 years and 6 RCP scenarios) in a process that proved difficult to streamline. A number of assumptions also had to be made (e.g. as to the validity of applying the Hutt River rainfall-to-flow relationship in the LWR context) which may have resulted in inaccuracies in discharge distributions in the hypothetical time series. This chapter also considered the possible use of currently available models for supporting DAPP-type approaches. Whilst there was potential for national models to expedite the modelling, their outputs proved to be either unusable (e.g. TopNet) or required significant processing to produce useful data (e.g. HIRDS). However, locally developed models, such as HRC’s MIKE 11, proved invaluable, including in translating RCP-influenced LWR discharges into flood depth grid inputs.

Having successfully developed LWR flood depth grids for an established hypothetical time series, these could then be used as inputs for the impact model developed in Chapter Four (module 2).
Chapter 4
MODULE 2: ASSETS

In order to fulfil Thesis Objective One and create a functioning impact models, the depth grids generated in module 1 needed to be converted into economic damages using LWR asset information. This chapter therefore sought to:

- assess the usefulness of existing building asset datasets;
- establish a current LWR building asset dataset comprising geospatial points in an ArcGIS layer and asset attributes in a Microsoft Excel spreadsheet;
- allocate costs, residents and employees to LWR buildings to enable direct tangible and direct intangible damage calculations;
- establish a similar database for LWR roads, three waters and high voltage electricity infrastructure; and
- apply relevant damage functions to assets to calculate damages based on the flood depth grids generated in module 1.

The resulting impact model was also tested using damages recorded from historical LWR floods and the viability of the overall method was considered.

4.1 Building Assets
Considering first building assets, this thesis sought to use a combination of two datasets, the RiskScape building asset dataset and a layer of building footprints from Land Information New Zealand (LINZ), as the foundation of an LWR asset database. When this was unsuccessful, a new database had to be compiled using satellite imagery and visual inspections.

4.1.1 RiskScape Dataset Comparison
The RiskScape software has previously been rejected for use in previous flood impact assessment studies as users are unable to directly view damage calculations, leading to ambiguity around how these outputs are calculated (e.g. Scheele, 2014). However, the core elements of RiskScape, including its wide array of damage functions developed specifically for New Zealand building assets, might still be used for standardised flood impact assessments (Reese and Ramsay, 2010). Furthermore, a national scale building dataset developed by the program using survey data and existing government and private datasets (King and Bell, 2009; Schmidt et al., 2011), has potential as a basic building inventory for use in developing flood vulnerability assessments.

To assess whether the existing RiskScape building dataset accurately represents current LWR assets, independent field surveys were carried out considering the following attributes:

- Building use category – residential, commercial, industrial, community and other
- Construction type – timber, brick, concrete
- Number of storeys – integer value
- Floor height – meters

In addition, the LINZ building footprint layer based on WDC data was used to physically assess floor areas (dated 13th August 2018). These footprints were assessed against available Google Earth Pro satellite imagery (dated 4th March 2018) to ensure their accuracy.

**LWR Building Field Surveys**

Three field surveys were carried out along transects across the LWR (Figure 4.1), with locations chosen to capture different building types and use categories. Locations selected included the dense residential area of Anzac Parade in Whanganui East (residential and “other” buildings), the central business district (CBD) on Taupo Quay (commercial buildings) and the city’s main industrial hub around Balgownie Avenue (industrial buildings). These areas have previously been identified by HRC as flood management priorities as they have experienced significant historical inundation (Blackwood, 2007a). Figures 4.2a-4.2c show the distribution of building types across each transect, covering 298 buildings in total. Field surveys were carried out over two three-hour periods on the 27th and 28th June 2018.

![Figure 4.1 – Building use category transect locations for field surveys used to establish validity for the LWR RiskScape building dataset.](image)
Observed Issues with RiskScape Building Data

Comparisons with the transect data highlighted significant inaccuracies in the LWR RiskScape building dataset, both regarding asset locations and attributes. This is despite many of these issues having previously been identified by both Scheele (2014) and the RiskScape program (King and Bell, 2009), suggesting further improvements are still required. In particular:

- Point locations for buildings within the dataset rarely corresponded with transect and Google Earth satellite imagery. Discrepancies were often greater than the 10m resolution of depth-grid outputs from module 1.
- Several buildings, particularly small buildings in the “other” use category, were missing.
- As noted by King and Bell (2009), individual units within larger building were often poorly differentiated. This mostly resulted under-reporting of the number of buildings although occasionally RiskScape would report a far greater number of units than were actually present.
- Asset attributes (including use category) were often incorrect. This is likely because the RiskScape dataset was derived from an aggregated Quotable Value New Zealand (QV) dataset, which would have
reported the number of buildings of different types in an area but assumed they were evenly distributed over that area rather than recording which buildings were where (Scheele, 2014).

- Historically, the RiskScape dataset has used the ratio of building floor areas to building footprints (usually based on council data) to represent the number of storeys. However, these indicators do not always give integer values (e.g. a building with a second storey half the area of the first would have a ratio of 1.5). This was problematic because damage functions could only be applied using whole numbers (Scheele, 2014). Furthermore, even when the number of storeys was rounded up appropriately, disparities with field data often remained (Table 4.1).

Comparisons between the RiskScape dataset and the field survey results revealed significant differences (Table 4.1). It was therefore decided that a new building asset dataset was needed to generate the necessary accuracy for impact modelling. This dataset could then also be used for future LWR flood impact studies.

**Table 4.1 – Comparisons between the RiskScape dataset and field survey results.**

<table>
<thead>
<tr>
<th>Building Attribute</th>
<th>RiskScape Dataset</th>
<th>Field Survey/LINZ Footprints</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Floor Height (m)</td>
<td>0.45</td>
<td>0.24</td>
</tr>
<tr>
<td>Mean Floor Area (m²)</td>
<td>305</td>
<td>551.74</td>
</tr>
<tr>
<td>Incorrect Use Categories (%)</td>
<td></td>
<td>43.29</td>
</tr>
<tr>
<td>Incorrect Construction Types (%)</td>
<td></td>
<td>37.58</td>
</tr>
<tr>
<td>Incorrect Rounded Number of Storeys (%)</td>
<td></td>
<td>26.17</td>
</tr>
<tr>
<td>Incorrect Number of Storeys Post-Rounding (%)</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Total Number of Buildings</td>
<td>240</td>
<td>298</td>
</tr>
</tbody>
</table>

**4.1.2 Collation of Building Attributes**

At present, the RiskScape dataset is the only readily available source of information about LWR building stock which details attributes for individual buildings. Therefore, a methodology based on visual inspection of freely available satellite and street-level imagery was needed to supplement existing field data and LINZ building footprints. Functions could then be applied to this new building inventory in Excel to assess possible direct tangible and intangible damages.

To identify which buildings should be included in this LWR asset database, a zone of possible inundation was developed based on the extent of inundation predicted for the largest potential discharge under the most extreme climate change scenario (Figure 3.15). An additional 10m buffer was then applied to the depth grid.
outline to ensure borderline buildings were fully captured. LINZ building footprints within this outline were identified in ArcGIS and allocated a geospatial point at the centre of each footprint. The point translation was necessary because the ArcGIS “sample” tool used in the impact modelling process to extract inundation heights from flood depth grids could only be applied to individual points (Section 4.5). These geospatial points were then transferred into Google Earth Pro where building attributes, including use category, construction type, number of storeys and floor height, were assessed using the most up to date imagery (dated May 2015) (based on Ramm et al., 2018b). Google Street View was particularly useful for splitting up building footprints for large structures (e.g. apartment blocks), thus overcoming a major issue with the RiskScape dataset (King and Bell, 2009).

To make the database as detailed as possible, attributes were collected for buildings identifiable from any of the LINZ footprint, Google Earth Pro satellite or Street View analyses, including for small shed and garage structures (<10m²) in the “other” use category. The inclusion of these structures may have resulted in errors as high-resolution satellite imagery, rather than established LINZ data, was used to determine their attributes. However, these small structures were found to comprise a large portion of the dataset (45% of total building stock), meaning that excluding them would have resulted in significant inaccuracies in the total LWR damage calculations.

A total of 10,204 buildings across the LWR were allocated attributes using these virtual survey methods.

_Extrapolation of Unknown Building Points_

Some buildings were not visible in Google Street View despite appearing on LINZ footprints. Fortunately, these were a minority, comprising only 239 buildings. For these buildings, attributes needed to be manually or statistically extrapolated based on the characteristics of surrounding buildings. Manual extrapolation involved copying attributes from buildings which were included in the Street View analysis, but this was only appropriate where buildings were likely to be similar to those around them (Scheele, 2014). For buildings without comparable properties, attributes were assigned in proportion with their prevalence in the known dataset.

All building asset information was then compiled into a single Excel database. Each building was linked to a corresponding ArcMap geospatial point using a unique identification number. This new building dataset contained details for 10,741 buildings, with attributes for 298 buildings derived from field surveys, 10,204 from virtual surveys and 239 from extrapolated data.

_4.1.3 Cost Allocation for All Building Types_

Structural and content replacement costs were assigned to each building in the dataset in order to generate direct tangible damages. When assessing inundation damage costs, the literature advocates an approach based on depreciated value (Merz, Kreibich et al., 2010). However, for this thesis, replacement costs were used for two main reasons:
• this thesis considers potential flood impacts rather than flood risk and as such the cost of replacing an asset with new material was more important than the reduction in the asset’s value; and
• calculating relative depreciation for assets would have required accurate construction dates for all assets which were not available.

To calculate structural replacement costs, RiskScape currently uses national QV 2009 multipliers for each square meter of a building, which differ depending on its attributes. The applicable multiplier is then applied to a building’s footprint area to generate an approximate building replacement cost. This thesis attempted to replicate this approach using QV 2018 structural multipliers. However, because such multipliers were not available for the LWR, data from Palmerston North was used, this being the closest region to the LWR covered by QV and therefore likely to best represent LWR building costs (due to similar labour and material costs etc.). This approach was expected to significantly improve the accuracy of building replacement cost estimates, as well as avoiding the need to account for inflation.

Once structural replacement costs (in 2018 NZ$) had been generated for each building asset, content replacement costs were added. For residential, communities and other use category buildings, these were generated using a percentage of the overall structural replacement cost identified in the literature (Cousins, 2009). For commercial and industrial buildings, stock and plant replacement costs were derived by applying a standard cost per square meter of floor space (Dowrick and Rhoades, 1995). In calculating these replacement costs, it was also necessary to account for potential efforts by individuals to move property out of harm’s way before evacuation. Table 4.2 highlights the key assumptions made to calculate content costs for different use categories in the LWR building dataset.
Table 4.2 - Assumptions made relating to the distribution of contents replacement costs for LWR buildings.

<table>
<thead>
<tr>
<th>Applicable Building Use Categories</th>
<th>Assumption</th>
<th>Evidence</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>11-12 hours of total warning time is given prior to each major flood event.</td>
<td>(HRC, 2017)</td>
</tr>
<tr>
<td></td>
<td>Translates to 6 hours in which contents can be moved before evacuation.</td>
<td></td>
</tr>
<tr>
<td>One Storey Residential</td>
<td>10% reduction in content damages for 6 hours active warning time.</td>
<td>(King and Bell, 2009),</td>
</tr>
<tr>
<td></td>
<td>Roof height of 2.2m.</td>
<td>(Reese and Ramsay 2010)</td>
</tr>
<tr>
<td>One Storey Commercial</td>
<td>5% reduction in content damages for 6 hours active warning time.</td>
<td>(King and Bell, 2009),</td>
</tr>
<tr>
<td></td>
<td>Roof height of 3.2m.</td>
<td>(Reese and Ramsay 2010)</td>
</tr>
<tr>
<td>One Storey Industrial</td>
<td>1% reduction in content damages for 6 hours active warning time.</td>
<td>(King and Bell, 2009)</td>
</tr>
<tr>
<td></td>
<td>Roof height of 4.2m.</td>
<td>(Reese and Ramsay 2010)</td>
</tr>
<tr>
<td>One Storey Community</td>
<td>5% reduction in content damages for 6 hours active warning time.</td>
<td>(King and Bell, 2009),</td>
</tr>
<tr>
<td></td>
<td>Roof height of 2.2m.</td>
<td>(Reese and Ramsay 2010)</td>
</tr>
<tr>
<td>One Storey Other</td>
<td>No reduction in content damages for 6 hours active warning time.</td>
<td>Author observations</td>
</tr>
<tr>
<td></td>
<td>Roof height of 2m.</td>
<td></td>
</tr>
<tr>
<td>Two Storey Residential</td>
<td>Second floor area is 50% of the ground floor area. Baseline distribution of</td>
<td>(King and Bell, 2009),</td>
</tr>
<tr>
<td></td>
<td>contents is 66% on the ground floor and 33% on the first floor.</td>
<td>(Reese and Ramsay 2010)</td>
</tr>
<tr>
<td></td>
<td>25% reduction in content damages for 6 hours active warning time. Assume 15%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of total contents is transferred from the ground floor to the second floor.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Therefore relative content on ground and first floors goes from 66% and 33%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>to 51.6% and 48.3% respectively before 10% of the total is subtracted from</td>
<td></td>
</tr>
<tr>
<td></td>
<td>the first floor.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Floors are 2.2m apart.</td>
<td></td>
</tr>
<tr>
<td>Applicable Building Use Categories</td>
<td>Assumption</td>
<td>Evidence</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Two Storey Commercial            | • Second floor area is the same as the ground floor area. Baseline distribution of contents is 50% on the ground floor and 50% on the first floor.  
• 7% reduction in content damages for 6 hours active warning time. Assume 2% of total contents is transferred from the ground floor to the second floor. Therefore the relative content on ground and first floors goes from 50% and 50% to 48% and 52% respectively before 5% of the total is subtracted from the ground floor.  
• Floors are 3.2m apart.  
• Stock and plant content floor distributions are not changed with warning time.                                                                                                                                                                                                 | (King and Bell, 2009), (Reese and Ramsay 2010)                                               |
| Three Storey Commercial          | • Second and third floor areas are the same as the ground floor area.  
• 7% reduction in content damages for 6 hours active warning time. Assume 2% of total contents is transferred from the ground floor to the second floor and none to the third. Therefore the relative content on ground, first and second floors goes from 33% each to 31.3%, 35.3% and 33.3% respectively before 5% of the total is subtracted from the ground floor.  
• Floors are 3.2m apart.  
• Stock and plant content floor distributions are not changed with warning time.                                                                                                                                                                                                 | (King and Bell, 2009), (Reese and Ramsay 2010)                                               |
| Two Storey Industrial            | • Second floor area is the same as the ground floor area. Therefore the baseline distribution of contents is 50% on the ground floor and 50% on the first floor.  
• Floors are 4.2m apart.  
• Stock and plant content floor distributions are not changed with warning time.                                                                                                                                                                                                                                                                               | (King and Bell, 2009), (Reese and Ramsay 2010)                                               |
| Two Storey Community             | • Second floor area is 50% of the ground floor area. Therefore the baseline distribution of contents is 66% on the ground floor and 33% on the first floor.  
• 7% reduction in content damages for 6 hours active warning time. Assume 2% of total contents is transferred from the ground floor to the second floor. Therefore the relative content on ground and first floors goes from 50% and 50% to 48% and 52% respectively before 5% of the total is subtracted from the ground floor. | (King and Bell, 2009), (Reese and Ramsay 2010)                                               |
4.1.4 Population Allocation for Residential Buildings

To calculate indirect tangible losses relating to the displacement of people, the number of inhabitants for each residential building needed to be identified. This was done by applying average household size figures from the 2013 census to corresponding geospatial areas identified in a separate LINZ data layer (Statistics New Zealand, 2013). Residential building points were then assigned relevant numbers of people depending on their area allocation. A RiskScape damage function could then be used to calculate possible displacement costs based on the number of people within each household (Reese and Ramsay, 2010).

4.1.5 Employee Allocation for Commercial and Industrial Buildings

RiskScape calculates loss of business (direct intangible damage) by multiplying the average value of goods and services per employee per day (from the Annual Enterprise Survey carried out by Statistics New Zealand) by the number of days of lost business due to inundation (Reese and Ramsay, 2010). To apply a similar function to the newly created LWR building asset dataset, the approximate number of full-time employees for each commercial and industrial building in the identified maximum inundation zone was first established using a standardised ratio of one full time equivalent employee per 12m² of floor space as recommended by Drivers Jonas Deloitte (2010). Whilst this ratio was likely to overestimate employees for particular building types (e.g. industrial warehouses), the approach offers a baseline for estimating business losses that can be improved in future studies.

4.1.6 Comparison of New LWR Building Asset Dataset with RiskScape Building Dataset

To determine whether the additional time and resources spent developing a new LWR building asset dataset had improved accuracy, a statistical comparison with the existing RiskScape dataset for the same inundation area was undertaken. Table 4.3 shows the number of buildings in each use category within the two datasets.

Table 4.3 – Summary statistics showing numbers of buildings in different use categories for the new LWR building asset dataset compared with the existing RiskScape Dataset.

<table>
<thead>
<tr>
<th>Use Category</th>
<th>Number of Buildings in RiskScape Database</th>
<th>Number of Buildings in New LWR Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>3,902</td>
<td>5,037</td>
</tr>
<tr>
<td>Commercial</td>
<td>141</td>
<td>325</td>
</tr>
<tr>
<td>Industrial</td>
<td>457</td>
<td>373</td>
</tr>
<tr>
<td>Community</td>
<td>82</td>
<td>165</td>
</tr>
<tr>
<td>Other</td>
<td>2,702</td>
<td>4,841</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7,284</strong></td>
<td><strong>10,741</strong></td>
</tr>
</tbody>
</table>

Table 4.3 highlights differences between the two datasets with the total number of buildings differing by more than 32% and RiskScape significantly underestimating the number of buildings in all but one of the use...
categories. For residential and other buildings, this included differences of more than 1,000 and 2,000 buildings respectively. In contrast, industrial buildings were significantly overestimated by RiskScape which in turn could result in exaggerated indirect business losses during impact modelling. Such results therefore suggested that a new LWR building database was indeed needed for accurate flood impact modelling.

A summary of the processes used to develop a new LWR building asset dataset is shown in Figure 4.3.

Figure 4.3 – Main steps used to create a new LWR building database. Geospatial data was incorporated using ArcMap 10.6 whilst attribute data was incorporated using Excel.

4.2 Infrastructure Assets

In addition to buildings, the overall asset database for the LWR needed to incorporate major infrastructure in order to comprehensively estimate total damages. Using existing information and new datasets when required, the building dataset developed for this thesis was expanded to include:

- roads;
- three waters infrastructure (comprising storm water, wastewater, and potable water); and
- high voltage electricity networks.
However, several infrastructure networks were omitted, most notably bridges, railways and telecommunications. These networks were omitted because:

- For large point infrastructure (i.e. bridges), these structures were assumed to be designed to withstand far larger flooding events than those modelled in this study given the standards required for critical life supporting infrastructure (New Zealand Transport Agency (NZTA), 2016). In addition, damage curves suited to each of the three very different bridge types in the LWR could not be readily identified from the literature, which would have prevented accurate damage estimates.
- Asset databases held by non-public contractors (e.g. for telecommunications) were unavailable.
- The final asset database could not be larger than the size of a single Excel spreadsheet (1,048,576 rows by 16,384 columns) to allow inundation depths to be transferred directly from ArcMap to Excel. In addition, large numbers of assets would greatly increase the processing time required to extract inundation data in ArcGIS. Therefore, it was necessary to keep the database concise and the absence of these identified infrastructure networks was considered unlikely to dramatically influence overall damages.

Road Data

Google Earth Pro satellite imagery (dated 4th March, 2018) was used to identify LWR road networks within the potential inundation zone using a polyline array. Road segments were then assigned an NZTA One Network Road Classification (ONRC) based on three criteria (NZTA, 2018):

- the amount of traffic;
- whether they lead to a significant destination; and
- whether they are the only transport route available.

To develop holistic damages for road network disruption, total road areas needed to be established and converted into geospatial points to enable the use of the ArcMap “sample” tool during impact modelling. Cross-sections were taken using Google Earth Pro for each ONRC and ArcGIS was used to calculate the road area based on the average of the cross-sections. The same approach was applied to the Whanganui Airport runway. Areas were then converted into points representing 10m x 10m grids (being the same resolution as the depth grid developed in module 1) that could be integrated into an LWR infrastructure database. This meant that the database was concise whilst maintaining accuracy. A summary of the different road classifications used in the LWR infrastructure dataset is shown in Table 4.4
Table 4.4 - Summary statistics for NZTA’s ONRC and their relative incidence in the LWR infrastructure dataset.

<table>
<thead>
<tr>
<th>ONRC</th>
<th>Daily Traffic Thresholds (NZTA, 2018)</th>
<th>Average Length of Cross-Sections (m)</th>
<th>Total LWR Road Length (km)</th>
<th>Total LWR Road Area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td>&gt;15000</td>
<td>7.65</td>
<td>1.376</td>
<td>3428</td>
</tr>
<tr>
<td>Arterial</td>
<td>&gt;5000</td>
<td>10.83</td>
<td>25.56</td>
<td>96059</td>
</tr>
<tr>
<td>Primary</td>
<td>&gt;3000</td>
<td>8.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector</td>
<td></td>
<td></td>
<td>38.532</td>
<td>117444</td>
</tr>
<tr>
<td>Secondary</td>
<td>&gt;1000</td>
<td>10.74</td>
<td>82.562</td>
<td>329453</td>
</tr>
<tr>
<td>Collector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Access</td>
<td>&lt;1000</td>
<td>9.48</td>
<td>43.232</td>
<td>144151</td>
</tr>
<tr>
<td>Low Volume</td>
<td>&lt;200</td>
<td>8.37</td>
<td>28.38</td>
<td>87025</td>
</tr>
<tr>
<td>Unknown</td>
<td></td>
<td>6.12</td>
<td>15.19</td>
<td>38480</td>
</tr>
<tr>
<td>Whanganui</td>
<td></td>
<td>44.2</td>
<td>0.582</td>
<td>7288</td>
</tr>
<tr>
<td>Airport</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unlike for building assets, there is limited research on the potential effects of inundation on roads. As road damage tends to be primarily caused by the impacts of flow velocity (Reese and Ramsay, 2010), no pre-determined cost relationship for different levels of inundation could be identified. It was therefore necessary to calculate a standard damage multiplier. Using data from the June 2015 flood provided by NZTA, a cost of $45,000 for silt damage to 1.1km of Anzac Parade was simplified into an approximate cost of ~$41/m². This estimate was then applied to each road point in the infrastructure dataset. Indeed, RiskScape currently uses similar method for calculating a cost per m² of road (Reese and Ramsay, 2010).

Three Waters Infrastructure Data

A geospatial dataset of current storm water, wastewater and potable water infrastructure for the LWR was provided by WDC. Asset attribute information was also supplied, including the expected date of replacement for all assets, current values based on depreciation and replacement costs. Focussing on life supporting networks, the following piping networks and point infrastructure assets were incorporated into the LWR infrastructure dataset:

- stormwater pipes;
- wastewater pipes;
- water pipes;
- wastewater pump stations;
- water pump stations; and
- water reservoirs.
Using the ArcMap “clip” function, the WDC dataset was reduced to assets within the maximum depth grid inundation zone (Figure 3.15), as was previously done for road and building assets. Whilst geospatial and cost information for point infrastructure (pump stations and reservoirs) could be automatically added to the LWR dataset, piping networks had to be split into 10m sections to maintain consistency with road and inundation grid resolution. Replacement costs for each section were then calculated as a proportion of the full replacement cost across the relevant network. As it was not practical to interrogate this data could for this thesis, its accuracy had to be assumed. However, the local councils who might apply the DAPP implementation methodology would be in a better position to test this assumption for their own three waters infrastructure datasets.

*Electricity Asset Data*

As data was not available for all electricity assets, only high voltage infrastructure was considered. In addition, available damage functions (FEMA, 2003) and expert recommendations both indicated that high voltage cables were unlikely to experience significant damages even at high flood magnitudes (>3m inundation), and so they too were excluded from the analysis.

Geospatial data for high voltage point infrastructure was provided by Powerco, the regional power supplier for the LWR. Scoping conversations with electrical engineers familiar with the case study were then used to establish approximate replacement costs and heights above ground level for each infrastructure class. This information could then be directly incorporated into the wider infrastructure dataset. A summary of these assets is shown in Table 4.5. Similar to the three waters infrastructure dataset, electricity asset data was assumed to be accurate as this could not be tested easily.

**Table 4.5 – Summary of Powerco high voltage electricity assets incorporated into the LWR infrastructure dataset.**

<table>
<thead>
<tr>
<th>Asset Type</th>
<th>Approximate Replacement Cost (NZ$2018)</th>
<th>Height Above Ground (m)</th>
<th>Number of Assets in LWR potential inundation zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substation Transformer</td>
<td>1,000,000</td>
<td>0.2</td>
<td>4</td>
</tr>
<tr>
<td>Ground Mounted Distribution Transformer</td>
<td>30,000</td>
<td>0.2</td>
<td>79</td>
</tr>
<tr>
<td>Ground Mounted High Voltage Switch</td>
<td>60,000</td>
<td>0.5</td>
<td>17</td>
</tr>
<tr>
<td>Ground Mounted Fuses</td>
<td>70</td>
<td>0.3</td>
<td>6</td>
</tr>
<tr>
<td>Substation Transformer Bushings</td>
<td>40,000</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

Figure 4.4 provides a final summary of the data sources and methods required to create the LWR infrastructure dataset.
4.3 Compiled LWR Asset Database

Once completed, the building and infrastructure asset datasets were combined into a single point-based geospatial layer in ArcMap 10.6 and a corresponding attribute database in Excel. Table 4.6 provides a summary of the final database characteristics.

Table 4.6 – Summary of the different asset classes included in the final asset database created for the LWR.

<table>
<thead>
<tr>
<th>Asset Class</th>
<th>Number of Data Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings</td>
<td>10,741</td>
</tr>
<tr>
<td>Roads</td>
<td>8,729</td>
</tr>
<tr>
<td>Three Waters Infrastructure</td>
<td>21,257</td>
</tr>
<tr>
<td>Electricity</td>
<td>110</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40,837</strong></td>
</tr>
</tbody>
</table>

The overall LWR asset database was then transformed into a functional impact model by allocating damage functions to each asset. This model would then be used to evaluate possible LWR interventions in module 3.
4.4 Damage Functions

Damage functions were applied to the overall LWR asset database in order to calculate both direct tangible and indirect tangible damages and enable realistic assessments of total LWR flood impacts under the hypothetical time series developed in module 1. In some instances (e.g. building assets), established relative functions from HAZUS and RiskScape were applied. For assets specific to the LWR (e.g. electricity assets), absolute functions based on consultations with industry professionals had to be used instead. Table 4.7 provides a summary of the different damage functions used in this thesis and their sources.

Table 4.7 – Summary of damage functions applied to the compiled LWR database.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Damage Function</th>
<th>Damage Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIWA/GNS RiskScape Program</td>
<td>Relative</td>
<td>• Structural replacement – residential, commercial, industrial and community buildings, and below ground three waters pump stations&lt;br&gt;• Contents replacement – residential and community buildings (same relationships used for stock and plant replacement costs)&lt;br&gt;• Human displacement time and subsequent temporary accommodation costs – populations in residential buildings&lt;br&gt;• Functional downtime and subsequent loss of business – function of expected income per business day per full time employee - $2,635.661 per day per employee calculated from 2018 Annual Enterprise Survey results (using the methods of King and Bell, 2009)</td>
</tr>
<tr>
<td>(Reese and Ramsay, 2010)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NZTA</td>
<td>Absolute</td>
<td>• Structural replacement – roads – approximate cost of damage repair per meter square derived from LWR 2015 flood impacts</td>
</tr>
<tr>
<td>HAZUS-MH (FEMA, 2003)</td>
<td>Relative</td>
<td>• Structural replacement – storm water, wastewater and potable water piping</td>
</tr>
<tr>
<td>Other Sources</td>
<td>Relative</td>
<td>• Structural replacement – other buildings&lt;br&gt;• Contents replacement – commercial, industrial and community buildings (based on Reese and Ramsay’s (2010) observations</td>
</tr>
<tr>
<td></td>
<td>Absolute</td>
<td>• Structural replacement – all electricity assets – critical thresholds determined by consulting industry professionals</td>
</tr>
</tbody>
</table>
4.5 Impact Modelling

Having established a fully functional impact model with integrated damage functions in a single Excel spreadsheet, direct depth grid outputs from module 1 could be quickly analysed to derive corresponding economic impacts using appropriate ArcGIS and Excel functions. Using the ArcMap “sample” tool, inundation depths were extracted from the depth grids for the location of each asset. This information was exported into the Excel spreadsheet where each asset’s floor height was subtracted from its relevant inundation depth. The final inundation depth was fed into the necessary damage functions to calculate a damage ratio which could then be multiplied by replacement costs to estimate direct economic impacts to households and firms (Reese and Ramsay, 2010). Each year in the hypothetical time series for each RCP was allocated its own copy of the Excel spreadsheet impact model (510 spreadsheets split into six 85 spreadsheet workbooks representing a different RCP). A summary of this process is shown in Figure 4.5. A theoretical direct structure test (Barlas, 1996) of damage outputs was then carried out using specifically calibrated MIKE 11 cross-section data for the June 2015 flood to evaluate the impact model’s accuracy (section 4.6).

![Figure 4.5 – Summary of the impact modelling process.](image)

4.6 June 2015 Flood Theoretical Direct Structure Test

The June 2015 flood was the highest magnitude event ever recorded for the LWR, with a peak flow of 5150m³/s recorded by HRC (Blackwood and Bell, 2016). As the most extreme and recent flood event for the Whanganui River, it is also well-documented. The actual costs associated with the June 2015 flood could therefore be compared with the expected costs of a modelled event with the same characteristics to evaluate the accuracy of impact model outputs. Peak inundation depths derived from a validated version of the MIKE 11 flood model based on the June 2015 flood, incorporating the particular characteristics of that flood including higher intensity rainfall in lower sub-catchments and increased tributary inflows, were obtained from the HRC river management team (Blackwood and Bell, 2016). These depths were then allocated to relevant flood elevation lines and fed into the HAZUS FIT to generate an accurate flood depth grid for the event. Associated costs were then calculated by applying the impact modelling process to this flood depth grid. As the stopbank at Balgownie Avenue was operational during the June 2015 event, assets behind this stopbank were assumed to be free of damage. However, assets behind the Anzac Parade stopbank were assumed to receive no protection due to its recorded failure (Cooke and Galuszka, 2015). Figure 4.6 shows the results of this analysis.
However, despite the June 2015 flood being relatively recent, there is limited information available regarding its cumulative economic impacts. Councils are not required to record hazard data and so disparate asset-specific damage records are held by multiple different agencies, preventing validation of the impact model’s total estimated damages ($93,263,149.55). Instead, costs had to be broken down and compared to the few records available. In addition, the damage records available often incorporated district-wide damages caused by the storm rather than just the flood, preventing direct comparisons. An examination of the applicable damage types, information sources and comparison with modelled costs is shown in Table 4.8.
Table 4.8 – Comparison of published and DAPP implementation methodology impact model economic damages for the June 2015 flood.

<table>
<thead>
<tr>
<th>Asset Type</th>
<th>Damage Record Source</th>
<th>Recorded Economic Damage (NZ$2018)</th>
<th>Impact Model Economic Estimated Damage (NZ$2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insurable Assets – structural, contents, stock, plant, marine, motor, crops and other</td>
<td>Insurance Council of New Zealand (ICNZ, 2018) – district wide insurance costs</td>
<td>42.4m</td>
<td>38.9m</td>
</tr>
<tr>
<td>Three waters infrastructure</td>
<td>WDC – district wide repairs</td>
<td>827,000</td>
<td>1.46m</td>
</tr>
<tr>
<td>Roads</td>
<td>WDC – district wide repairs</td>
<td>27.757m</td>
<td>55,350</td>
</tr>
<tr>
<td></td>
<td>NZTA – silt damage from Whanganui River</td>
<td>45,000</td>
<td></td>
</tr>
</tbody>
</table>

In general, the impact model produced adequate approximations of actual damages resulting from the June 2015 flood. Estimates for insurable assets in particular were very similar to ICNZ records. However, other modelled damages, including for three waters infrastructure, differed significantly from WDC records suggesting that the damage functions used could be improved.

Road damages showed the largest variations. WDC records for the June 2015 event indicate damages exceeded $27.5m compared to an impact modelling estimate of just over $55,000. However, as noted above, such a comparison is misleading given the council’s estimate includes damages beyond the main floodplain, including erosion and landslip repairs for roads throughout the district. As such, NZTA records may offer a better comparator as they represent only the cost of removing silt from State Highway 4 (management zones 5, 6 and 7).

Overall, the comparison suggests that the damage calculations used in the impact modelling component of the DAPP implementation methodology could use further refinement. Nevertheless, relative changes in the existing damage estimates could still be used to investigate the impacts of LWR interventions, providing valuable information for management agencies. Therefore, with the impact model assembled, an Excel-based analysis into the efficacy of possible flood interventions was conducted as part of the management and assessment module (module 3) of the DAPP implementation methodology.

4.7 Summary

This chapter developed the vulnerability component of flood impact assessments within a decision-support framework to enable appropriate flood damages to be calculated for key LWR assets. This was done by developing an overall asset database for the LWR comprising relevant buildings and infrastructure before assigning relevant damage functions. As with module 1, developing a new overall asset database and resulting
impact model was possible but very time consuming and still required significant assumptions (including as to the reliability of infrastructure datasets that could not be checked). This further highlights the need for local government agencies to be provided with adequate resources to undertake thorough impact modelling and support decision-making. The chapter concluded with a series of comparisons used to assess whether the impact model could reproduce historical LWR damages associated with the June 2015 flood event. Whilst the analysis identified significant disparities between the impact model and historical damages, the model may still prove useful for analysing proportional differences in overall damages associated with different LWR interventions.

The incorporation of possible LWR interventions into the basic impact model is investigated in Chapter Five (module 3).
Chapter 5

MODULE 3: MANAGEMENT AND ASSESSMENT

Having assembled a basic impact model in modules 1 and 2 of the DAPP implementation methodology, the next step was to use that model to assess which interventions would be most effective for the LWR and complete Thesis Objective One. This chapter therefore sought to:

- divide the LWR into a series of management zones based on previous investigations;
- identify possible LWR interventions based on HRC policy;
- incorporate interventions for each LWR management zone into the impact model;
- assess the likely costs of those interventions;
- evaluate impact model outputs associated with interventions using a DAPP decision-support code (the Eaves code); and
- reflect on the practicalities of the methods used.

As with the previous modules, a 64-bit version of Microsoft Excel 2016, rather than a dedicated coding program, was used to replicate the resources and expertise likely to be available to local councils.

5.1 LWR Management Zones

On taking over management of the LWR from WDC in 2007, HRC commissioned MWH New Zealand to investigate and identify priority areas for flood protection, as well as possible interventions (MWH, 2007). The investigation identified the following priority areas (MWH, 2007):

- Balgownie Avenue industrial area;
- Kowhai Park/Anzac Parade residential area;
- Putiki upstream of Cobham Bridge culturally significant area; and
- Moutoa frontage/Taupo Quay commercial area.

However, the four priority areas identified by MWH do not encompass the entire LWR. Three additional management zones were therefore established in this thesis to include surrounding areas. Dividing up the LWR in this way allowed intervention schemes to be broken down by zone and assets outside of high priority areas to be considered in intervention assessments. Figure 5.1 identifies the final seven LWR management zones.
Figure 5.1 – Seven identified management zones for the LWR used to assess the efficacy of different flood intervention schemes.

Table 5.1 identifies the key characteristics of each management zone. In particular, it highlights the differences between asset types in each area. For example, zone 1 comprises a large area and extensive housing, generating the highest total asset replacement cost. However, it is currently a low priority area for interventions given its elevation and relatively low replacement cost per km$^2$. In contrast, zones 2, 3, 5 and 6 are significantly smaller, but have higher replacement costs per km$^2$ and are more prone to flooding, making them the focus of previous protection efforts.
**Table 5.1 - Key attributes of identified LWR management zones based on observations and the LWR asset database.**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Location</th>
<th>Key Features</th>
<th>Zone Area (km²)</th>
<th>Number of Residents in Asset Database</th>
<th>Asset Database Estimated Replacement Cost (NZ$2018)</th>
<th>Estimated Replacement Cost per km² (NZ$2018)</th>
</tr>
</thead>
</table>
| 1    | Somme Parade and Paipati Road | • Residential, lifestyle and some agricultural buildings  
• Mix of low density (upriver) and high density (downriver) buildings | 12.45 | 6723 | 1,611,345,234 | 129,425,320 |
| 2    | Taupo Quay – Union Rowing Club to Cobham Bridge | • High density CBD with some residential and commercial buildings  
• Significant buildings include the riverboat moorings and museum, courthouse and river traders markets | 1.29 | 27 | 448,807,542 | 347,912,823 |
| 3    | Balgownie Avenue – Wharf Street to Affco Imlay Freezing Works | • High density industrial and manufacturing centre | 5.97 | 463 | 1,204,399,415 | 201,741,946 |
| 4    | Lower Putiki – Below Cobham Bridge | • Includes State Highway 4, city airport and water treatment plant  
• Low density lifestyle buildings | 9.75 | 72 | 62,177,459 | 6,377,175 |
| 5    | Upper Putiki – Above Cobham Bridge to Georgetti Road | • Cultural centre for Tupoho hapū encompassing Putiki Marae and Putiki urupā  
• Low density residential buildings | 4.55 | 175 | 75,335,401 | 16,557,231 |
<table>
<thead>
<tr>
<th>Zone</th>
<th>Location</th>
<th>Key Features</th>
<th>Zone Area (km²)</th>
<th>Number of Residents in Asset Database</th>
<th>Asset Database Estimated Replacement Cost (NZ$2018)</th>
<th>Estimated Replacement Cost per km² (NZ$2018)</th>
</tr>
</thead>
</table>
| 6    | Anzac Parade – Georgetti Road to Eastown Road | • Predominantly high density residential buildings  
• Some additional commercial buildings | 4.33 | 3153 | 810,864,678 | 187,266,669 |
| 7    | Riverbank Road and State Highway 4 | • Residential, lifestyle and some agricultural buildings  
• Mix of low density (upriver) and high density (downriver) buildings | 19.98 | 961 | 224,451,264 | 11,233,797 |

### 5.2 LWR Intervention Options

After considering cost constraints and existing proposals for LWR interventions, four possible LWR management options were selected for analysis using the impact model developed in module 2:

- stopbanks in zones 2, 3, 5 and 6 (MWH, 2007);
- increased floor heights for building assets in all zones (Stowell, 2018);
- managed retreat for all zones (Stowell, 2018); and
- doing nothing.

Section 5.3 considers how the above intervention types were coded into the Excel impact model and applied to each zone. A method for determining the costs of these possible interventions is then developed in section 5.4.

### 5.3 LWR Interventions in Management Zones

**Stopbanks**

The MWH (2007) report proposed building stopbanks across the four priority areas identified, rejecting managed retreat and raising asset floor heights as being too expensive (HRC, 2008; MWH, 2007). Other options, including lower river dredging and the construction of a 500m long sandspit overflow weir, were also considered, but ultimately rejected because of ongoing maintenance costs (HRC, 2008).

Locations for the possible stopbanks to be investigated in this thesis were based on the report’s recommendations. Scoping conversations with the HRC river management team indicated that existing LWR...
stopbanks generally exhibit either complete success or complete failure during major flooding events. That is, if stopbanks are overtopped during flooding then they will lose structural integrity and fail completely, resulting in damage to assets behind the stopbanks. However, where stopbanks are not overtopped, assets in the stopbank protection zone (Figure 5.2) will not suffer any damage. Observations from the June 2015 flood (approximately 1 in 130-year event at Town Bridge) support this view; when the 1 in 50-year protection stopbank at Anzac Parade was overtopped, it offered almost no protection, while the 1 in 200-year protection stopbank at Balgownie Avenue was not overtopped and offered complete protection (Wilson, 2015). Other studies have sought to assign a probability of failure to such structural interventions (e.g. Kwakkel et al., 2013; Kwakkel et al., 2016). However, given HRC’s views, the observations from the 2015 flood and the additional resources that assigning such a probability would require, this approach was not taken in this thesis, although case studies considering other areas may need to include this step.

To apply the complete success versus complete failure approach in the Excel impact model, each modelled stopbank was controlled by an “if” statement. The model then triggered a “YES” or “NO” response to the “if” statement by comparing the discharge the stopbank was designed to protect against with the relevant hypothetical time series discharge at the Te Rewa gauge. If the time series discharge was lower than the stopbank design level, all building and infrastructure assets within the relative protection zone were assumed to be completely protected. If the time series discharge was higher than the stopbank design level, then the stopbank was assumed to be ineffective, offering no protection.

![Figure 5.2](image)

Figure 5.2 – Locations of investigated stopbanks (bold lines) in LWR management zones 2, 3, 5 and 6 and their corresponding protection zones (based on findings from MWH, 2007).
**Managed Retreat and Increased Floor Height**

The impact model was also adapted to include two managed retreat scenarios. The first assumed that all assets within 100m of the river channel were moved outside the potential area of flooding while the second removed all assets within 200m. This was modelled by assuming that any assets within a retreat zone were completely protected, regardless of the modelled discharge. However, assets outside the retreat zone would be inundated if the discharge was large enough to reach them.

Increased floor heights were also modelled by adding a specified increase (0.5m, 1.0m, or 1.5m) to baseline floor heights for all buildings within 200m of the river channel. The new floor heights were then subtracted from the inundation depth for a flood event in the impact model to find the inundation level above the new floor height. This was then used to calculate damages using the damage functions previously identified.

To apply the selected interventions, each of the 85 asset database Excel spreadsheets contained in the RCP workbooks produced in module 2 were allocated their own management spreadsheet. The effects of the different intervention types were coded using simple “if” statement switches in Excel controlled by the management spreadsheets. These switches could be turned on and off to simulate different intervention combinations using “YES” and “NO” user inputs. Each management spreadsheet was then linked to a master spreadsheet that allowed selected interventions to be applied quickly and consistently across the RCP workbook and therefore each year of the hypothetical time series created in module 1. This maximised computational efficiency and reduced human error by only requiring changes to a single spreadsheet.

A summary of the processes used to code LWR interventions into the impact model is shown in Figure 5.3.
Figure 5.3 – Conceptualisation of the method used to apply effects of LWR management interventions to the impact model developed in module 2.
5.4 LWR Management Costs

Having established the interventions to be modelled, their implementation costs needed to be estimated. These costings would then be added to total modelled damages over the course of the hypothetical time series for a specified RCP scenario to establish the overall economic impact of adopting that intervention. Whilst basing intervention costs purely on expenditure omits several considerations (e.g. community opposition, environmental impacts etc.), it allows simple financial comparisons to inform decision-making (van Berchum et al., 2018).

Given the risks of inaccuracy in generating economic damages through the impact model, this thesis instead focused on the differences in total costs of interventions in order to identify the most effective interventions. As little information on intervention costs was available, several methods were used to generate plausible cost differences between interventions.

*Stopbanks*

The 2007 MWH report provided cost estimates for four stopbank options across LWR management zones 2, 3, 5 and 6 for 50, 100, 200-year return periods and a “global warming” scenario (MWH, 2007). Each option also included a 0.5m freeboard allowance for modelling inaccuracies (MWH, 2007). Whilst return period calculations for LWR floods have been updated several times since (most recently in 2016 following the June 2015 flood), cost estimates have not. The 2007 stopbank costs therefore required updating to account for 2016 return period calculations.

After adjusting for inflation, the MWH stopbank cost estimates were plotted against their corresponding Te Rewa discharges (Figure 5.4). The resulting linear relationships were then used to extrapolate new cost estimates for stopbanks designed to cope with updated 2016 discharges (Table 5.2). These new cost approximations were then added to the Excel master spreadsheets for impact modelling.

![Figure 5.4](image-url)

**Figure 5.4** – Linear regression relationships used to derive updated stopbank building costs for LWR management zones 2, 3, 5 and 6. Based on data from (Blackwood, 2007b; MWH, 2007).
Table 5.2 – Updated Construction costs for stopbanks in relevant LWR management zones. Based on data from MWH (2007) and Blackwood & Bell (2016).

<table>
<thead>
<tr>
<th>Stopbank Design Level</th>
<th>2007 Modelled Discharge (m$^3$/s)</th>
<th>2016 Modelled Discharge (m$^3$/s)</th>
<th>Updated Stopbank Construction Costs (NZ$2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zone 2</td>
<td>Zone 3</td>
<td>Zone 5</td>
</tr>
<tr>
<td>50-Year</td>
<td>4441</td>
<td>4517</td>
<td>2,058,116</td>
</tr>
<tr>
<td>100-Year</td>
<td>4882</td>
<td>4971</td>
<td>2,359,090</td>
</tr>
<tr>
<td>200-Year</td>
<td>5321</td>
<td>5424</td>
<td>2,658,966</td>
</tr>
<tr>
<td>“Global Warming”/ 500-Year</td>
<td>5760</td>
<td>6022</td>
<td>3,054,596</td>
</tr>
</tbody>
</table>

Floor Heights and Managed Retreat

The 2007 investigations into the possibility of raising LWR buildings by 0.5m suggested an approximate cost of $25,000 per structure (Blackwood, 2007b). However, scoping conversations with representatives from local house moving firm, Brittons Housemovers, indicated that costs today would be nearer $50,000 for an average residential property, although they noted that each property is unique and that specific foundation types and building materials can significantly increase overall raising/moving costs. Therefore, while $50,000 is used as an average raising cost for residential buildings in this thesis, subsequent research may be needed to develop a more accurate figure.

As Brittons could only provide average raising costs for residential buildings, a method for estimating raising costs for other building use categories was needed. It was assumed that the cost of raising a building would be related to its structural replacement cost (determined in section 4.1.3), as both depend on its area, number of storeys, materials etc. Therefore, by taking the ratio of the average raising cost ($50,000) to the average residential building structural replacement cost ($276,778.11), this could be then be multiplied by the structural replacement costs for other building use categories to estimate raising costs.

No estimate could be found for the cost of raising buildings by 1.0m or 1.5m, so for the purpose of the model, it was assumed that these would cost a further 15% and 30% of the total raising costs respectively for any given building. The cost of raising LWR infrastructure has not yet been investigated by HRC so these assets were not included in floor raising interventions.

Finally, it was assumed that the cost of retreating a building would be approximately double the cost of raising it by 0.5m in the LWR. While this approach most likely overestimated retreat costs on average, it ensured that additional costs, including reassembling and transport fees as well as the buying out of properties unsuitable for moving, were accounted for. Infrastructure in retreated zones was assumed to have been abandoned, with
new infrastructure having to be built elsewhere. The replacement costs identified in section 4.2 were therefore used for these assets under retreat scenarios.

Figure 5.5 summarises the methods used to allocate costs to investigated LWR interventions.

![Diagram of methods used to allocate costs](image)

**Figure 5.5** – Main steps used to estimate costs for investigated interventions across LWR management zones.

### 5.5 LWR Intervention Evaluation

Assets within stopbank protection zones or areas designated for managed retreat or raised floor heights were identified and linked to the relevant “if” statements in the Excel impact model master spreadsheets. Interventions could then be selected and applied to relevant assets for each year of the hypothetical time series using simple inputs to the master intervention spreadsheet user interface (shown in Figure 5.6). Whilst costs for each stopbank intervention could be applied directly, costs for retreat and raising interventions were calculated based on numbers of assets within protection zones multiplied by the costs identified in section 5.4. Damages the different interventions had failed to prevent under a specific RCP scenario were then added to the estimated intervention costs to give a total economic impact.

There were 32 possible intervention combinations available for LWR management zones where stopbanks were not proposed (zones 1, 4 and 7) and 1024 combinations for stopbank management zones (zones 2, 3, 5 and 6). For each management zones, every relevant combination needed to be modelled against all six RCP iterations of the hypothetical discharge time series. To automate the process of applying interventions to the impact model and recording associated total economic impacts, lines of re-usable code (macros) were developed using the Visual Basics Analysis (VBA) coding software within Excel. First, a “loop code” applied each
intervention combination to the master spreadsheet in turn using an Excel V-lookup function. Once damages had been calculated for an individual intervention scenario, a second VBA macro was then triggered to record the total economic impact associated with the intervention and particular RCP scenario. While still time-consuming to create, this method prevented a user from having to manually enter each intervention combination, speeding up the process considerably.

Figure 5.6 – Master interventions spreadsheet user interface for activating possible LWR interventions in the impact model. Stopbank and managed retreat interventions are activated using “YES” statements. Increases in floor heights can be specified numerically. Inputs are then applied to control spreadsheets for each year in the hypothetical time series to establish overall economic costs under different RCPs.

The resulting total economic impacts associated with each intervention combination, RCP scenario and LWR management zone could be analysed using a decision-support code to assess the relative total costs of each strategy.

The Eaves Code

A new statistical decision-support code developed by Ashton Eaves at the University of Auckland was used to assess intervention effects based on principles of minimal regret identified by Lempert (2003) and expanded upon by Callaway (2014). This Eaves code ranked interventions from least to most regret for each management zone under each RCP scenario using total economic impacts and RCP weightings. The option with the highest overall ranking across all examined scenarios represents the most robust option, being the least sensitive to future climate projections (Lempert, 2003; Lempert et al., 2006). Whilst the code was developed primarily for the Robust Decision-Making decision-support method, its ability to identify the most robust option within specific scenarios means it can also evaluate pathways as part of DAPP investigations.

While other decision-support codes were available, each offering different insights, the Eaves code was preferred for this thesis primarily, because of its ability to process a range of damage inputs directly from Excel whilst offering time and cost efficiencies. The code can also provide insights into how interventions perform
both across and within different RCP scenarios, thus highlighting climate scenarios under which interventions might fail. Councils can then monitor for these scenarios, and change tactic if they appear likely in accordance with DAPP (Haasnoot et al., 2013). However, subsequent studies may wish to use alternative codes to see if they produce similar results. A repository with the source code for the Eaves code and the total economic impacts data used in this thesis can be found on GitHub (https://gitlab.com/aceaves/dappy_lite).

Figure 5.7 summarises the process used to identify and evaluate plausible LWR interventions.

Figure 5.7 – Summary of the assessment and evaluation processes for investigated LWR flood interventions.

Total economic impacts of flooding under different RCP scenarios for each management zone were run separately through the Eaves code with an equal weighting assumed for each RCP. Figure 5.8 shows an example of the Eaves code output when applied to total economic impacts for management zone 1, identifying minimum regret interventions across all six RCP scenarios (options with $0 wasted). The regret of other interventions is also presented proportionally to the minimum regret option. The figure indicates that the minimum regret option for management zone 1 is implementing 100m of managed retreat (intervention strategy 7). Figure 5.9 then shows how the full range of interventions for management zone 1 perform under each RCP. These results highlight that the baseline RCP scenario results in the smallest economic impacts across all intervention strategies, with costs increasing exponentially for more extreme RCP scenarios.
Figure 5.8 – Parallel boxplot output from the Eaves code when applied to total economic costs from management zone 1 over the investigated hypothetical time series for six RCP scenarios. Each option is presented in terms of proportional regret to the minimum regret option. Highlighted are the minimum regret (100m of managed retreat) and current (no interventions) strategies.
Figure 5.9 – Parallel boxplot output from the Eaves code highlighting the performance of all interventions for management zone 1 across different RCP scenarios. Minimum total economic costs for all intervention strategies are achieved under the baseline scenario. Each subsequent RCP scenario is then presented in terms of proportional regret to this scenario.

Table 5.3 presents the minimum regret interventions identified by the Eaves code for all seven LWR management zones, with the total economic impacts of those interventions shown in Table 5.4.

Table 5.3 – Minimum regret interventions from the Eaves code analysis of LWR management zones for six RCP iterations of the hypothetical time series. The magnitude of each intervention is indicated by a number. The type of intervention is indicated by a letter: M = managed retreat, F = floor raise, S = stopbank.

<table>
<thead>
<tr>
<th>LWR Management Zone</th>
<th>Eaves Code Minimum Regret Intervention Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RCP Baseline</td>
</tr>
<tr>
<td>1</td>
<td>100M</td>
</tr>
<tr>
<td>2</td>
<td>1.5F</td>
</tr>
<tr>
<td></td>
<td>500S</td>
</tr>
</tbody>
</table>
### Table 5.4 – Total economic impact (comprising damages and intervention costs) for overall minimum regret options across LWR management zones compared with current management.

<table>
<thead>
<tr>
<th>LWR Management Zone</th>
<th>Difference in Total Economic Impact of Minimum Regret Strategy Compared to Current Interventions (NZ$2018)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RCP Baseline</td>
</tr>
<tr>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
</tr>
</tbody>
</table>

Comparing minimum regret options for each LWR management zone against current management shows that interventions could significantly reduce potential damages to assets. As Tables 5.3 and 5.4 illustrate, minimum regret options from the Eaves code tended to comprise two interventions suggesting that combinations of strategies have most potential for the LWR. This is likely because combining two or more interventions allowed...
different asset types to be targeted (e.g. buildings specifically by raised floors and other assets by managed retreat) resulting in greater overall protection.

Table 5.4 also indicates that the largest total economic impact reductions were possible for the most extreme RCP scenarios (specifically RCPs 8.5 and 8.5 x 1.2). Putting interventions in the priority management areas previously identified by HRC (zones 2, 3, 5 and 6) also led to the greatest reductions in predicted damages. Interestingly, selecting 500-year stopbank protection in HRC priority management areas gave the greatest reduction in cost, but only when used in conjunction with other interventions such as raising floor heights and managed retreat. This was because there were still significant damage costs from the most extreme flood events when stopbanks were overtopped, suggesting that stopbanks should not be the sole means of protection for extreme climate change scenarios.

Finally, zones were ranked in terms of their management priority using total economic impact reductions across all six RCPs (Table 5.5). This analysis indicated that management zone 2 (Taupo Quay in the CBD) should be prioritised moving forward; when the minimum regret option was selected, it resulted in potential damages being almost halved across the hypothetical time series. Much of this appears to have been because indirect costs for businesses were avoided as these were the dominant damage type for the June 2015 theoretical direct structure test (section 4.6).

**Table 5.5** – LWR management zones ranked in terms of possible reductions in cost associated with modelled minimum regret intervention strategies recommended by the Eaves code.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56,611,120</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>940,388,591</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>924,667,140</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>157,502,410</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>262,604,964</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>11,847,359</td>
<td>6</td>
</tr>
</tbody>
</table>

**5.6 Summary**

This chapter addressed the final components of Thesis Objective One by modelling LWR management interventions using the impact model developed in modules 1 and 2 and evaluating these using a decision-support code (the Eaves code) in line with a model-based DAPP approach. The approach involved analysing possible LWR interventions from past and current proposals, applying possible damage reductions to the impact model, and estimating costs associated with interventions. As for previous chapters, obtaining
necessary information (particularly relating to intervention costs) was challenging, meaning several assumptions were necessary when selecting modelling actions (e.g. complete success versus complete failure of stopbanks). In other cases, additional complexity had to be incorporated into the methodology to speed up otherwise time-consuming processes (e.g. use of VBA code to automatically run the impact model for different intervention combinations).

Reflecting on Chapters Three, Four and Five as a whole, this thesis has shown that DAPP investigations into possible river flood hazards can be carried out predominantly using local models and datasets. However, the required processes can be time-consuming and the assumptions made raise questions as to accuracy. Potential users of the DAPP implementation methodology should be aware of these limitations so that they can make informed decisions as to whether it is a reasonable use of available resources.

Having developed the necessary models for the DAPP implementation methodology, Chapter Six now examines how these models might be used to engage stakeholders with deep uncertainty through developing serious games.
Chapter 6

MODULE 4: ENGAGEMENT

The first three modules of the DAPP implementation methodology established accessible methods for developing a flood impact model to evaluate possible LWR interventions. This chapter then sought to investigate how this model could be used to communicate deep uncertainty and adaptive planning concepts in line with Thesis Objective Two. Two activities were therefore undertaken:

- a serious game session based around the impact model to expose LWR flood management professionals to deep uncertainty; and
- follow-up interviews with self-selected game session participants to further investigate concepts raised in the game session and how they might be applied in the LWR flood management context.

The serious game looked to examine how LWR flood management decisions are made when little contextual information is available. It sought to identify key drivers of individuals’ decisions; this information could then be used to better tailor future impact models and serious games to decision-maker requirements. The game would also allow the impact model and other aspects of the DAPP implementation methodology to be assessed and evaluated by management professionals responsible for developing LWR management plans. Finally, a game session could provide a mechanism for presenting basic damage outputs and adaptation concepts to stakeholders in novel ways (e.g. 3D inundation maps), thus facilitating conversations about dynamic planning.

Carrying out the DAPP-inspired game session and collecting relevant results involved the following steps:

- identifying game objectives;
- adapting the impact model for LWR interventions from module 3 into a serious game;
- obtaining ethical approval from the University of Auckland Human Participants Ethics Committee (UAHPEC) (reference number 021727);
- carrying out the game session and follow-up interviews; and
- analysing qualitative results using thematic analysis to inform future decision-support method and serious game research.

6.1 Game Objectives

A series of game objectives was developed to guide game structure and mechanics (Table 6.1). The principal goal was to see if participants would, by taking part in the game session, gain new insights into adaptation concepts which would inform their decision-making. To accomplish this, the game sought to encourage players to work as a team to create a sustainable management plan for the LWR from 2016-2100.
Table 6.1 – Objectives used to guide the creation of a serious game to illustrate adaptation concepts and participant engagement in the LWR case study.

<table>
<thead>
<tr>
<th>Game Objective</th>
<th>Mechanisms to Facilitate Objective</th>
</tr>
</thead>
</table>
| Create serious game for management professionals to illustrate deep uncertainty and adaptation concepts | • Adapt models from modules 1, 2 and 3 based on the Sustainable Delta Game (SDG) to stimulate adaptive decision-making  
• Refine game through trials                                                                 |
| Study decision-making drivers for LWR management professionals                  | • Thematic analysis of game session discussion and feedback                                                                                                     |
| Facilitate learning and engagement opportunities that could be applied within and outside the formal game session | • Demonstrate capacity of new 3D inundation maps to illustrate possible flood risk and impacts as recommended by the literature  
• Present economic damage outputs using innovative graphics  
• Use game storyline to promote opportunities for adaptive decision-making  
• Examine strengths and weaknesses of DAPP implementation methodology models |
| Promote awareness of deep uncertainty concepts                                  | • Use game storyline to emphasise deep uncertainty around future climate change impacts on the LWR                                                                |
| Promote opportunities for professional feedback on DAPP implementation methodology models | • Present results of June 2015 theoretical direct structure test and allow participants to formulate their own conclusions about the models’ viability |

6.2 Game Development

The game attempted to provide an opportunity to learn about deep uncertainty and dynamic adaptation by giving players flood scenarios which they would have to manage, and showing them the damages that would result from their chosen strategies. For this, a storyline of increasingly high LWR annual maximum discharges was used to reflect possible climate change (similar to the SDG – Deltares, 2016). Players’ choices were then studied using thematic analysis to assess the drivers for decision-making and inform future game development.

A storyline was manufactured using the hypothetical future time series of LWR discharges developed in module 1 (Figure 3.9). In particular, the RCP 8.5 iteration of the time series was selected for the game session because it included several high magnitude flooding events where adaptation would be necessary, whilst still being in-keeping with current IPCC climate change projections. Like the SDG, the game was divided into five rounds with players allowed to deploy two active interventions (other than do nothing) per round. This gave players time to get used to the game and implement their plans, with management decisions made based on the information provided at the start of each round (Van Pelt et al., 2015).

Figure 6.1 shows the allocation of years in the time series to each management round. Whilst most rounds used discharges of large sizes, round four had small discharges designed to make the players question whether to implement additional interventions before the extreme discharges of round five.
Additional materials (such as maps, fictitious newspaper articles etc.) were provided throughout the game to maintain the established storyline and to ensure community opinion was considered in decision-making (Reed et al., 2010). These additional materials (detailed in Appendix A) and their purposes are identified in Table 6.2.

**Table 6.2** – Additional materials used to facilitate the serious game session.

<table>
<thead>
<tr>
<th>Contextual Element</th>
<th>Purpose</th>
</tr>
</thead>
</table>
| Game briefing statement | • Ensure common understandings between players and to establish the game rules  
• Establish management priorities of:  
  o Mitigating flood risks  
  o Gaining community acceptance of policy  
  o Curbing unnecessary expenditure |
| 3D interactive maps and animations of LWR flood inundation under each annual maximum created using ArcScene | • Provide visual contextualisation of inundation depths relative to building assets.  
• Enable participants to assess modelled physical inundation against their own experiences  
• Created by merging HAZUS FIT depth grids with the LWR DEM in ArcMap to create a new depth layer. This layer was then overlaid onto the original LWR DEM to give an indication of flood depths relative to the DEM. |
| Maps of LWR management zones | • Establish management context and key characteristics of each zone, including population, building and industry characteristics |
| Intervention options | • Illustrate the intervention options available for each LWR management zone |
| Intervention selection sheets | • Encourage players to develop clear justifications for selected interventions  
• Opportunity for researcher to analyse management justifications after the game session |
In addition, players had to work within a set of game rules whilst implementing their sustainable management plan for the LWR. Specifically, for each management round, teams needed to (adapted from Deltares, 2016):

- determine their overall strategy and point of view;
- account for community opinions as depicted in fictitious newspaper articles;
- choose a maximum of two active interventions across all LWR management zones; and
- negotiate preferred actions between teams (if multiple teams were playing).

These rules required teams to discuss different intervention strategies and consider other teams’/community opinions before deciding how to proceed.

6.3 Ethical Considerations
As the game session and follow-up interviews involved participants, ethics approval from the UAHPEC was required (reference number 021727). Informed consent was obtained from all participants and the organisations they represented. Consent from organisations was deemed necessary because of the potential for participants to give organisation-specific insights. A pre-approved email was sent to organisations, with individual participants receiving an invitation to participate from an organisation liaison on behalf of the researcher once organisation approval was given. Research information was collected during the game session and researcher and participant notes were subsequently subject to thematic analysis. Follow-up interviews were also recorded with participant consent and later transcribed for analysis. Appendix B contains all participant information sheets (PIS), consent forms (CF) and initial contact emails. Participants names are excluded from this thesis and only organisation names and area of expertise used.

6.4 The Game Session
Various regional and local government specialists were invited to take part in the serious game session, each having a unique perspective on river flood management (Table 6.3). As for the SDG, players would be divided into teams (depending on numbers) and instructed to elect a team captain who would make final decisions and adjudicate disagreements (Deltares, 2016). A separate log keeper would be selected to record chosen interventions and justifications for decisions (Deltares, 2016).
Table 6.3 – Organisations and specialists invited to participate in the serious game session and follow-up interviews.

<table>
<thead>
<tr>
<th>Organisation</th>
<th>Specialists</th>
<th>Anticipated Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRC</td>
<td>Regional Councillors</td>
<td>• Experience of flood-based decision-making processes and engaging with stakeholders to achieve management outcomes.</td>
</tr>
<tr>
<td></td>
<td>River Managers</td>
<td>• Experience in developing models to assist decision-making, assessing management priorities and working with other specialists and communities to facilitate management objectives.</td>
</tr>
<tr>
<td></td>
<td>Policy Planners</td>
<td>• Experience in developing policy to drive management goals. Capable of providing insights into long-term implementation of decision-support methods.</td>
</tr>
<tr>
<td>WDC</td>
<td>District Councillors</td>
<td>• Knowledge of LWR community views and priorities. Experience with flood impacts.</td>
</tr>
<tr>
<td></td>
<td>Policy Planners</td>
<td>• Experience in using policy to drive management goals. Specialist knowledge of current legislation surrounding LWR flood management.</td>
</tr>
<tr>
<td>Whanganui Civil Defence and Emergency Management</td>
<td>Civil Defence Personnel</td>
<td>• Experience in identifying management priorities and first-hand knowledge of interventions’ performance during major flood events.</td>
</tr>
</tbody>
</table>

A trial game session was undertaken with university colleagues to assess game mechanics and acquire feedback. For the game session proper, six participants agreed to take part, specifically:

- Whanganui District Civil Defence personnel [CD1 and CD2];
- WDC stormwater engineer [DC1];
- HRC engineering officer [HRC1]; and
- HRC river management analysts [HRC2 and HRC3].

The formal focus group and serious game session was held from 9am-1pm on the 1st September, 2018 in the WDC infrastructure team offices (Figure 6.2).

![Figure 6.2 – Photographs taken from the serious game session.](image-url)
Given the number of participants, it was decided that they should form one team, rather than two smaller teams, to maximise opportunities for discussion within the group. After completing the main gaming activity, the group was then asked a set of pre-approved questions to assist in the examination of Thesis Objective Two (Appendix C).

After the game session, three participants agreed to take part in a follow-up interview, as did a senior HRC representative [HRC4] who had been unable to attend the game session. These interviews were all conducted in the participant’s place of work and at a time of their choosing using another set of pre-approved questions (Appendix C).

Observations regarding how the team selected interventions were used to promote discussions during the game session and in the follow-up interviews regarding whether decision-support methods including DAPP are applicable to, and could be implemented for, LWR management. Such qualitative data was then analysed to identify themes pertinent to wider decision-making processes. This analysis is shown below.

6.5 Game Results

Table 6.4 shows the intervention options selected by the team throughout the serious game session. Out of ten opportunities to deploy interventions (two per round) the team used only five, all of which were applied to the four priority management areas previously identified by HRC. In selecting intervention options, the team acted consistently with current HRC policy by focussing on stopbanks in management zones 3 (Balgownie Avenue) and 6 (Anzac Parade). Zone 2 (Taupo Quay) saw the most interventions in an effort to reduce the significant indirect business losses predicted for the Whanganui CBD. However, a reliance on stopbanks to protect management priority areas resulted in significant damages when these were overtopped (particularly during the extreme discharges of round 5). As such, whilst the team’s plan was consistent with historical management approaches, it was ill-equipped to deal with extreme floods foreshadowed by long-term climate projections.

Table 6.4 – Participants’ management decisions during the serious gaming session.

<table>
<thead>
<tr>
<th>Game Round</th>
<th>Active Intervention Choices For Each Game Round</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>• None</td>
</tr>
<tr>
<td>2</td>
<td>• Zone 2 – 200-year design level stopbank</td>
</tr>
<tr>
<td>3</td>
<td>• Zone 3 – 500-year design level stopbank</td>
</tr>
<tr>
<td></td>
<td>• Zone 6 – 100m managed retreat</td>
</tr>
<tr>
<td>4</td>
<td>• Zone 5 – 1.5m floor raise</td>
</tr>
<tr>
<td>5</td>
<td>• Zone 2 – 500-year design level stopbank</td>
</tr>
</tbody>
</table>

The serious game session thus identified widespread support within local government agencies for current management plans. Although players were able to explore alternative strategies, they often chose to simply increase stopbank design levels (60% of active intervention choices). However, increasing damages and waning community support eventually made the team question its stopbank-based strategy and select other options in later rounds (3 and 4).
**Thematic Analysis**

Observations of participant engagement were analysed using Nowell et al.’s (2017) six phases of thematic analysis for qualitative research (Figure 6.3). This thematic approach allowed multiple aspects of the game to be examined, including direct evaluations of modelling components, insights into key drivers of decision-making and the attitudes of participants. Observations were derived from researcher and participant notes from the game session, as well as written transcripts of follow-up interviews.

**Figure 6.3**—Nowell et al.’s (2017) six phases of thematic analysis, describing how each phase was applied to the qualitative information collected during the focus group and follow-up interviews.

Sources of data for the serious game and follow-up interviews as well as the findings and themes they revealed are shown in Table 6.5.

**Table 6.5**—Types of qualitative data collected during the focus group game session and follow-up interviews, their associated findings and themes.

<table>
<thead>
<tr>
<th>Qualitative Data Source</th>
<th>Findings</th>
<th>Themes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedback on the accuracy of the current DAPP implementation methodology and its constituent model suites based on personal experiences and results of theoretical direct structure test</td>
<td>Model as a static instrument</td>
<td>• Uncertainty vs accuracy</td>
</tr>
<tr>
<td>Identification of areas for possible modelling improvement</td>
<td>Model as an evolving instrument</td>
<td>• Non-economic values</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Coupled hazard modelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Free-thinking space</td>
</tr>
<tr>
<td>Examination of group dynamics and individual understandings</td>
<td>Model as a facilitator of individual learning</td>
<td>• Awareness of deep uncertainty</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Realism</td>
</tr>
<tr>
<td>Examination of team work and decision-making</td>
<td>Model as a facilitator of group learning</td>
<td>• Proactive vs reactive</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Experience and attitude</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Role of communities</td>
</tr>
<tr>
<td>Feedback on whether decision-support methods such as DAPP might be viable for the LWR flood management context</td>
<td>Model as a decision-support tool</td>
<td>• Management versus engagement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Storytelling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Powerlessness</td>
</tr>
</tbody>
</table>
Figure 6.4 summarises the processes used to develop the serious game and analyse its results.

Figure 6.4 – Overview of the processes used to develop and implement a serious game based on the DAPP implementation methodology model suite and generate thematic results based on research observations and follow-up discussions.
Finding 1 - Model as a Static Instrument

The first theme, derived from researcher observations, was the capacity for the game session to provide feedback on the uses and limitations of the DAPP implementation methodology. Participants’ feedback focused on the cost outputs the model generated. Because the model design had prioritised ease of use, there was potential for some inaccuracy in damage estimates, meaning that the trends shown were generally more relevant than the actual figures. However, in general, participants were satisfied with the accuracy of the models’ outputs, with one HRC representative stating “Yeah, those costs seem to add up”, although some participants expressed concern over specific uncertainties relevant to their area of expertise. Participant DC1 reflected: “I think there could be a lot of refinement on it... some of the underground infrastructure costs I thought were a bit on the high side,” but “your resources have been limited.” These accuracy issues resulted in a minority of participants feeling that the model was too simplistic – such participants were generally more interested in exact numbers rather than using the modelling to explore damage trends in different scenarios. This demonstrates that some decision-makers may have unrealistic expectations of what models can and should be used for since no model can project the future with complete accuracy. Nevertheless, models can still give insights into possible future climate trends and compare potential intervention options as part of decision-support methods such as DAPP.

Finding 2 - Model as an Evolving Instrument

Many participants gave feedback on how the model could be improved. Data was collected regarding participants’ perceptions of the methodology and game and how they thought the models could be developed to enhance their utility as part of a decision-support method. Participants were particularly keen to see non-economic values, including social, aesthetic and perceived investment values, included in the model, since these considerations have historically prevented HRC from fully implementing management plans (Wilson, 2015). In the literature, non-economic values have generally been incorporated into model suites using significance ranking systems that prioritise key areas/buildings for protection (e.g. Vojinovic et al., 2016). Whilst such a system was not included in this thesis given the desire to minimise model development time for local government personnel, the flexibility of Excel coding means it could be added in future. The external scenario weighting system used by the Eaves code could also be applied to prioritise intervention schemes for reasons other than economic cost-benefit.

During the follow-up interviews, participants also wanted to see the model complex expanded to simulate multiple simultaneous hazards. In particular, participants wanted to explore the effects of both sea level rise and erosion in conjunction with main channel river flooding across the LWR sub-catchment. “I would like to see... the quantification of other damages across the catchment... I think that would be really useful” [DC1]. However, this type of tandem hazard modelling would require relationships between different hazards and their impacts to be established. Given the difficulties experienced in identifying hazard damage relationships for the LWR due to inadequate record keeping, this would likely require further extensive research.
When prompted, participants in the game session also suggested other possible LWR interventions for the DAPP implementation methodology to consider. Younger participants especially, were more willing to consider unorthodox suggestions. The most popular of these were hydraulically mounted stopbanks that could be lowered to maintain amenity value and raised to provide flood protection. Other suggestions focused on strategies to reduce clean-up time and costs after a flood event by investing in improved response systems and rebuilding assets with flood resilient materials. The game session thus provided a safe space for specialists to come together, share ideas and be creative without being constrained by existing council policy. This highlights the potential for new adaptation approaches to be developed when professionals who would not usually exchange ideas come together (Lawrence and Haasnoot, 2017).

Finding 3 - Model as a Facilitator of Individual Learning

The game session also demonstrated the model’s capacity to promote individual understandings around deep uncertainty through traditional cognitive learning (Baird et al., 2014). Prior to the focus group, none of the players had heard of deep uncertainty or considered how it might be incorporated into flood impact assessment models. Participant HRC2 reflected “It [flood management uncertainty] is not currently accounted for, some climate change allowance will have been input into design of some of the major infrastructure but I’m unsure about the modelling.” Although the impact model developed was primarily focussed on climate uncertainties, the game session also encouraged players to think about other uncertainties, particularly in terms of the differences between practical management and modelling. For instance, participant HRC2 stated “From the workshop, I think the largest uncertainty (in flood management) is the socio-economic pressures following a flood event”. For some participants, this meant considering how management would affect areas both within and outside of their areas of expertise. As participant HRC1 reflected, “It’s good to see what you can do and what effect that will have”. This broader perspective could have considerable benefits, both in terms of understanding the components of the deep uncertainty problem and in translating these understandings into an impact modelling context to support future LWR decision-making.

Sudden exposure to deep uncertainty in the LWR context resulted in participants being particularly surprised by the magnitude of potential flood discharges, even though they had been told the model was based on the “worst case” RCP scenario. “I was a bit flabbergasted” said one participant, suggesting a disparity between perceptions of future climate change effects and modelled trajectories. However, none thought the projected discharges unrealistic.

Finally, participants were positive regarding the use of models and the flood graphics from the serious game as tools to demonstrate potential flood damage and intervention effects to communities. One participant stated “I think these kinds of damage models in conjunction with 3D graphic representations of flooding would be very useful in getting public buy-in.” They also felt that DAPP as a methodology offered great promise in promoting community involvement in flood management by offering engagement opportunities throughout the process (e.g. identifying interventions, indicating preferred pathways).
Finding 4 - Model as a Facilitator of Group Learning

The game session also allowed investigation of group learning through examining how the team made decisions, the motivations behind those decisions and how these changed over time. Only having one team meant that all negotiations surrounding intervention strategies were within the team or between them and the “community” (played by the researcher through fictitious newspaper articles). Whilst inter-team competition was considered a critical component of Lawrence and Hassnoot’s (2017) serious game session for the Hutt River, its absence in this game session did not prevent active discussions regarding the appropriateness of overarching strategies. Partly this was because participants held a wide range of views. In earlier rounds, more experienced participants generally dominated the discussion and their preferred strategy was implemented. Such strategies were often reactive, with flood protection only increased after existing measures had failed. This style of management was expected to prevent unnecessary spending and community alienation.

Younger players disagreed with this reactive approach, preferring to implement more long-term preventative strategies gradually across the management rounds. This approach (validly) assumed that the game’s flood events would likely get more extreme as it progressed, given the nature of IPCC climate change projections. By implementing strategies gradually across all management rounds, necessary flood protection could have been attained before serious flood damages were incurred whilst minimising community resistance. However, because of opposition from other team members, those preferring this more gradual strategy were unable to lay the foundations in the earlier rounds. This meant that when urgent protection was required for extreme events in later rounds, the team was unable to achieve high enough levels of protection quickly enough across all zones. This issue was acknowledged in the follow-up interviews with participant HRC1 stating “Probably instead of the first round where we went with the status quo... I think initially I would have put some kind of protection around Taupo Quay and the CBD”. In addition, having an adaptable plan from the outset was identified as a way of reducing stress within the team by alleviating the need to develop new management schemes every time something went wrong.

The supplied community opinion also influenced the game session significantly. In particular, using community opinion to question and sometimes actively prevent particular interventions from being implemented forced the team to provide more rigorous justifications for their decisions. These interactions also illustrated the benefits of using adaptive pathways to signal management changes ahead of time with participant HRC2 reflecting “If one management approach is no longer viable and we have to go another pathway, the public were made aware of the alternatives before they were implemented and they weren’t a ‘surprise’”. The participants felt that such an approach could build trust with communities which would in turn allow management authorities to act when necessary. Participant HRC2 further stated “If there are multiple pathways in place the council will be held more accountable and the options presented to the public will be more clear and backed up”.

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Finding 5 - Model as a Decision-Support Tool

As part of the follow-up interviews, participants were invited to consider potential future applications for the game session and DAPP implementation methodology. These discussions also gave insight into how local government personnel thought deep uncertain flood problems might be modelled and managed.

The main point of difference between participants was what the role of decision-support investigations should be. All participants agreed that tools like the game could be useful, but opinions were divided on whether it would operate best as a community engagement and social learning tool to explore intervention options, or as a decision-making aid for river managers. Participants liked the 3D inundation maps overlaid on the LWR, saying that this enabled them to see the scale of flooding and to visualise the extent of the damage, which would not have possible using numeric outputs alone. On this topic, participant HRC2 reflected “The workshop was a good experience to show the impact of flooding in a visual way, which is very useful at engaging an audience”. Decision-support methods would also allow decision-makers to see the potential effects of their decisions before making them. As participant HRC1 further stated “For councillors to... actually see the effects of different scenarios then it might actually change their perspectives on things... usually they just go with what the community says”. However participants also acknowledged that the recommendations of specialist decision-support codes (e.g. the Eaves code) should not be taken at face value and that human decision-making remained vital.

The participants also agreed that decision-support tools like this model and game could aid community engagement by explaining complex uncertainty problems in a manner that was easy to understand. This was an aspect of flood management that participants felt local and regional government had handled poorly and required improvement. Participant HRC4, when asked about current engagement practices, stated “No, we don’t do enough... we give communities snapshots of particular design levels and expect them to fill in the rest... there’s nothing cohesive... there’s no story.” Showing annual accounts of possible floods under different RCP scenarios in a visual way was identified as a potential way to bridge this management-community gap and to better communicate specialist knowledge. Indeed, the potential packaging of the current model as part of a web-based application that members of the community could access at home to develop personal understandings of the deep uncertainty flood management challenge was a popular suggestion. This would enable the decision-support game and method to go beyond merely providing “support” to select decision-makers. Instead it could be used to foster relations between managers and communities through knowledge sharing to enable better informed discussions about future flood management strategies.

Finally, interviewees were asked to reflect on their new knowledge of decision-support methods, specifically DAPP, to assess whether they might assist in the future management of the LWR. All agreed that these approaches offered new ways to conceptualise dynamic adaptation and could provide many benefits to both local government agencies and communities. Participant HRC1 reflected “I think it’s a great start and could help quite a lot”. Whether these assessments will result in changes in management attitudes remains to be seen.
However, it was encouraging to note how willing participants in both the focus group and interviews were to accept these new management ideas despite them differing significantly from historical management practices in the LWR. Indeed, it was apparent that some individuals (particularly younger participants) were acutely aware of the possible dangers associated with climate change but had so far felt powerless to make necessary management changes. This may be due to entrenched short-term planning instruments (e.g. 30-year infrastructure plans) preventing inter-generational planning coupled with an engrained management approach focused on trying to ensure protection against certain return periods. As such, while participants felt that there was little scope to implement a decision-support method themselves in their council roles, they were interested in exploring such strategies as part of the game. Whilst a single game session seems unlikely to change entrenched practice, it at least allowed participants to consider these ideas further.

6.6 Summary

This chapter investigated how a serious game session developed using the first three modules of the DAPP implementation methodology model suite might aid local government decision-making through communicating deep uncertainty concepts, in line with Thesis Objective Two. It demonstrated that the impact models developed during the previous three DAPP implementation methodology modules could be readily adapted to create a new serious game specific to the LWR that utilised engaging graphics without the need for extensive modelling knowledge. It was also demonstrated that using thematic analysis to assess serious game outcomes can generate useful findings beyond the learning types identified by other evaluation techniques (e.g. validation of game models). Overall, the serious game provided a useful learning experience for participants, allowing them to engage with impact model outputs and concepts in a way that might not have been possible had they been presented as mere numbers.
Chapter 7
DISCUSSION AND CONCLUSIONS

7.1 Introduction

This thesis investigated what could be learned from applying low-cost, time-efficient DAPP approach to support uncertain decision-making in the LWR. To do this, it first sought to develop a modelling methodology capable of implementation by local government to evaluate LWR flood intervention strategies in line with modern decision-support methods (specifically DAPP). Second, this thesis investigated how applying the resulting models in a serious game setting might aid local government decision-making through enhancing community engagement with deep uncertainty concepts.

This chapter discusses the extent to which these objectives were achieved and offers recommendations regarding future iterations of the DAPP implementation methodology. For each thesis objective, it provides conclusions regarding:

- elements that were successful;
- elements that were less successful;
- compromises that had to be made; and
- areas warrants further investigation.

The chapter finishes by briefly evaluating the potential for standardised decision-support methods to support local government flood management in New Zealand.

7.2 Lessons from the Modelling Components of the DAPP Implementation Methodology

Decision-support methods have been found to support flood management decisions in various New Zealand and international contexts (e.g. Lawrence et al., 2019; Haasnoot et al., 2013; Ranger et al., 2013). These studies have culminated in MFE recommending that New Zealand local government use DAPP to support decision-making regarding coastal hazards (MFE, 2017). Despite similar guidance for river flooding anticipated in the coming years (with the last MFE river guidance document published in 2010 – MFE, 2010), it is nevertheless unclear whether decision-support methods are capable of implementation by New Zealand local government.

Objective one of this thesis sought to address this gap in the literature by developing a time and cost-efficient methodology (the DAPP implementation methodology) to facilitate a model-based DAPP investigation of possible interventions for the LWR. This method comprised three modules, specifically:

- Module 1 investigated how to generate hypothetical time series of future LWR discharges, including incorporating climate effects in line with different RCPs and converting the resulting time series into depth grids for use in impact modelling.
Module 2 sought to create a new database of LWR building and infrastructure assets using existing and purpose-built datasets to provide the vulnerability component of impact modelling. Hazard data for the June 2015 flood event was then used to assess the model’s accuracy.

Module 3 applied proposed LWR interventions to the impact model to calculate overall economic costs. The resulting differences in overall economic costs between interventions were then analysed using the Eaves code to identify robust options and re-assess management priority zones.

### 7.2.1 Elements that were successful

Elements of the first three DAPP implementation methodology modules that were successful included:

- use of local scale models and datasets;
- development of new asset databases;
- creation of basic absolute damage functions;
- use of Excel which allowed impact model errors to be easily identified; and
- use of the Eaves code in evaluating LWR interventions.

Considering first local scale models and datasets, these proved invaluable in applying the DAPP implementation methodology. In particular, the HRC MIKE 11 flood model outputs and infrastructure datasets provided by WDC and Powerco were crucial for creating and streamlining the hazard and vulnerability components of the impact model. Indeed, all local level models and asset databases considered during this project were ultimately incorporated into the final model (Table 7.1). This reliance on local resources reflected the need for high resolution models and data in assessing flood impacts in detail as part of the DAPP implementation methodology (Nguyen et al., 2016). As such, local councils will need to be aware that establishing local scale datasets may be a necessary first step to undertaking flood impact modelling as part of decision-support methods.
This thesis also demonstrated that a local asset database can be developed using limited resources. For buildings, Google Street View was used to visually assess attributes across the seven LWR management zones, providing a greater level of accuracy than extrapolating attributes from transect data would have done (as seen...
in Scheele et al., 2014). The road dataset was similarly constructed using satellite imagery to identify road outlines and cross-sections and to establish road areas. These approaches allowed new asset databases to be created without specialist expertise.

Turning then to damage functions, this thesis developed case study-specific absolute damage functions for road and electricity assets based on scoping conversations with professionals familiar with the impacts of historical LWR floods. Whilst these absolute functions were often crude and unable to distinguish between different levels of damage, they offered a simple and low-cost mechanism for local councils to approximate possible damages in the absence of formal damage functions (Merz, Kreibich et al., 2010).

Using Excel for most modelling also provided advantages in terms of cost as it can be used with limited expertise and is widely available. Traditionally, iterative forecasting functions relating to deep uncertainty investigations are carried out by dedicated coding programs (e.g. Kwakkel et al., 2016), but for this thesis it was found that using these programs often meant reviewing many lines of complex code for calculation and scripting errors, which was highly time-consuming. In contrast, because Excel requires complicated damage calculations to be broken down over a series of cells, problems with overall formulae could be found quickly.

Continuing this theme of easy access, like Excel, the Eaves code provided an easy and cost-effective way of achieving outcomes, in this case, evaluating possible interventions for the LWR. In addition, the code could extract information directly from Excel spreadsheets and required no further input, reducing opportunities for human error and ranking the 1,024 intervention options for LWR stopbank zones by regret in less than one minute. As such, the Eaves code had distinct advantages over other decision-support codes in terms of its usability and efficiency, making it highly suitable for this methodology.

### 7.2.2 Elements that were less successful

Aspects of the first three DAPP implementation methodology modules that were less successful were:

- use of national scale models and datasets;
- use of damage functions derived from the literature for infrastructure and indirect tangible damages;
- maintaining accuracy despite outdated satellite imagery and overly simplified building classes in the overall LWR building database; and
- validation of the impact model against historical data.

Considering first national models and datasets, these were included in the DAPP implementation methodology where possible in an effort to relieve pressure on local councils to gather and maintain their own data. Even so, few national models made it into the final methodology, largely because they would have required extensive modifications before they could be used (Table 7.2). In particular, TopNet RCP affected discharges for the Te Rewa gauge were found to be too extreme to be of use in evaluating the effectiveness of interventions. Additionally, LWR damages could not be calculated using RiskScape building dataset because it is based on
average characteristics rather than recorded attributes for specific buildings. As such, it would have been impossible to calculate accurate damages using RiskScape data. Instead, local models (e.g. HRC MIKE 11) and asset databases (e.g. WDC three waters infrastructure) had to be used, supplemented with collected data.

Table 7.2 – The national scale models and data sources considered for the DAPP implementation methodology.

<table>
<thead>
<tr>
<th>Data Source</th>
<th>Data Resolution</th>
<th>Applicable Module</th>
<th>Final methodology</th>
<th>Reasoning</th>
</tr>
</thead>
</table>
| TopNet semi-distributed hydrological model     | National        | Climate and Inundation  | No                | • Extreme differences between projected LWR discharges under RCP scenarios and historical record  
  • Modelled discharges too large to provide useful feedback on possible interventions |
| HIRDS                                          | National        | Climate and Inundation  | Yes               | • Produced realistic RCP-based effects on precipitation which in turn could be used to assess possible changes in LWR discharges |
| HAZUS FIT                                      | International   | Climate and Inundation  | Yes               | • Easily accessible depth grid simulator                                  |
| RiskScape building asset database              | National        | Asset                   | No                | • Extensive inaccuracies in geospatial and attribute classifications      |
| QV Costbuilder replacement cost database       | National and Local | Asset                  | Yes               | • Only available source of cost data for buildings within LWR management zones |
| LINZ road asset dataset                        | National        | Asset                   | No                | • Had limited coverage of small roads and no means of distinguishing between different road types  
  • Polyline format when polygon format was required |
| RiskScape hazard software                      | National        | Management and Assessment | No              | • Difficult to transfer depth grid results into software  
  • Had no capacity to simulate the effects of interventions on damages |

This thesis also attempted to use direct tangible damage functions based on investigations into New Zealand assets stocks, such as those used by RiskScape for building assets, in order to best approximate flood impacts on LWR assets. However, for other asset types (e.g. specific three waters infrastructure), New Zealand-derived damage functions were not available. Instead, damage functions were sourced from the United States-based HAZUS program, which may have resulted in inaccuracies due to two factors. Firstly, the experimental conditions used to derive the HAZUS functions were likely different to those for the RiskScape program. Secondly, whilst similar asset types were investigated, asset characteristics are unlikely to be identical (e.g. due to differences in construction materials, shape etc.) resulting in further inaccuracies in the model.
Other indirect tangible damage functions (temporary accommodation cost and loss of business income) were also included in the DAPP implementation methodology. This was intended to give a more holistic estimate of overall damages and to provide insights into intermediate and long-term inundation effects (as rebuilding time was not accounted for in the model suite). The linear nature of these functions resulted in large values for corresponding damages meaning that overall management priority rankings were biased towards zones dominated by commercial and industrial building use categories (i.e. zones 2 and 3) (Reese and Ramsay, 2010). However, these functions are based on several assumptions. For loss of business income, the most fundamental assumptions were the number of employees in each business and that every employee for all businesses brought in the same amount of revenue per day (Reese and Ramsay, 2010) which is unlikely to be true across different business types. As a result, there was a risk that these functions may have significantly overestimated LWR flood damages.

In addition, whilst Google Street View was easy to use, it may have contributed to some asset database inaccuracy. Street View imagery is several years old (dated May, 2015) and some building replacement may have taken place since. In an effort to correct this, WDC building footprints validated against recent satellite imagery (dated 4th March, 2018) were used; however, these could only verify a building’s geospatial location, providing no information regarding asset attributes. In addition, a small proportion of buildings in the dataset were not visible on Street View and had to have attributes extrapolated based on the buildings around them, risking further inaccuracy (Scheele, 2014).

Grouping buildings into asset types may have also impacted asset database accuracy. The original QV costbuilder database, which was used to provide replacement cost multipliers, divided LWR buildings into 33 use categories (QV Costbuilder, 2018). These had to be simplified to 11 final use categories to reflect the limited number of damage functions available in the literature, again resulting in potential inaccuracy. However, such simplification was inevitable as it was not possible to account for every building type and keep the model’s implementation time and cost-efficient.

Attempts to compare impact model outputs with damages based on the June 2015 flood event also met with limited success. Inadequate damage records meant only some aspects of the model could be validated and even this was problematic due to damages being recorded at a district scale. Although accurate hazard damage recording might (understandably) not be a priority during the initial flood response, such data is necessary for the generation of accurate model suites to inform future management. Recognising this, the Ministry of Civil Defence and Emergency Management (MCDEM) has published hazard recording templates in an attempt to standardise reporting (MCDEM, 2006). However, without legislative requirements enforcing their use, necessary hazard and damage data will continue to be lost, preventing critical validation of impact models.
7.2.3 Compromises

In addition, aspects of the first three DAPP implementation methodology modules had to be compromised. In particular:

- only the effects of climate change on river flooding (and not sea-level rise) in the LWR were considered;
- assumptions had to be made about the characteristics of LWR floods;
- assumptions had to be made regarding the LWR precipitation-flow relationship for the Whanganui River;
- compromises had to be made in obtaining, converting and validating provided infrastructure datasets;
- compromises had to be made in using key models (e.g. HAZUS FIT), creating asset datasets and establishing hypothetical time series to ensure that these could be completed within a reasonable time period; and
- specialist VBA coding was used to automate the collection of damage outputs from the impact model.

First, compromises had to be made in accounting for climate change. Evidently, the model needed to account for climate change effects on flooding; however, given Whanganui’s location at the river’s mouth, sea-level rise is also likely to impact LWR floods in the future. That said, as none of the available models consider the interactions between sea-level rise and increased river discharges, this thesis could only focus on climate change effects on river discharges. Given this compromise may have resulted in underestimations of potential future hazard impacts for the LWR, it should be investigated further.

To ensure the models could be readily implemented by local councils, damage functions focussing on depth of inundation only were used. However, additional factors including flow velocity, flood duration and submersion period, may also impact the damage experienced (Pistrika et al., 2014). In particular, Scheele (2014), in examining Christchurch tsunamis, used fragility functions to investigate the effects of unpredictable debris. Fragility functions are not traditionally used for flood impact assessments and no functions applicable to river flooding could be located. That said, scoping conversations with individuals familiar with LWR flooding indicated that erosion in the upper catchment frequently results in trees coming downstream during large flood events. Therefore, in the extreme flows modelled at the end of the hypothetical time series (some more than 50% larger than the June 2015 event), a large amount of debris would be expected. This could in turn cause additional damage to assets (including bridges which are currently unaccounted for in the final LWR asset database). However, as these components of flood damage would still be expected to have less of an impact on overall flood impacts than inundation depth, they were omitted from this investigation in order to conserve resources.

Other assumptions relating to the physical characteristics of LWR floods may also have had an effect on the model suite’s accuracy. In particular, the use of a rainfall-to-flow relationship from the Hutt River probably caused an overestimation of climate change effects on LWR discharges due to the different catchment...
characteristics. This would likely result in a corresponding overestimation of possible damage over the hypothetical annual maxima time series, which may have affected the evaluation of LWR interventions. Evaluations of interventions will also have been affected by assumptions relating to the time required to implement interventions and assumptions within the impact model itself (e.g. distribution of contents within buildings, 6 hours of warning time in which contents could be moved by residents, etc.). However, whilst such assumptions were inevitable, they should not have affected how LWR interventions were evaluated overall given that this depended on relative differences in damages rather than exact values.

In addition, obtaining existing LWR asset datasets, converting the data into usable formats and checking its accuracy was found to be very challenging. Acquiring data through local government channels often took time. Once acquired, datasets were often incompatible, having been assembled by different agencies using different protocols. For example, whilst most geospatial data provided by external agencies was compatible with ArcMap 10.6, specific components were not (e.g. WDC flood depth raster files in enhanced compressed wavelet formats). Most compatibility issues were overcome through basic format conversions within GIS, but additional time was required. In addition, for these local government datasets, there was no way to check the accuracy of the data supplied (unlike with building assets). Instead, they had to be assumed to be accurate and there was no practical way of assessing whether this assumption was correct.

Compromises also had to be made to ensure that modules 1 to 3 could be completed within a reasonable time. This issue largely arose because the methodology was made up of multiple independent parts rather than being a single fully integrated model as is usually the case for decision-support studies (e.g. Kwakkel et al., 2016). In particular, the use of HAZUS FIT to create depth grids for 520 LWR discharges (6 RCP scenarios x 85 years in the time series) in module 1 took over 170 hours of computer processing alone. Whilst this could be sped up by running multiple devices simultaneously, there was no way to eliminate this significant time commitment. It should also be remembered that this processing time was to develop grids for only a single iteration of the time series (out of a possible 2.8x10^{128} discharge bin allocations and 500 possible numbers within each bin); carrying out a full DAPP process exploring all possible LWR discharge time series would take much longer.

Additional time-based compromises were necessary in module 2 when creating new asset databases for the LWR. In particular, creating a new building inventory for identified flood risk areas using Street View imagery took a month to complete but was still less complicated than trying to adapt the existing RiskScape dataset, highlighting a potentially significant time commitment for local government.

In contrast, VBA coding was used to automate the process of collecting time series data for LWR interventions, thus reducing the time required; however, this approach did require some limited coding knowledge. The automation also meant that processing could be carried out simultaneously with other aspects of the research. However, the results collection process still took a minimum of 24 hours for each RCP scenario for stopbank management zones, even using a 64-bit processor.
Ultimately then, modules 1 to 3 of the DAPP implementation methodology are, in theory, capable of implementation by local governments; however, the overall methodology can be time-consuming, difficult to apply and results may require additional calibration (e.g. Figure 7.1). Whilst the effects of accuracy issues could be minimised by focussing on proportional differences in damage reductions between LWR interventions, there were few practical opportunities to streamline fundamental modelling processes. Future users of the methodology should therefore decide for themselves which aspects are the most important for their decision-support method investigation and make appropriate changes to facilitate these.

7.2.4 Areas for Future Research

Aspects of modules 1 to 3 in the DAPP implementation methodology which could benefit from further research include:

- improving national models and datasets to allow their inclusion in decision-support method investigations;
- development of additional damage functions calibrated for New Zealand assets;
- reducing the time and cost requirements of implementing decision-support methods; and
- investigating and/or removing the need for the assumptions underpinning this thesis.

Regarding the role of national models and datasets, these have the potential to avoid local councils needing to develop their own models and datasets, reducing the time and cost requirements for applying decision-support methods. Current national datasets and models which include the LWR, however, are outdated, poorly calibrated or non-existent. This is particularly problematic because the upkeep of such models and datasets is critical to the successful ongoing implementation of decision-support methods, or indeed any basic natural hazard risk assessment. For DAPP in particular, practitioners continually emphasise its cyclical nature and the need to use updated datasets so managers can re-evaluate existing plans (e.g. MFE, 2017; Haasnoot et al., 2013; Kwakkel et al., 2016). However, such ongoing maintenance is currently lacking. For asset databases, this is likely because local councils do not generally use impact models to inform decision-making and so do not expend time and resources on collecting the highly detailed breakdowns of asset types and locations needed. Indeed, when interviewing New Zealand risk managers, Crawford et al., (2018) noted that local governments and outside agencies often did not see it as their responsibility to collect or update asset data. Having a national scale asset database would therefore relieve local governments of some of these responsibilities whilst also ensuring better consistency in data collection.
Figure 7.1 – Final conceptualisation of the modules 1 to 3 of the DAPP implementation methodology.
For national databases to operate effectively, agency responsibilities for data collection need to be clearly defined. Data collection must also be done on an ongoing basis. It is therefore recommended that asset database maintenance be directly linked with resource consent application processes, with applicants required to provide the necessary data to keep the database current. Through legislative amendments to the Resource Management Act (1991) and the Building Act (2004), changes to existing building and infrastructure stocks could be automatically recorded as alterations are approved or new assets are built. In addition, linking decision-support method database requirements into existing local, regional and national policy frameworks would streamline the process for maintaining the relevant databases and remove reliance on satellite and Google Street View imagery.

As for national scale modelling, it is clear that more research is needed to allow models to be calibrated to the local scale. Whilst such research would take time, the ability to model hydrological effects of various climate change projections on different catchments using the same model would be invaluable for the widespread implementation of decision-support methods across New Zealand.

Modules 1 to 3 of the DAPP implementation methodology also highlighted current gaps in the literature regarding flood impacts on New Zealand assets. Whilst absolute damage functions could be developed in the LWR case study based on data from the recent June 2015 flood, developing new functions may not be possible for all case studies. As such, future research should aim to find more widely applicable solutions, such as the development of new relative electricity and road damage functions, which could also then be integrated into RiskScape.

Indirect tangible damages are another area requiring further research, with the approach taken in this thesis requiring multiple assumptions that could ultimately prove incorrect. Whilst some authors advocate using a proportion of direct tangible damage costs to assess indirect damages (e.g. Olesen et al., 2016), this was assumed to be less accurate than using the damage functions developed by RiskScape. However, the fact that indirect tangible damages far exceeded all other damage types in the June 2015 flood theoretical direct structure test and LWR intervention evaluation suggests that the assumptions made by these functions may not hold true for the LWR. Greater accuracy in calculating these damages might have been possible using a dedicated indirect damage software package such as the “Measuring the Economics of Resilient Infrastructure” (MERIT) model suite (MERIT, 2019). However, this approach was ultimately rejected for this thesis due to licensing restrictions. Nevertheless, it may become viable for local government use in the near future. Ultimately, the value of integrating new methods into the DAPP implementation methodology to improve accuracy will always need to be carefully considered against complexity and time constraints.

Further research is also needed to identify and overcome common barriers to widespread implementation of decision-support methods. As these methods have only been applied in isolated case studies in New Zealand and overseas (funded by research institutions rather than national agencies), there have been few opportunities to study their implementation and identify problems (e.g. Barnett et al., 2014; Ranger et al.,
Furthermore, whilst accounts of the impact modelling processes used in these investigations are available (e.g. Ramm et al., 2018b), these are difficult to find and follow. It is therefore imperative that where decision-support methods are used, their implementation is appropriately recorded and scrutinised.

In addition, efforts to reduce the time required to implement decision-support methods are needed. In this thesis, generating an asset database for the LWR case study, processing required flood depth grids and evaluating intervention options required considerable time and computational resources. The literature offers some potential options for streamlining these processes through upscaling micro scale flood impact assessments to meso and macro levels (e.g. de Moel et al., 2015). These studies also highlight opportunities for creating large asset databases (particularly for buildings) more efficiently using remote sensing techniques (e.g. Gerl, Bochow, & Kreibich, 2014). However, these techniques require specialist data and software and therefore additional investment which local councils may not be willing to undertake. Further research into more cost-efficient approaches is therefore needed. Such efforts should also consider how to overcome the methodology assumptions made throughout modules 1 to 3.

In some cases, necessary research to facilitate standardised decision-support method implementation in New Zealand has already begun. The RiskScape program has recently announced that it intends to overhaul its existing national and regional asset inventories as well as upgrade software interface and damage functions (RiskScape, 2017). The HIRDS model has also been updated, to incorporate greater numbers of rainfall records and anticipated changes in precipitation associated with different RCP scenarios, enhancing accuracy (Carey-Smith et al., 2018). These developments are encouraging for the future of decision-support methods in New Zealand. However, it remains to be seen if there will be sufficient uptake of model-based decision-support methods before the effects of climate change begin to be felt.

7.3 Lessons from the Serious Game Component of the DAPP Implementation Methodology

The literature review undertaken in Chapter Two revealed that serious games have rarely been used in New Zealand either generally or more specifically to promote local government and wider stakeholder understandings of deep uncertainty and adaptive management concepts. The review also highlighted that serious game evaluations have traditionally been limited to considering particular learning types and that these may restrict opportunities for participants to evaluate the models sitting behind serious games. The fourth and final module of the DAPP implementation methodology therefore sought to explore how the three previous modelling modules could be used to encourage stakeholder engagement with deep uncertainty in line with Objective two. In particular, a game session calibrated for the LWR flood management problem and a series of follow-up interviews with LWR local government stakeholders were used to:

- illustrate adaptation concepts for the LWR;
- study decision-making considerations affecting LWR management professionals;
• facilitate learning and engagement opportunities that could be applied within and outside the formal game session;
• promote awareness of deep uncertainty concepts; and
• assess the usefulness of the underlying impact model to local government.

7.3.1 Elements that were successful

Elements of the engagement module which proved successful included:

• using 3D interactive maps to illustrate possible flood consequences to participants;
• allowing participants to engage with impact modelling by demonstrating complicated damage calculations using Excel;
• specifically focussing on climate change uncertainties associated with river flooding to introduce deep uncertainty; and
• using thematic analysis to investigate serious game results.

First, using visuals to communicate the extent of possible hazards proved to be a major strength of the game session. Whilst numeric damage outputs could be more readily compared, visual data displays were generally preferred by participants. 3D interactive maps showing inundation relative to a virtualised building asset dataset were particularly popular, allowing a better appreciation of the extent of potential flooding. Participants also agreed that being able to see flooding depths and change viewing perspectives could significantly improve engagement practices which have tended to revolve around 2D flood outlines for specific return periods (e.g. HRC, 2008). In turn, by enabling communities to assess model outputs for themselves, greater buy-in for intervention plans based on model suites might be achieved.

Moving on to impact model engagement, using Excel to generate the impact model in modules 1 to 3 meant that it was straightforward to demonstrate how damages were calculated for each asset. This could then be shown to the participants in the game session. As such, the “open, honest and transparent modelling processes” (p.216) previously identified by Parker et al. (2002) as a necessary component of successful integrated environmental modelling could be achieved efficiently. Players were thus able to inspect the practical components and assumptions and to discuss their validity (Granell et al., 2013). Furthermore, Excel enabled additional graphs and other visual representations of damage data to be easily produced, providing ready feedback within the game session which was useful in maintaining realism and interest.

The game session also demonstrated that a full examination of all possible uncertainties (as proposed by much of the deep uncertainty literature e.g. Kwakkel et al., 2016) is unnecessary for providing deep uncertainty learning opportunities. In general discussion, participants agreed that an explicit focus on climate-based uncertainties affecting river flooding specifically was useful in maintaining simplicity and was appropriate based on their experience. Participants then had the basic tools to begin considering other sources of uncertainty and how they might contribute to the overall deep uncertainty problem. In particular, some participants referenced
additional social and economic factors that were considered too complex for the model suite to incorporate but are critical for enacting management plans, including community acceptance and required funding. As a result, there would appear to be some benefit from limiting uncertainty analyses to climate uncertainties only as it enabled a more practical and streamlined modelling approach whilst allowing game session participants to engage with deep uncertainty concepts without being overwhelming.

Turning now to game evaluation, using thematic analysis to investigate serious game findings offered a level of flexibility that could not have been attained using an established evaluation method. Instead of trying to force or uncover particular findings, research data was collected and analysed without preconceived notions of what it should have revealed. As a result, findings from the game session were not limited to the factors influencing decision-making but also included findings as to the best ways to communicate information and engage with communities.

7.3.2 Elements that were less successful

Whilst allowing game session participants to investigate the functionality of the models provided useful feedback on the validity of some components, there were disadvantages. Having grown accustomed to complex environmental models within their own organisations, participants were suspicious of a flood impact model they could readily understand, believing it too simple to adequately deal with this difficult problem. Whilst this suspicion is understandable (as identified in Jakeman, Letcher, & Norton, 2006), it reflects an incorrect assumption by management agencies that complicated models will be more useful than simple ones (Wainwright & Mulligan, 2005). Participants were also quick to notice the disparities between costs associated with the impact model and the June 2015 flood event. However, this ignored the fact that the model was developed to focus on the differences between interventions in reducing total damage costs rather than trying to accurately predict overall costs which would have been impossible given the limited resources and research available. For game session participants to expect the model to produce dollar accurate damage costs was unrealistic but highlighted the risk that local government professionals may misinterpret the results of even the most accessible models if they go in assuming that accuracy is always the main objective.

7.3.3 Compromises

There were also elements of the engagement module where compromise was necessary. In particular, the time required to create 3D interactive maps of flood inundation and run the impact model during the game session needed to be reduced in order for this approach to be useful for local councils.

To create the 3D interactive maps, each of the 85 depth grids associated with RCP 8.5 time series had to be merged with the LWR DEM in ArcMap to create a new depth layer and overlaid on to the original DEM. This inevitably took time and thus, despite their considerable value, local governments may have to compromise and forgo creating 3D interactive maps if resources are especially limited.
Running the game session itself also took considerable time due to the impact model having to re-establish damages associated with the LWR hypothetical time series based on participant decisions over 180 Excel spreadsheets simultaneously (85 asset database spreadsheets, 85 management spreadsheets, and a master spreadsheet and results spreadsheet for each of the five rounds). Whilst participants were usually understanding given the complex model procedures being carried out, slow processing times reduced game flow and became increasingly frustrating. Organisers of similar game sessions may therefore have to compromise and use less complex models in order for game sessions to run smoothly.

### 7.3.4 Areas for Future Research

Some aspects of serious game module could also benefit from additional research. In particular, these were:

- streamlining methods to create engaging maps to illustrate flood hazards;
- using serious games to get stakeholder feedback on the viability of impact models; and
- using thematic analysis to explore serious game results.

The use of 3D inundation maps in game sessions is widely recommended by the literature as a means of better engaging stakeholders and indeed it was successful here (Chen et al., 2018; Macchione et al., 2019). However, as noted above, assembling these types of map took a considerable time. Future research should therefore investigate how to better streamline this process so as to encourage greater uptake of these communication options in place of traditional 2D maps.

Turning then to the possible roles of serious games, the literature has historically focussed on their use in communicating concepts such as deep uncertainty that can be separately applied to real-world management problems (den Haan and van der Voort, 2018; Walker et al., 2013). In contrast, module 4 attempted to show how opening up the models that sit behind these games to criticism can also offer valuable opportunities for feedback from flood management professionals. Adopting this approach means that the impact model created in modules 1 to 3 could be updated in a targeted fashion (e.g. participants wanted a specific focus on WDC infrastructure assets) to be of greater use to LWR decision-makers. However, this remains a relatively novel concept and further research into the use of serious games to gather feedback on model utility would be advantageous.

Wider research into the use of thematic analysis to evaluate serious game performance should also be encouraged. Unlike traditional analyses which tend to focus only on participant learning (e.g. Baird et al., 2014), thematic analysis provided insights into the use of serious games as both static and evolving instruments as well as tools to examine how local government decisions are made. Future research into serious games should seek to establish whether thematic analysis can offer similar insights in respect of other games currently available.
7.4 Final Conclusion: The Future of DAPP and Decision-Support Methods in the Local New Zealand Context

This thesis sought to answer a fundamental research question, specifically what could be learned from applying a time and cost-efficient DAPP approach to aid uncertain flood-based decision-making processes in a New Zealand river case study. This question was broken down into two objectives concerned with developing an accessible, practical approach to implementing quantitative decision-support methods for national river flood management in New Zealand; and using the models and results of this approach to facilitate a serious game session with LWR professionals. By successfully completing these objectives, this thesis has attempted to address several gaps in the literature including how decision-support methods that have generally been used by academics might become standard practice for local government, and how calibrated serious games might promote stakeholder engagement with deep uncertainty problems.

However, addressing these objectives presented several challenges pertinent to future local government implementation of decision-support methods such as DAPP. These include difficulties arising from the inadequacies of existing national scale models, compromised asset databases, and limited computational resources to evaluate interventions under deep uncertainty conditions. Therefore, whilst this thesis has shown that a DAPP implementation methodology can be implemented at the local scale, it has also highlighted that the process can be time consuming and complex. This was despite efforts to minimise the resources required given the inevitable restrictions on local government budgets. As such, until significant changes to national level models are made to speed up this process, the widespread application envisaged by MFE guidelines for coastal hazards to river systems is unlikely.

This said, qualitative findings from a serious game session were positive and discussions with LWR management professionals revealed a clear appetite for change. Although these local government participants were not aware of the terminology behind deep uncertainty problems and dynamic adaptation, they were clearly frustrated with current practices focussed on protection against floods of specific return periods and were keen to investigate other approaches. As participant HRC2 reflected, “An adaptive approach is necessary due to the social pressures of flood management, people are reactive. But Council shouldn’t be so reactive in their management as they are seen as the experts in the field.” This ability to self-reflect and identify areas for possible improvement is a necessary first step in improving management practices and is indicative of evolving agency perspectives away from traditional flood protection (Butler and Pidgeon, 2014). Such findings suggest that, provided that agencies have access to the right tools and technologies, adaptive flood risk management practices may indeed have a place in the future of New Zealand local government.
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References


Rouse, H., 2012. Flood risk management research in New Zealand: Where are we, and where are we going?


Te Awa Tupua Act, 2017.


Your Mission

• You have recently been assigned to the Horizons Regional Council Flood management team as an adaptation specialist
• Your goal is to develop a sustainable management plan for the Lower Whanganui River up till 2100.
• Your main concerns are:
  * Mitigating flood risks
  * Community acceptance of policy
  * Curbing unnecessary expenditure
  * Having fun!

**Figure A1** – Serious game session briefing statement (adapted from Deltares, 2016).

**Figure A2** – Isolated image from a 3D interactive inundation map developed in ArcScene. Buildings along Anzac Parade are shown on the left river bank.
Seven Zones To Manage

Figure A3 – LWR management zone map.
### Possible Interventions

<table>
<thead>
<tr>
<th>Flood Zone</th>
<th>Do Nothing</th>
<th>Raise Floor Heights (m)</th>
<th>Stopbanks</th>
<th>Managed Retreat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>NA</td>
<td>100m, 200m</td>
</tr>
<tr>
<td>2</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>50, 100, 200, 500 ARI</td>
<td>100m, 200m</td>
</tr>
<tr>
<td>3</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>Current, 50, 100, 200, 500 ARI</td>
<td>100m, 200m</td>
</tr>
<tr>
<td>4</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>NA</td>
<td>100m, 200m</td>
</tr>
<tr>
<td>5</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>50, 100, 200, 500 ARI</td>
<td>100m, 200m</td>
</tr>
<tr>
<td>6</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>Current, 50, 100, 200, 500 ARI</td>
<td>100m, 200m</td>
</tr>
<tr>
<td>7</td>
<td>Applicable</td>
<td>0.5, 1, 1.5</td>
<td>NA</td>
<td>100m, 200m</td>
</tr>
</tbody>
</table>

**Figure A4** – Intervention option sheet.

**Team Name:**

We have chosen the following intervention strategies:

<table>
<thead>
<tr>
<th>Flood Zone</th>
<th>Intervention</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

We have chosen these strategies because:

**Figure A5** – Intervention selection sheet.
**Figure A6** – Fictitious newspaper articles (adapted from Deltares, 2016).

<table>
<thead>
<tr>
<th>Turbulent Times</th>
<th>Turbulent Times</th>
<th>Turbulent Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>More Floods Hit Whanganui Despite Recent Management Efforts – Regional Council to Announce New Scheme</td>
<td>“We Spent It All” – Regional Council Looking Foolish After Draining Coffers on Failed Management Solutions</td>
<td>All Is Well in Whanganui – No Significant Flooding For Years</td>
</tr>
</tbody>
</table>

**Figure A7** – Citizen overrule card (adapted from Deltares, 2016).
Appendix B: Ethics Documents

Local Government Group – Initial Contact Email Distributed to Potential Participants by Key Contact on Behalf of the Student Researcher

To whom it may concern

I am emailing on behalf of Matthew Hardcastle, a Master of Science student (majoring in Environmental Science) from The University of Auckland. Matthew’s research is examining opportunities to support local decision-making for New Zealand river flood management in spite of large associated uncertainties. Using the Whanganui River as a case study, he has created a methodology that seeks to incorporate dynamic adaptation planning into the decision-making process using contemporary decision-support frameworks and flood impact modelling.

In order to assess the utility of his approach and provide greater local context, Matthew wishes to run a focus group session with relevant decision-makers, river managers and policy planners from throughout the region. Afterwards he also would like to hold some one on one interviews with interested focus group participants to further investigate the practical applications of some of the issues raised.

The focus group session is expected to take place in October 2018 at a yet to be arranged venue and is should to take no more than three and a half hours. It is anticipated that follow-up interviews would be carried out in the week following the focus group session at a participant’s choice of location and time. Interviews will take no more than thirty minutes each.

Further information about the focus group and interview process can be found on the attached participant information sheet. If you would like to take part in the research then please read and fill out the attached consent form before emailing it back to Matthew at the address provided. If you have any additional questions about the research and what it involves, please email Matthew directly using the details provided.

Kind regards

...


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For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Ethics Committee, The University of Auckland, Office of the Vice Chancellor, Private Bag 92019, Auckland 1142. Telephone 09 3737599 ext. 83711, email re-ethics@auckland.ac.nz

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON _____________for (3) years, Reference Number: 021727.

Figure B1—Recruitment email sent on behalf of the student researcher by key contacts within approached organisations.
PARTICIPANT INFORMATION SHEET – EMPLOYER

Project title: Feeling the Flow – An Improved Method to Support Uncertain Flood-Based Decision-Making

Researcher: Matthew Hardcastle

Supervisors: Dr Susan Owen and Associate Professor Giovanni Coco

My name is Matthew Hardcastle. I am a Master of Science student (majoring in Environmental Science) in the University of Auckland’s School of Environment. The purpose of my research thesis is to investigate a new decision support method (Dynamic Adaptive Policy Pathways - DAPP) for local river flood management. Specifically, I am looking at how the handling of key uncertainties (e.g. size of floods due to climate change) in flood inundation modelling as part of this method can be used to create adaptive management plans. The thesis has three key phases: a first phase centred on generating DAPP for a specific case study using flood impact modelling, a second phase looking at the usefulness of the techniques involved in generating the DAPP through a combination of focus group sessions and semi-structured interviews with river management professionals, and a third phase looking to explore the range of non-economic values associated with the LWR and why these should be accounted for in future flood impact assessments through focus groups with local hapū.

I would like to ask permission for the opportunity to have a focus group session with approximately six to ten appropriate and relevant members of your staff to discuss concepts raised in the thesis. I would also like to request permission to do follow-up interviews with a subset of participants individually to get more detailed focus group findings and how these might be applied to professional practices. Furthermore, I would like to ask permission for a staff member within your organisation to circulate an invitation to your relevant staff that invites them to take part in this research on my behalf. I would also like to use your organisation’s name as a means of differentiating participants in any subsequent academic publications or presentations. Finally, I would like to request the opportunity to use your premises as a venue to conduct the focus group session. To conduct both the focus group session and interviews, however, I must first have your assurance that the decision of the employees to participate or not in this research will not affect their employment status or their relationship with you. This assurance can be given by signing the attached Consent Form. With your permission I would also like to use the organization’s name in the context of the focus group and staff interviews.

Participation in this study is voluntary.
The Research Project:

This project aims to investigate current understandings around deep uncertainties in river flood management and how these might be improved using impact modelling to promote opportunities for adaptive planning using DAPP. Due to its extensive history of frequent high magnitude inundation events, the Lower Whanganui River has been selected as an appropriate case study.

Your employees’ insights into these matters will be beneficial due to their unique knowledge and experiences.

Focus Group Request:

I would like to run a focus group with members of your staff to investigate the usefulness of a DAPP-based approach in flood management of the Lower Whanganui River. The session will aim to achieve the following objectives:

- Establish current understandings of the deep uncertainties that affect impact modelling and decision-making amongst decision-making, river management and regional policy specialties.
- Investigate how these understandings may have informed past planning approaches through a serious flood simulation and management game.
- Enable participants to identify areas for improvement in how they approach flood management problems through structured group discussion and an introduction to DAPP concepts.

The focus group will follow a semi-structured program composed of presentations, general discussion and small group activities. It will take up to three and a half hours. The session is expected to be run in October 2018. During the group activities I will take notes. I may also take photographs to document the written work of groups after the session is completed for the purposes of thesis data collection; no third parties will be involved in any of the above processes.

Follow-Up Interview Request:

I would like to further speak to a subset of focus group participants individually about their reflections on dynamic adaptation processes and principles discussed in the session. In particular, I would like to talk to them about what they found beneficial to their own understanding of the deep uncertainty problem and the benefits/constraints they may see for the implementation of DAPP-like approaches in the region. It would also be useful to talk at greater length about some of the practical techniques used to generate a set of DAPPs and their possible applications. The discussion may explore the following topics:

- Whether identified intervention plans would be realistic in a real-world context.
- How deep uncertainties might be better accounted for in future council impact modelling exercises.
- If decision-support methods (such as DAPP) can be used to generate greater public buy-in for long-term flood management plans.
• Whether there is potential for decision-support methods to be taken up into regional policy frameworks.

The interviews will be conducted one on one and follow a semi-structured format. They will take an estimated time of up to thirty minutes each. The timing and location for the interview will be based on what is convenient for them. During the interview process I will take notes. If participants agree I will also audio-record the interview. If they agree to be audio-recorded, they may ask for the recorder to be stopped at any time for any reason. Audio-recorded interviews will be transcribed by the researcher; no third parties will be involved in the process.

Use of Collected data:

The data collected during this research project will be used to complete master’s thesis research and for the production of the thesis. Data may also be used in publications or presentations arising from this thesis.

A summary of the relevant research findings will be made available to participants if they choose to receive a copy.

Privacy:

The information collected about participants will be kept private. Personal information in regards to the participants will be excluded from academic publications and presentations arising from this research. While the nature of the focus group means that the identities of the participants will be known to each other I will ensure that every possible effort will be made to ensure the identity of participants remains anonymous in associated outputs, although anonymity cannot be guaranteed. A generic position descriptor (job position/ organisation name) will be used with their permission. While names will not be used in my research, given the specific nature of the research and the expert roles of the participants the use of a generic position descriptor may mean that individuals become recognisable.

Data Storage and Consent:

All data related to the study will be stored securely in a locked filing cabinet and password protected on a computer. Material will be retained for six years, and then will be either deleted or shredded.

The information they provide will only be used for the purpose of this research project and it will only be disclosed with their permission.

Right to withdraw:

Participants will be allowed to withdraw from the focus group session or interviews at any time, without giving a reason. Participants in the focus group will be informed that if they withdraw due to the collective nature of the group it will not be possible to withdraw an individual’s information. Participants in interviews will be able to withdraw information from the research up to four weeks after the interview. Interview participants will also be offered the opportunity to receive a copy of the resulting transcript. If participants do receive a copy of the transcript...
they will have the opportunity to edit the transcript of the interview recording and return it to the student researcher within two weeks of receiving it.

Please read this information carefully. Ask questions about anything that you do not understand or want to know more about before deciding whether or not to respond.

Thank you very much for your time. If you have any queries or wish to know more please feel free to contact me or my supervisor through the details at the bottom of this letter.

Research funding:
This research is supported by a $3000 grant from Horizons Regional Council as part of a Don Linklater Memorial Bursary scholarship. The purpose of these awards is to support students living in the Horizons region and studying in areas relevant to Horizons Regional Council’s work; in particular resource management, river and drainage engineering and modelling, and environmental planning.

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Professor Paul Kench
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Tel: +64 9 3737599
Email: p.kench@auckland.ac.nz

For any queries regarding ethical concerns you may contact the Chair, The University of Auckland Human Ethics Committee, The University of Auckland, Office of the Vice Chancellor, Private Bag 92019, Auckland 1142. Telephone 09 3737599 ext. 83711, email ro-ethics@auckland.ac.nz

APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON _____________ for (3) years, Reference Number: 021727.

Figure B2 – Participant Information Sheet (PIS) sent to heads of organisations approached for the serious game and follow-up interviews.
PARTICIPANT INFORMATION SHEET – EMPLOYEE – FOCUS GROUP

Project title: Feeling the Flow – An Improved Method to Support Uncertain Flood-Based Decision-Making

Researcher: Matthew Hardcastle

Supervisor: Dr Susan Owen and Associate Professor Giovanni Coco

My name is Matthew Hardcastle. I am a Master of Science student (majoring in Environmental Science) in the University of Auckland’s School of Environment. The purpose of my research thesis is to investigate a new decision support method (Dynamic Adaptive Policy Pathways - DAPP) for local river flood management. Specifically, I am looking at how the handling of key uncertainties (e.g. size of floods due to climate change) in flood inundation modelling as part of this method can be used to create adaptive management plans. I would like to invite you to participate in a focus group session as a part of this study. I have the assurance of your CEO/Manager that your decision to participate or not participate will not affect your employment status or your relationship with them. Participation in this study is voluntary.

The Research Project:

This project aims to investigate current understandings around deep uncertainties in river flood management and how these might be improved using impact modelling to promote opportunities for adaptive planning using DAPP. Due to its extensive history of frequent high magnitude inundation events, the Lower Whanganui River has been selected as an appropriate case study.

Your insights into these matters will be beneficial due to your unique knowledge and experiences with the Lower Whanganui River and wider river management concepts.

Focus Group Request:

I would like to invite you to participate in a focus group session with other decision-makers, river managers and policy planners operating in the Lower Whanganui River. Its aim will be to investigate current practitioner understandings of the uncertainties relating to river flood management and perspectives on the usefulness of DAPP methods to support decision-making.

The focus group will follow a semi-structured program composed of presentations, general discussion and small group activities. It will take up to
three and a half hours. The focus group will be held at either Horizons Regional Council or Whanganui District Council premises in October 2018. During the group activities I will take notes. I may also take photographs to document the written work of groups after the session for the purpose of thesis data collection. No third parties will be involved in any of the above processes.

Follow-Up Interviews:

As part of this research, I am also interested in conducting a series of one on one follow-up interviews with a small number of focus group participants. In these sessions I would like to speak with individuals in greater detail about their reflections on dynamic adaptation processes and principles discussed in the session. Interviews will take an estimated time of no longer than thirty minutes and will be conducted at a time and place convenient to the participant. Interviews may also be audio-recorded subject to participant approval. If you are interested in taking part in an interview, please indicate so on the focus group consent form by filling in the required fields.

Use of Collected data:

The data collected during this research project will be used to complete master’s thesis research and for the production of the thesis. Data may also be used in publications or presentations arising from this thesis.

A summary of relevant research findings will be made available to participants if they choose to receive a copy.

Privacy:

The information collected about participants will be kept private. Personal information in regards to the participants will be excluded from academic publications and presentations arising from this research. While the nature of the focus group means that the identities of the participants will be known to each other I will ensure that every possible effort will be made to ensure the identity of participants remains anonymous in associated outputs, although anonymity cannot be guaranteed. A generic position descriptor (job position/ organisation name) will be used with their permission. While names will not be used in my research, given the specific nature of the research and the expert roles of the participants the use of a generic position descriptor may mean that individuals become recognisable.

Data Storage and Consent:

All data related to the study will be stored securely in a locked cabinet and on a secured hard drive. Material will be retained for six years, and then will be either deleted or shredded.

The information you provide will only be used for the purpose of this research project and it will only be disclosed with your permission.

Wish to withdraw:

Participants will be allowed to withdraw from the focus group at any time, without giving a reason. However, due to the collective nature of the group it will not be possible to withdraw an individual’s information.
Please read this information carefully. Ask questions about anything that you don’t understand or want to know more about before deciding whether or not to take part.

Participation in this research is voluntary. If you don’t wish to take part, you don’t have to.

If you decide you want to take part in the research project, you will be asked to **sign the consent form**. By signing it you are telling us that you:

- Understand what you have read
- Consent to take part in the research project

**Research funding:**

This research is supported by a $3000 grant from Horizons Regional Council as part of a Don Linklater Memorial Bursary scholarship. The purpose of these awards is to support students living in the Horizons region and studying in areas relevant to Horizons Regional Council’s work; in particular resource management, river and drainage engineering and modelling, and environmental planning.

Thank you very much for your time. If you have any queries or wish to know more please feel free to contact me or my supervisor at:

**Researcher contact information:**

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**Head of School:**

Professor Paul Kench  
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APPROVED BY THE UNIVERSITY OF AUCKLAND HUMAN PARTICIPANTS ETHICS COMMITTEE ON ____________for (3) years. Reference Number: 021727.

Figure B3 – PIS for individuals who expressed interest in taking part in the serious game session.
PARTICIPANT INFORMATION SHEET –
EMPLOYEE – FOLLOW-UP INTERVIEW

Project title: Feeling the Flow – An Improved Method to Support Uncertain Flood-Based Decision-Making

Researcher: Matthew Hardcastle

Supervisor: Dr Susan Owen and Associate Professor Giovanni Coco

My name is Matthew Hardcastle. I am a Master of Science student (majoring in Environmental Science) in the University of Auckland’s School of Environment. The purpose of my research thesis is to investigate a new decision support method (Dynamic Adaptive Policy Pathways - DAPP) for local river flood management. In this phase of the research, I am looking at how the focus group session you attended may have contributed to professional understandings of deeply uncertain river management problems. I am also interested in the perceived benefits/constraints associated with the implementation of DAPP-like approaches in the region.

I would like to invite you to participate in an interview as a part of this study. I have the assurance of your CEO/Manager that your decision to participate or not participate will not affect your employment status or your relationship with them. Participation in this study is voluntary.

The Research Project:

This project aims to investigate current understandings around deep uncertainties in river flood management and how these might be improved using impact modelling to promote opportunities for adaptive planning using DAPP. Due to its extensive history of frequent high magnitude inundation events, the Lower Whanganui River has been selected as an appropriate case study. This academic and contextual background informed the series of activities you were involved in as part of the focus group session.

Your additional insights into the role of deep uncertainty in both general river management and your own speciality will be beneficial due to your active engagement in the previous focus group session.

Interview Request:

I would like to conduct a one on one interview with you about your thoughts on the topics raised at the focus group session held as part of this research thesis.
Specifically, the ways in which it may have challenged your understanding of deeply uncertain environmental problems and how you might incorporate any new knowledge into practice. Of particular interest is the potential usefulness and uptake of decision-support methods (such as DAPP) into regional/district council management and policy with the aim of encouraging adaptive planning. I am also interested in getting feedback on the series of DAPP I produced prior to the focus group session and the techniques used to assemble them.

The interview will follow a semi-structured format. It will take up to thirty minutes. The timing and location for the interview will be based on what is convenient for you. During the interview process I will take notes. If you agree I will also audio-record the interview. If you agree to be audio-recorded, you may ask for the recorder to be stopped at any time for any reason. Audio-recorded interviews will be transcribed by the researcher; no third parties will be involved in the process.

If you wish you may receive a copy of the resulting transcript. If you do receive a copy of the transcript you will have the opportunity to edit the transcript of the interview recording and return it to the student researcher within two weeks of receiving it.

**Use of Collected data:**

The data collected during this research project will be used to complete master’s thesis research and for the production of the thesis. Data may also be used in publications or presentations arising from this thesis.

A summary of relevant research findings will be made available to participants if they choose to receive a copy.

**Privacy:**

The information collected about participants will be kept private. Personal information in regards to the participants will be excluded from academic publications and presentations arising from this research. I will ensure that every possible effort will be made to ensure the identity of participants remains anonymous. A generic position descriptor (job position/ organisation name) will be used with your permission. While names will not be used in my research, given the specific nature of the research and the expert roles of the participants the use of a generic position descriptor may mean that individuals become recognisable.

**Data Storage and Consent:**

All data related to the study will be stored securely in a locked cabinet and on a secured hard drive. Material will be retained for six years, and then will be either deleted or shredded.

**Wish to withdraw:**

Participants will be allowed to withdraw from the interview at any time, without giving a reason. Furthermore, you have the right to withdraw your data from the
research within a four week period after the interview process without giving a reason.

The information you provide will only be used for the purpose of this research project and it will only be disclosed with your permission.

Please read this information carefully. Ask questions about anything that you don’t understand or want to know more about before deciding whether or not to take part.

Participation in this research is voluntary. If you don’t wish to take part, you don’t have to.

If you decide you want to take part in the research project, you will be asked to **sign the consent form**. By signing it you are telling us that you:

- Understand what you have read
- Consent to take part in the research project

**Research funding:**

This research is supported by a $3000 grant from Horizons Regional Council as part of a Don Linklater Memorial Bursary scholarship. The purpose of these awards is to support students living in the Horizons region and studying in areas relevant to Horizons Regional Council’s work; in particular resource management, river and drainage engineering and modelling, and environmental planning.

Thank you very much for your time. If you have any queries or wish to know more please feel free to contact me or my supervisor at:

**Researcher contact information:**

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**Supervisor contact information:**

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Figure B4 – PIS for individuals who took part in the serious game session and expressed interest in taking part in a follow-up interview.
CONSENT FORM - EMPLOYER

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Feeling the Flow – An Improved Method to Support Uncertain Flood-Based Decision-Making

Researcher: Matthew Hardcastle

Supervisor: Dr Susan Owen and Associate Professor Giovanni Coco

I have read the Participant Information Sheet and understand the purpose of this research and why my organization has been selected. I have had the opportunity to ask questions and have them answered to my satisfaction.

- I give my permission for the researcher to approach my employees and invite them to take part in this research.
- I give my permission for a staff member to circulate an invitation to my employees that invites them to take part in this research on behalf of the researcher.
- I give my permission for the researcher to carry out a focus group session and a series of follow-up interviews on my organisation’s premises.
- I understand that participation in this study is voluntary.
- I give my assurance that the decision of the employees to participate or not in this research will not affect their employment status or their relationship with me.
- I understand the focus group session may take up to three and a half hours.
- I DO/DO NOT give permission for the focus group to be held in a suitable venue on the organization’s premises.
- I understand that if the participants choose to be involved in a follow up interview this may take up to thirty minutes, and occur at a time and location that is most convenient for the participants.
- I understand data collected in this interview process will be used by the student researcher to complete his Master of Science thesis and may also be used in other publications/presentations.
- I give permission for the organization’s name to be used in the context of this research.
- I understand that participants will not be identified by name in this research and that a generic position description will be used.
- I understand that while a generic position descriptor will be used in the research, in an endeavour to protect participants’ identities, that due to the
small number of staff working in this field their anonymity cannot be
guaranteed and that they may be recognisable.

• I understand all data will be stored safely for 6 years, after which time it
will be destroyed.
• I understand that if I wish I will be given a signed copy of this document to
keep and sent to my email.
• I wish/do not wish to receive a summary of the relevant research findings,
which can be emailed to me at this email address:

Name (please print)

________________________________________

Signature ___________________________ Date ___________________________

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COMMITTEE ON _____________ for (3) years, Reference Number: 020892.

Figure B5 – Consent form (CF) sent to heads of organisations approached for the serious game and follow-up interviews.
CONSENT FORM – EMPLOYEE – FOCUS GROUP

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Feeling the Flow – An Improved Method to Support Uncertain Flood-Based Decision-Making

Researcher: Matthew Hardcastle

Supervisor: Dr Susan Owen & Associate Professor Giovanni Coco

I have read the Participant Information Sheet and understand the purpose of this research and why I have been chosen to participate. I have had the opportunity to ask questions and have them answered to my satisfaction.

- I understand I have my employer’s permission to partake in this research.
- I agree to participate in this research.
- I understand the focus group session may take up to three and a half hours.
- I understand that I am free to withdraw at any time during focus group session without giving a reason.
- I understand that due to the nature of the focus group session my contributions will not be anonymous to other participants.
- I understand that I will be unable to withdraw information I have contributed to the focus group session due its collective nature.
- I understand that photographs may be taken of the work produced during the focus group session for the purpose of thesis data collection.
- I understand that I will not be identified by name in this research and that a generic position description and organization name will be used.
- I understand that while a generic position descriptor will be used in the research, in an endeavour to protect my identity, that due to the small number of people working in this field my anonymity cannot be guaranteed and that I may be recognisable.
- I understand focus group data will be to complete the student researcher’s Master of Science thesis and may be used in other publications/presentations.
- I understand all data will be stored safely for six years, and then destroyed.
- I understand that if I wish I will be given a signed copy of this document to keep and sent to my email.
- I DO/DO NOT wish to take part in a follow-up interview conducted by the researcher about topics relevant to the focus group session. I give permission for the researcher to email me at the following email address to arrange a time and location for this interview: ___________________________
- I wish/do not to receive a summary of the focus group findings, which can be emailed to me at this email address: ___________________________

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Figure B6 – CF for serious game session participants
CONSENT FORM – EMPLOYEE – FOLLOW-UP INTERVIEW

THIS FORM WILL BE HELD FOR A PERIOD OF 6 YEARS

Project title: Feeling the Flow – An Improved Method to Support Uncertain Flood-Based Decision-Making

Researcher: Matthew Hardcastle

Supervisor: Dr Susan Owen and Associate Professor Giovanni Coco

I have read the Participant Information Sheet and understand the purpose of this research and why I have been chosen to participate. I have had the opportunity to ask questions and have them answered to my satisfaction.

- I understand my employer has given permission for me to partake in this research.
- I agree to participate in this research.
- I understand the interview may take up to thirty minutes.
- I understand that I am free to withdraw at any time during the interview and to withdraw any information provided by me within one month of the interview without giving a reason.
- I DO/DO NOT give permission to be audio-recorded and understand I may request that this is turned off at any stage during the interview.
- I DO/DO NOT wish to receive a copy of the transcript/digital recording produced by the student researcher.
- I understand that if I do receive a copy of the transcript I will have the opportunity to edit the transcript and return it to the researcher within two weeks of receiving it.
- I understand that I will not be identified by name in this research and that a generic position description and the organisation name will be used.
- I understand that while a generic position descriptor will be used in the research, in an endeavour to protect my identity, that due to the small number of people working in this field my anonymity cannot be guaranteed and that I may be recognisable.
- I understand data collected in this interview process will be used by the student researcher to complete his Master of Science thesis and may also be used in other publications/presentations.
- I understand all data will be stored safely for six years, after which time it will be destroyed.
- I understand that if I wish I will be given a signed copy of this document to keep and sent to my email.
- I understand that I will be able to withdraw information up to four weeks after my interview date.
- I wish to receive a summary of the relevant research findings, which can be emailed to me at this email address: ___________________
Figure B7 – CF for serious game session participants.
Appendix C: Focus Group and Follow-Up Interview Questions

Local Government Group Focus Group Session – Guiding Itinerary and Potential Questions

- The session will begin with a short introduction from the student researcher about his research and its relation to the focus group, the ethical issues associated with the session, and a basic program for the day’s activities.
- Participants will be split into approximately two equal sized groups made up of a range of different professional roles and experience levels.
- Participants will be asked about their current understandings of deep climate uncertainties and be asked to right down some of their approaches for managing them.
- Participants will be introduced to the Te Ara River case study used in the Sustainable Delta game.
- Groups will be asked to elect a team captain who is responsible for coordinating their team’s discussions and activities and ensuring that appropriate actions are taken at the correct time.
- A log keeper will also be elected by both groups to keep track of the justifications used for specific management actions. These notes will be photographed by the student researcher at the end of the session.
- The game will be run in which a series of plausible flooding events are imposed on the Te Ara River across a 100-year planning horizon. Groups must devise a series of management strategies in order to ensure that wider societal objectives are upheld. Such strategies must react to global and local pressures and be fundamentally accountable to the general public. The game is expected to take approximately two hours.
- Once the game is completed, the student researcher will present the results of the game to the session, analysing the strategies of each group.
- The student researcher will then ask the groups to reflect on the activity through a series of verbal questions including:

  1. Were you successful in managing the case study river?
     - Offers insights into the characteristics of flood management prioritised by different groups.
  2. Did your group make any decisions that you would revisit in hindsight?
     a. Were there specific decisions that forced your group to manage in a particular way for the rest of the game? What were these?
  3. Was your management style dictated by the river, human factors or a combination of both?
  4. Are there any similarities between the game scenarios and the flood management context of the Whanganui River?

- The student researcher will then introduce the ideas surrounding decision-support tools like Dynamic Adaptive Policy Pathways and show how these might be incorporated into future-based impact modelling scenarios centred on the Whanganui River. Commentary on the ideas raised will then be sought from the wider group.
Figure C1 – Guiding itinerary and questions used in the serious game session.
Local Government Group Follow-Up Interviews – Guiding Questions

1. Briefly, what is your experience relating to flood management of the Lower Whanganui River?
2. In your opinion, what are the main management concerns relating to flooding of the Lower Whanganui River?
3. In light of the focus group session you recently participated in, what is your understanding of the uncertainties relating to flood management of the Lower Whanganui River?
4. How are such uncertainties accounted for in council impact modelling exercises?
   a. Could this be improved?
5. In your opinion, is a Dynamic Adaptation Policy Pathways approach appropriate for future management of the Lower Whanganui River?
   a. Why do you feel that this is the case?
6. Could decision-support methods (such as Dynamic Adaptive Policy Pathways) be used to generate greater public buy-in for long-term flood management plans in the region?
7. Do you believe there is potential for decision-support methods (such as Dynamic Adaptive Policy Pathways) to be taken up into regional policy frameworks?
8. Is there anything else you wish to discuss in relation to the focus group session or the wider research?

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Figure C2 – Questions used in follow-up interviews