THE REALITIES OF ADAPTIVE FLOOD RISK MANAGEMENT

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ABSTRACT

In recent decades, the Ōpāwaho/Heathcote River catchment in Christchurch has experienced a series of floods which have severely affected people, buildings and the environment. The risk of flooding has been substantially exacerbated following the Canterbury Earthquake Sequence, and now the catchment faces increasing risk with climate change, in particular, rising sea levels. As part of ongoing wider work to build resilience and plan for a range of natural hazards, Christchurch City Council is developing a catchment-wide flood management plan for the Ōpāwaho/Heathcote. The planning is embedding recognised climate adaptation principles to prepare for a 100 years' time horizon.

This paper presents a range of observations made through the planning process in this complex catchment. Whilst no decision has been made within the project timeframe to implement any of the potential long-term adaptive option pathways developed, two important outcomes have resulted at this stage. Firstly, the specific information developed for this key catchment in the city is informing the engagement and ongoing drive for resilience to all hazards, and particularly how such dynamic catchments can adapt to the impacts of climate change. Secondly, having already worked towards an in depth understanding of the catchment and the range of possible options when flooding occurred in July 2017, the Council was able to rapidly consult and approve significant works which are underway.

These works, understood in the context of longer-term adaptation, will substantially reduce flooding in the current climate and some way into the future. This paper outlines some challenges and solutions encountered in the ongoing planning process which have relevance to the wider management of flooding both inland and near the coast. Climate change may be viewed as a 'creeping' hazard at the present time, but influential events can occur suddenly, and having a level of planning in place facilitates timely, sustainable and adaptive responses.

KEYWORDS

Adaptation, Climate Change, Flood Management, Natural Hazards

PRESENTER PROFILE

David is a Chartered Scientist and Water and Environmental Manager with over fourteen years' experience in consultancy and academic research environments. His technical expertise encompasses many areas of water and environmental management, focusing particularly on the sustainable management of flood risk (stormwater and groundwater) and interactions with other natural hazards. He relocated from the UK to New Zealand in July 2015 to deliver complex land drainage recovery, economic and strategic stormwater projects. In the UK, he was a technical director in the Climate Resilience and Adaptation Group, with responsibilities for delivering diverse projects for central and local government. He presents work at international conferences and has authored numerous journal papers.

1 INTRODUCTION

The Ōpāwaho / Heathcote River flows through the New Zealand city of Christchurch in a typically narrow populated floodplain from upland rural areas to a dynamically changing estuary. The river environment is highly valued by the communities when it is not causing major disruption and damage. Flooding has been an issue along the Ōpāwaho / Heathcote River since human settlement along the river corridor intensified, particularly when the lower river terraces were settled in the early 20th century. In recent decades, floods have severely impacted people, buildings and the environment (e.g. increased sediment runoff following Port Hills fires in February 2017), the most recent in July 2017.

In 2010-11, the Canterbury Earthquake Sequence ('earthquakes') increased both the severity and frequency of flooding across Christchurch. Key effects for the Ōpāwaho / Heathcote River were:

- Loss of channel capacity (bank slumping, lateral spread and liquefaction);
- Tectonic uplift at the mouth of the river (up to ~400 mm) and reduced hydraulic gradient; and
- Land settlement in places resulting in a drop of some land levels adjacent to the river.

In the key middle reach of the river (approximately 9 km long), the number of buildings at risk of frequent overfloor flooding (taken as a 10 year Average Recurrence Interval, ARI) is now more than five times greater than before the earthquakes (4 has increased to at least 23), and the number at risk of overfloor flooding in a more extreme 50 year ARI event has almost doubled (85 has increased to at least 152). Some houses have flooded four times since the earthquakes, as a result of the earthquakes and a particularly wet period. Other impacts of the post-earthquake flooding are wastewater and sediment contamination and restriction of access to properties along flooded roads.

On top of these earthquake impacts currently being experienced, the predicted impacts of climate change on flood risk in the catchment without further mitigation are even more significant. For a 10 year ARI event occurring with sea levels having risen 1m and rainfall having increased by 16%, 113 buildings are predicted to be at risk of overfloor flooding, an almost five-fold increase from current levels. For a 50 year ARI event, the risk of overfloor flooding is predicted to increase from 152 to 265 buildings. The latest guidance for New Zealand (MfE, 2017) highlight that these projections (+16% rainfall, +1m sea level rise) could be conservative, and the impacts within 100 years could be greater.

Whilst flooding is Christchurch's most frequently occurring natural hazard, it has been powerfully demonstrated through the earthquakes and other events, that it is only one of many. As such, the following non-flood hazards operating in the catchment were considered in this work: tsunami, coastal erosion and inundation, groundwater rise, earthquakes (including vertical displacement and liquefaction) and mass movements (including landslide). The aims of considering these hazards in a flood study were to assess whether a:

(i) non-flood hazard event is likely to exacerbate flood risk (e.g. earthquakes uplifting the downstream Heathcote catchment);

(ii) response to pluvial and fluvial flooding could be modified to also assist with managing another hazard (e.g. stopbanks also for tsunami protection); or

(iii) flood management response would need to be differently designed to function in a hazard event (e.g. earthquake settlement of stopbanks, rising groundwater within detention basins).

Jacobs was engaged to develop an adaptive floodplain management plan for the Ōpāwaho / Heathcote River within these key contexts of the earthquakes, climate change and other natural hazards under Christchurch City Council's Land Drainage Recovery Programme. The overall post-earthquake programme was set up to repair damage, restore pre-earthquake flood risk levels, and to identify opportunities for betterment. The strategy for betterment was defined following city-wide flooding in March 2014, when the hydraulic impacts of the earthquakes were still obvious. The Long Term Plan committed Council to achieve an ongoing reduction in the number of dwellings flooding above floor level relative to those which flooded in March 2014. The Ōpāwaho / Heathcote River catchment experienced the second largest number of buildings damaged in the city, which highlighted the high priority of managing flooding in the catchment.

At the outset, the programme recognised the need to develop an adaptive approach, most likely combining physical works and policy responses. In an adaptable approach, measures are introduced at different times to limit the increase in flood risk due to climate change to an acceptable level. In the Ōpāwaho / Heathcote River catchment, this approach is being extended to include additional complexities of restoring an acceptable level of flood risk following the earthquakes, and increasing resilience to a range of natural hazards. This complexity means that work is ongoing and no decision has been made within the project timeframe to implement any of the potential long-term adaptive option pathways developed. However, this paper presents a range of observations made through the planning process which have relevance to the wider management of flooding both inland and near the coast outside of Christchurch. These observations are presented in the following structure:

- Section 2: Setting objectives and outcomes for an adaptive management plan
- Section 3: Developing a decision-making framework to define adaptive option pathways
- Section 4: The importance of understanding the catchment
- Section 5: Making use of multi-hazard information
- Section 6: Development of individual options
- Section 7: Developing adaptive option pathways
- Section 8: Discussion

2 SETTING OBJECTIVES FOR THE PLAN

An adaptable approach to flood management has interventions at points to limit the increase in flood risk due to climate change to an acceptable level. Setting this acceptable level requires careful consideration and should be set by an overall policy or strategy, and in consultation with the communities concerned:

- **Metric:** what is used to measure acceptable? Examples are: the number of buildings flooding above floor level or the water level/flow at a given location. Whilst flooding above floor incurs greatest economic damage, underfloor flooding including blocked access may be a great concern.

- **Value of metric:** success of the adaptive plan will ultimately be judged upon this value. If the chosen metric is flooding of floor levels, a value of zero indicates greatest commitment by Council but could be too expensive to achieve. Of particular importance is whether this value should be allowed to increase with climate change, or whether a single value will be maintained.

- **Magnitude of flood event:** typical design standards for flood (not drainage) infrastructure include 50 and 100 year ARI events. However, providing this standard in all places may not be achievable. Therefore, focusing on more frequent events (e.g. 10 year ARI) and accepting damage at less frequent events targets limited resources at the most vulnerable.

- **Time to achieve acceptable level:** returning to pre-earthquake levels of flooding as soon as possible was a high priority for this project, and therefore the available time to achieve the target was minimised. In other situations, known funding constraints or availability of land, for example, may result in a longer time period being acceptable.

- **Period to maintain the acceptable level:** whilst this is best viewed as a defined sea level rise rather than a time period, the period over which the plan maintains the risk level must be defined.

- **Geographical extent of acceptable level:** the possibility of having different acceptable levels in different areas of a political area or catchment should be considered upfront. Having varying levels could lead to complications, but the same level may not be achievable everywhere.

For the purposes of this study, the acceptable level set as the scenario for the plan was defined as follows for the 50 year ARI event in current and future climates across the study area:

- Metric: overfloor flooding of habitable areas of residential buildings;

- Value of metric: zero overfloor flooded buildings over a 100 year time period;

- Time to acceptable level: achieve immediately to restore at least pre-earthquake levels; and

- Period to maintain acceptable level: zero above floor flooded buildings for the next 100 years.

Note that this working target does not reflect any wider Council policy or agreement. This project scenario is illustrated in Figure 1 by the orange line. Figure 1 illustrates other options considered which were: (in green) maintain post-earthquake level, (in red) return to pre earthquake and either maintain or allow to increase with climate change, or (in blue) provide betterment over pre-earthquake levels and either maintain or allow to increase with climate change.

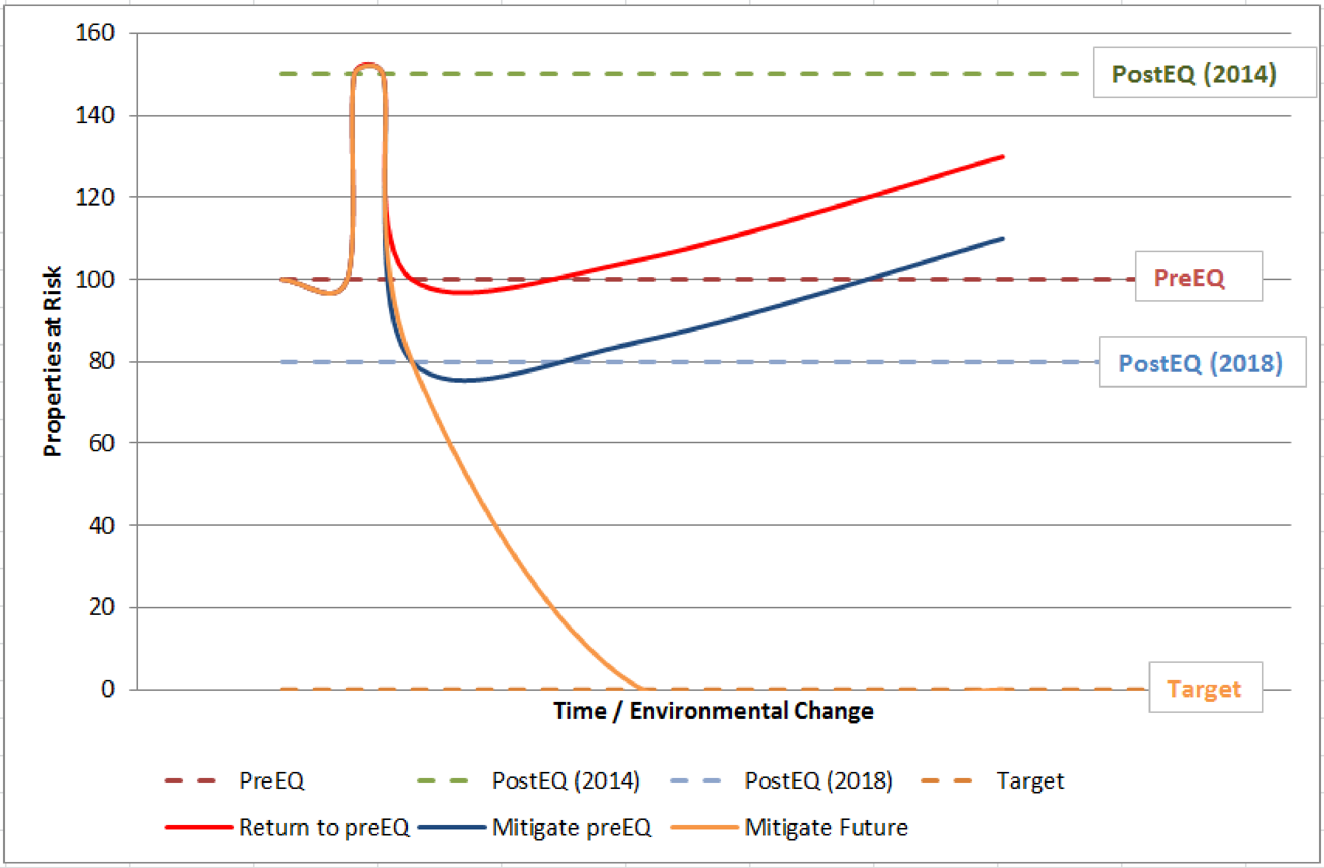

Figure 1: Schematic of possible flood management targets for a given probability flood event

3 A DECISION-MAKING FRAMEWORK FOR ADAPTATION

Having defined a working target for the adaptation plan to achieve, we developed a decision making framework to assess options and program these into a plan. In keeping with good principles of adaptation (e.g. European Topic Centre on Air and Climate Change, 2010), the plan aimed to identify a number of possible flood management options at each decision point.

A review of frameworks highlighted that decision makers still largely use traditional economic analysis techniques for appraising options, even though these struggle to account for uncertainty. New approaches are increasingly being discussed, but applications remain scarce. Dittrich *et al.* (2016) reviewed a number of emerging approaches (e.g. Real Options Analysis), but these largely rely on substantial modelling and analysis resources which were not available for this study. Therefore, a three-stage framework was used (schematised in Figure 2) which modified the traditional benefit:cost and Multi-Criteria Analysis (MCA), where options can be either engineering or policy responses:

(i) **Options must contribute a useful hydraulic benefit to be considered.** The primary outcome for the adaptive plan is to provide hydraulic benefit. Whilst a single intervention was unlikely to achieve the agreed standard, each option was judged according to whether it could provide an important contribution to a combination of options which together achieves the target. Hydraulic benefit was therefore taken out of its prior place in the MCA and given prominence upfront. Whilst some high cost options which achieved a minimal hydraulic benefit were screened out at this stage, cost itself was not a focus of the decision-making so that the best technical solutions could be identified.

Therefore, options which were likely to provide an important contribution to a combination of options were taken forward to analysis of their other criteria.

(ii) **Options were prioritized on their MCA score.** Although in a flood study hydraulic benefit is the primary consideration, MCA is used to guide development of options and select adaptable solutions. Council's standard MCA was extended to include:

- Impact of multi-hazards on the viability of the option. This captures the various possible interactions (positive and negative) identified in Section 5; and
- Degree of adaptability of the option. This was defined as the extent to which options lock in future decisions or overly depend on external decisions being made.

The results of the MCA were used to prioritise available options at each decision point.

(iii) **Options are grouped into pathways according to climate change projections.** The range of potential individual options are programmed into possible pathways, allowing for the plan to be reviewed and updated at key decision points as risk thresholds are approached. Arranging the option pathways against a timeline of climate change (primarily sea level rise) communicates the adaptability of the plan.

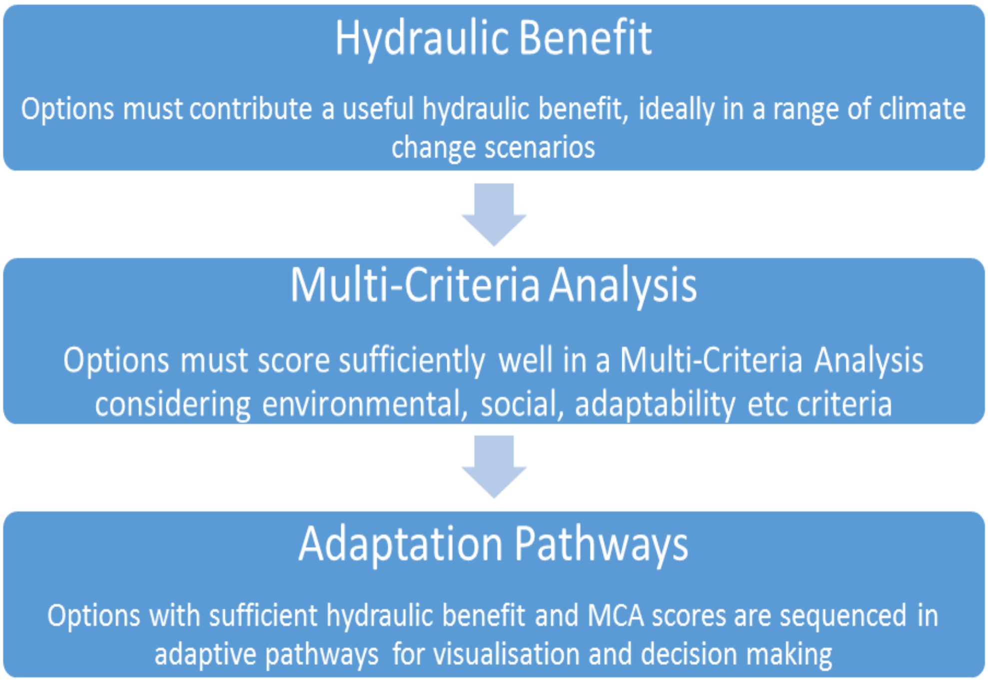

Figure 2: Schematic of proposed three-stage decision making framework

4 CATCHMENT UNDERSTANDING

A significant up-front effort was made to understand the mechanisms of flooding across the catchment, both in current and future climates. The hydraulic model was used as follows:

- **Sensitivity of flooding to downstream tidal levels:** this revealed that discharge at the lower end of the catchment in the current climate was primarily constrained by the capacity of the channel, whereas with sea level rise the influence of tidal levels would increase. This steered options development and led us to model only the fluvial flood for a given scenario, rather than following the accepted 'max of the max' technique of modelling comparable fluvial and coastal floods and taking the maximum. This reduced the modelling burden without compromising the results.

- **Increments of climate change:** an adaptive plan defines decision points based on trigger levels. Therefore, how baseline flood risk changes with climate change is important to understand. The catchment is influenced by both sea level and rainfall, which will vary together with increasing temperature. Incremental scenarios were developed to tie together changes in both of these to projections of temperature rise, and attributed to timescales based on MfE (2017) guidance and IPCC scenarios.

- **Impact of Other Hazards:** the multi-hazards analysis (see next Section) identified that raised groundwater levels, coastal inundation, earthquakes and mass movement are most likely to impact flood risk. Because of the known effects of the 2010-11 earthquakes, the impacts of a future earthquake scenario were modelled. From possible future earthquake scenarios, we modelled the same ground movement experienced across the catchment in the earthquakes occurring again. Levels of all topography and structures in the hydraulic model were modified, as were the floor levels of buildings. The modelling indicated that, largely because of the uplift of floor levels (i.e. up to 400 mm), the number of buildings at risk following a future earthquake decreases. This result was specific to the particular type of event, but it indicated that the impacts of a future earthquake were unlikely to be central to future flood risk management in with climate change.

This understanding of mechanisms was used to zone the catchment study area into three main reaches (lower, middle and upper) and develop management options. The basis for the zones was the similarity of hydraulic characteristics (both in the current climate and with climate change), and within which similar options were most effective. The boundaries between the reaches were not designed to be rigid and, indeed, changed through the study as our understanding evolved. From our understanding of how flood mechanisms varied both across the catchment and with time, it was clear that any overall solution would require a combination of options in space and time.

5 MULTI-HAZARD CONTEXT

As with many river catchments in New Zealand, the Ōpāwaho / Heathcote catchment is exposed to multiple natural hazards. A number of these hazards could interact with each other and with flooding, which could generate a highly complex analysis problem. So as not to overcomplicate the analysis, flood risk was kept as the focus of the study but information on natural hazards operating in the catchment and the potential impacts on flood risk was developed and used as a guide.

Through analyzing and mapping the variation of the individual hazards across the catchment, raised groundwater levels, coastal inundation, earthquakes (including liquefaction and other effects), and mass movement were determined to interact most with flooding. Further, all of the multi-hazard interactions except earthquakes were determined to consistently increase flood risk.

In the extended MCA element of the decision-making framework (Section 5), each flood management option was assessed as to whether it could also assist with managing a non-flood hazard:

- Dredging: bank stabilization works as part of dredging could reduce lateral spread in an earthquake, and any liquefaction material generated through an earthquake could be removed by planned maintenance dredging;

- Stopbanks: could provide some increased protection from a tsunami;

- River Mouth Pump Station: tide gates and associated stopbanks could potentially be designed to offer protection from upstream propagation of a tsunami; and

- Options involving raising or relocation of buildings: new foundations will adhere to the latest building codes and have improved resilience to seismic hazards. Removing dwellings removes exposure to other hazards.

Each option was assessed as to whether it could be majorly impacted in a non-flood hazard event. Existing standards for structural options require a certain level of resilience e.g. to earthquakes. However, long linear infrastructure (e.g. stopbanks and channel diversion culverts) will be particularly vulnerable to seismic events. It was judged unlikely that raised groundwater ponding within large flood storage areas would significantly reduce the available storage volume, but increased ponding of groundwater behind stopbanks would have to be pumped away, as for surface water. In fact, the only option which could be significantly modified by a non-flood hazard is any which involves works to individual properties. In this case, the occurrence of a major non-flood hazard event could trigger an earlier onset of works to individual properties than otherwise envisaged.

6 INDIVIDUAL OPTIONS DEVELOPMENT

6.1 THE OVERALL PROCESS

The adaptive flood management planning involved developing individual options (providing benefit focused on a certain location and at a certain time) which were then combined into potential adaptive pathways as follows, which fits with the decision making framework (Section 3):

(i) Early conceptual options: a range of options was conceived within the source-pathway-receptor framework, which included a mix of engineering and policy responses;

(ii) Individual options: concept designs for individual options were hydraulically modelled where possible to understand their benefits under current and future climate scenarios. Results were used to discount some from further consideration based on minimal benefit;

(iii) Combined options: rather than modelling a huge number of option combinations to define possible option pathways, the impacts of individual option results were analysed and logic used to predict the outcome of combining options.

Individual engineering options were developed as for a typical flood management study; to address flooding by specific mechanisms throughout the catchment, where some of the mechanisms were understood to vary with climate change. Options included further upstream storage, stopbanks, diversion channels, dredging, a river mouth pump station and works to individual properties (e.g. house raising or other forms of Individual Property Protection). Of more interest to this paper on the realities of adaptive flood management, however, was the initial work undertaken towards defining options comprising a reduced flood protection standard in some areas, and the different possible ways of implementing Individual Property Protection are provided.

6.2 FOCUSSING RESOURCES ON THOSE MOST AT RISK

The ongoing cost of targeting zero overfloor flooded buildings in a 50 year ARI event across the catchment with climate change may be prohibitive. Instead, overfloor flood protection only in more frequent flood events was developed as a policy option which was then used as a foundation of a range of adaptive options pathways. Those properties which flood most frequently are those most at risk, and which limited resources could be focused on. For the purposes of this study, frequent flooding was defined as a 10 year ARI event. Options and pathways were thus developed to reduce the number of above floor flooding dwellings in a 10 year ARI event to zero. These included similar engineering and policy options, but these did not need to be as high (e.g. for stopbanks), large (e.g. for diversion channels) or extensive (e.g. works to individual properties). Clearly, remaining buildings would be at risk of flooding in any event more extreme than a 10 year ARI.

6.3 INDIVIDUAL PROPERTY PROTECTION

Because of the distributed nature of flooding across the large catchment, it became clear that options targeting the source and pathway of a flood could not always achieve zero dwellings flooding above floor, particularly in a 50 year ARI event. Therefore, works to individual buildings (broadly termed Individual Property Protection; IPP) are likely to be increasingly required to mitigate the impacts of climate change. Two main forms of IPP are resistance (keeping water out through e.g. house raising, relocating the building, bunding and pumps) and resilience (minimising damage, raised services etc.). Under this broad heading of Individual Property Protection, a range of engineering and policy options were considered.

The Flood Intervention Policy (FIP) is an existing earthquake-specific Council policy which addresses flooding at a property level and is designed to help property owners who are at risk of frequent above-floor flooding, where the flooding has been worsened by the earthquakes, and planned flood mitigation schemes will not offer a timely or effective reduction to their flood risk. Through this policy, the Council offers localised drainage improvements, house raising or voluntary property purchase to individual dwellings. This policy option became an important component of restoring pre-earthquake levels of flood risk across the catchment.

Where the current or future risks at a property do not relate directly to earthquake impacts, an option was conceived whereby the same set of responses could be offered. However, we identified that the practicalities of providing IPP on a significant scale, which introduces issues including consenting the cumulative displacement of floodwater, required further investigation if developed into a policy.

Finally, an option was conceived to remove infrastructure from flood-prone areas and to replace it with an enhanced floodplain environment. Whilst there are international case studies where retreat has been implemented as a response to climate or natural hazards

(Hino et al., 2017), and within New Zealand there are examples from which lessons could be learned (Parliamentary Commissioner for the Environment., 2015), this option requires extensive further development before it can be successfully implemented (LGNZ, 2014).

6.4 HIGH LEVEL COSTING OF OPTIONS

Options were costed at a high level to inform the assessment. However, the cost of the options was purposely downplayed in the decision making so that the best technical solutions could emerge. The most difficult option to cost with reasonable certainty was the option involving relocation of properties.

It is clear that the total cost of this option is greater than the market value of the properties to be removed, and should also consider at least removal or relocation of services, provision of a level of flood protection whilst properties remain and turning the land to some alternate use. To estimate some of these additional costs, information from LINZ around property purchase in Christchurch following the earthquakes to establish the Residential Red Zone was considered. This suggested at a very high level that an additional 10% of the market value of each property is required to demolish and maintain each property over a 5 year period.

Costing of options highlighted that providing a reasonable level of flood management into the future will be expensive, and often in excess of the flood damage avoided when measured using standard methods (Cobby et al., 2016). One unresolved element of the economics of adapting to climate change is the choice of social discount rate, which has a substantial effect on the value of future damage, damage avoided and the cost of investment. This study used a discount rate of 5% which is broadly in line with New Zealand and international practice, but even this can mask increases in damage which arise through climate change, and makes economic justification for mitigation difficult.

Even at rates of 2-3%, economists struggle to justify substantial spending in the present to fight climate change. Whilst adaptive management seeks to defer some interventions and spend into the future, a certain level of investment (for e.g. planning, purchase of land for schemes) should be undertaken now. In the 2006 Economics of Climate Change: The Stern Review, a 0% discount rate was used to justify investment in the present to combat climate change, but this was controversial. The UK Treasury recommends a variable discount rate: 3.5% in years 0 to 30, 3% from years 31 to 75 and 2.5% from year 76 to 99, for a 100 year appraisal. The appropriate social discount rate is an unresolved issue and guidance from central government is required for a consistent approach.

7 COMBINING OPTIONS INTO ADAPTIVE PATHWAYS

The aim of the study was to work towards a management plan comprising option pathways. Each pathway could comprise one or more options at different locations in the catchment and implemented at a different point in time. An adaptive pathway is one which leaves open further options if the environment (natural, developed, multi-hazard) changes differently to that anticipated.

The hydraulic benefits achieved by following a particular pathway could only be fully understood through a series of model runs, where implementing the option at a different time (actually, a different degree of climate change) would vary the benefit and could be used to optimise the pathway. Repeating this for all possible option pathways, and to test all combinations of options in space and time, would have required a prohibitive number of hydraulic model runs.

Instead, logic, based on available results from individual options modelling and our understanding of the catchment, was used to derive a range of viable options pathways. This logic was based on the two key elements of the decision making framework (Section 3):

- The anticipated hydraulic benefit of each individual option at a point in the changing climate, and therefore its likely contribution to achieving the overall target; and
- The prioritisation of options at any point in time based on their MCA score.

Possible pathways were developed firstly for each of the three zones of the catchment, and to achieve both 10 year ARI and 50 year ARI targets. Developing these pathways for the individual subcatchments kept the option permutations to a manageable number. However, once these were defined for each subcatchment, an overall set of pathways was developed for the whole catchment, in which pathways which worked together were retained, and contradicting pathways were modified. The result was three catchment-wide sets of adaptive pathways, or three floodplain management plans, each of which was predicted to achieve a different target of zero overfloor flooding:

- 10 year ARI: no above floor flooding across the catchment;
- 50 year ARI: no above floor flooding across the catchment; and
- Varying target, from a 10 year ARI target in the lower catchment to a 50 year ARI target in the upper catchment.

Figure 3 illustrates a set of option pathways developed for one subcatchment to achieve zero overfloor flooded dwellings in a 50 year ARI event over the nominal 100 year timeframe. The modelled increments of sea level rise are indicated from left to right across the bottom of the chart. The baseline options are those which are already being implemented. The four option pathways are shown in decreasing order of preference, based on the outcome of the MCA. Following a pathway across through time indicates when an intervention will be required by, with the arrows indicating that the option continues to provide useful hydraulic benefit.

8 DISCUSSION

No decision was made within the project timeframe to implement any particular option pathway, since wider debate and consultation within Council is required. However, having developed such specific information for a key catchment in the city has informed the ongoing debate about how such a dynamic catchment can adapt to the impacts of climate change. Indeed, at this time when there is a renewed focus at a high level on the appropriate response to natural hazards and climate change (MfE 2017a,b), having a detailed test-case, from which it is reasonable to draw some generalities, is of great value. The timeliness of the study was also amply demonstrated during the July 2017 flooding in the catchment. Having the in depth understanding of the catchment and the range of possible options prior to the event, enabled the Council to consult and approve significant works in a timely manner, which are now being implemented (Christchurch City Council, 2017). These works substantially reduce flooding in both 10 and 50 year ARI events in the current climate and some way into the future. This is an important reality of adaptive management; climate change may be occurring relatively slowly at the present time, but influential events (including natural hazards, political changes etc.) can occur suddenly. Plans must be in place so that relevant aspects of them can be implemented when opportunities arise.

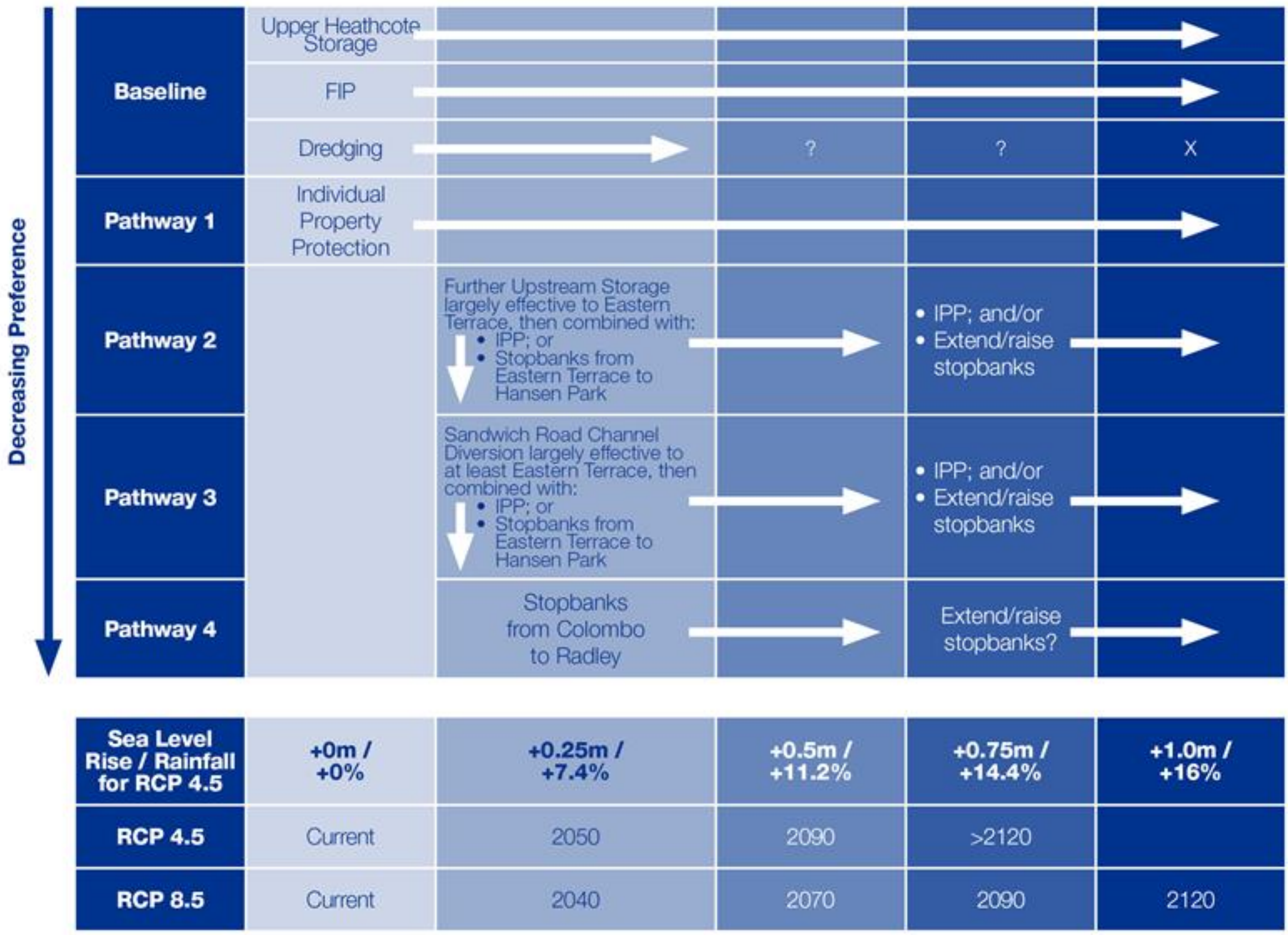

Figure 3: Illustrative set of option pathways to achieve a 50 year ARI target for one particular subcatchment

Although apparently obvious, a thorough understanding of flood mechanisms, both in the current and future climates, is a fundamental starting point for any study. This step is too easy to overlook when complex hydraulic models are available to rapidly test numerous options. Some key messages for the Heathcote catchment which guided many aspects of the study were:

- Earthquakes increased flood risk, but climate change will introduce more significant increases;

- Flood levels – particularly in frequent flood events – will rise with climate change more at the downstream end of the catchment than upstream, highlighting the relative importance of sea level rise over predicted increases in rainfall intensity; and

- In such a long narrow floodplain, options may only influence a certain reach and therefore understanding the combination of options required at any point in time is important.

As well as providing a solid technical foundation, this understanding enabled an important reduction in the modelling burden through the study, as matching each fluvial event with a comparable probability tidal event, and taking the maximum of the flood levels, was not required in the current climate.

Change in risk with climate has been understood here through a series of increments, where sea level rise and rainfall intensity increase together with projections of global temperature. The increments can be approximately dated based on IPCC scenarios, which enables costing of options proposed to be implemented at different times. It is recommended that more extreme future scenarios than current guidance suggests (e.g. sea level rise of 2m) are modelled to (i) understand whether flood risk will be substantially different and (ii) indicate whether the same flood management options would be selected.

Defining upfront what the acceptable level of flood risk, or standard of protection, is highly important to decision making later in the study and should ideally be set by an overall policy or strategy, and in consultation with the communities concerned. This future-looking study has been undertaken in the complex context of restoring pre-earthquake levels of risk and an overall policy based on reducing risk observed in past events. As the study evolved, and the reality of providing protection to all buildings at risk of above floor flooding in a 50 year ARI event with climate change became apparent, additional option pathways to provide protection in a 10 year ARI event were explored. In turn, this raised the complex issue of providing different standards of protection in different areas of the catchment.

Dividing such a large catchment into reaches of similar land use and/or flood characteristics has proved useful in this project requiring complex analysis and communication. Boundaries should be based on thorough understanding of the catchment as it responds to climate change. No boundaries will be perfect and should therefore be viewed as 'fuzzy', but they facilitate detailed development of options at a local level which can then be assessed for compatibility in the wider catchment plan.

Understanding flood risk and options to manage flooding in the context of other interacting natural hazards is a desirable outcome, but full analysis could be complicated unless there are substantial resources to deliver the project. However, we have developed useful hazard information to inform flood option development based on potential interactions of individual non-flood hazards with flooding. Further work being undertaken on a parallel project for Christchurch City Council (Parsons et al., 2018) is extending the analysis across the tidal areas of the city to understand impacts of hazards which are spatially co-located (affecting the same spatial location), temporally coincident (occur at the same time and in the same location) or cascading (the likelihood or impact of a second hazard is altered by the occurrence of the first). In particular, the outcomes of this fuller analysis will inform future land use planning in the context of exposure to all hazards.

Multiple engineering and policy options to manage flooding in the catchment have been developed and assessed. To assess individual options and group these into adaptive pathways, a decision making framework was developed. Whilst new approaches to make decisions between numerous possible combinations of options and outcomes are being developed, these were found to be prohibitively complex for a study of this scale. Instead, more traditional analyses of hydraulic benefit and multi-criteria were modified here into a three stage process:

(i) Individual options were assessed primarily on their hydraulic benefit, and likely contribution to a combination of options. Cost was considered but options were not discounted based on high cost alone;

(ii) The wider benefits and/or adverse impacts of individual options were assessed (including their degree of adaptability and interaction with other natural hazards) in a multi-criteria analysis and the scores used to prioritise options considered at any decision point; and

(iii) Combination of options were programmed into option pathways based on increments of climate change and anticipated timescales linked to IPCC scenarios.

One option which became important in defining the set of adaptive pathways, was to focus protection on the most vulnerable at risk of overfloor flooding in more frequent flood events. Therefore, a series of possible adaptive pathways were defined for both 10 and 50 year ARI events within approximately the next 100 years of climate change. This highlighted the different scale of works required to achieve each. However, it also raised the possibility of aiming for a different target at different locations in the catchment and/or at different points in time. A variable target throughout the catchment, or with time, will be complex to communicate and agree. Indeed, deciding between any of these outcomes will require extensive discussion and consultation within Council and with the communities effected and cannot be resolved within the confines of this study.

In summary, because this project has studied the likely impacts and responses to climate change in a good level of detail in such a high profile catchment in the city, it has tackled important broader issues in attempting to develop a realistic plan. The benefit of this planning has already been demonstrated in Council's timely response to recent flood events as well as informing the wider debate about risk and adaptation in the city. As expected, there are a number of technical and political gaps which remain, and it is hoped that ongoing studies will lead to a greater capacity for management of flood risk to adapt to the significant challenge of climate change.

REFERENCES

Christchurch City Council (2017) Available at: https://www.ccc.govt.nz/services/water-and-drainage/stormwater-and-drainage/stormwater-projects/whats-happening-in-your-neighbourhood/heathcote-catchment/

Cobby, D. et al. (2016) Making Better Decisions: Calculating the Benefits of Stormwater Infrastructure. Presented at Water NZ Annual Conference and Expo, Rotorua, October 19 – 21.

Dittrich, R., Wreford, A., Moran, D. (2016) A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? Ecological Economics, 122, 79-89

European Topic Centre on Air and Climate Change (2010) Guiding Principles for adaptation to climate change in Europe. Technical Paper 2010 / 6. November 2010

Hino, M., Field, C. B., & Mach, K. J. (2017). Managed retreat as a response to natural hazard risk. Nature Climate Change, 7, 364–370

Local Government New Zealand. (2014). Managing natural hazard risk in New Zealand – towards more resilient communities. Wellington, New Zealand.

MfE (2017a) Coastal Hazards and Climate Change: Guidance for Local Government. Ministry for the Environment

MfE (2017b) Adapting to Climate Change in New Zealand. Stocktake Report from the Climate Change Adaptation Technical Working Group

Parliamentary Commissioner for the Environment. (2015). Preparing New Zealand for rising seas: Certainty and Uncertainty.

Parsons, T., Todd, D., Cobby, D., Hart, D., Kingsbury, P. (2018) Christchurch Multi-Hazard Analysis Approach. Unpublished - to be presented at this conference.