Christchurch Multi-Hazards Stage 3 Report

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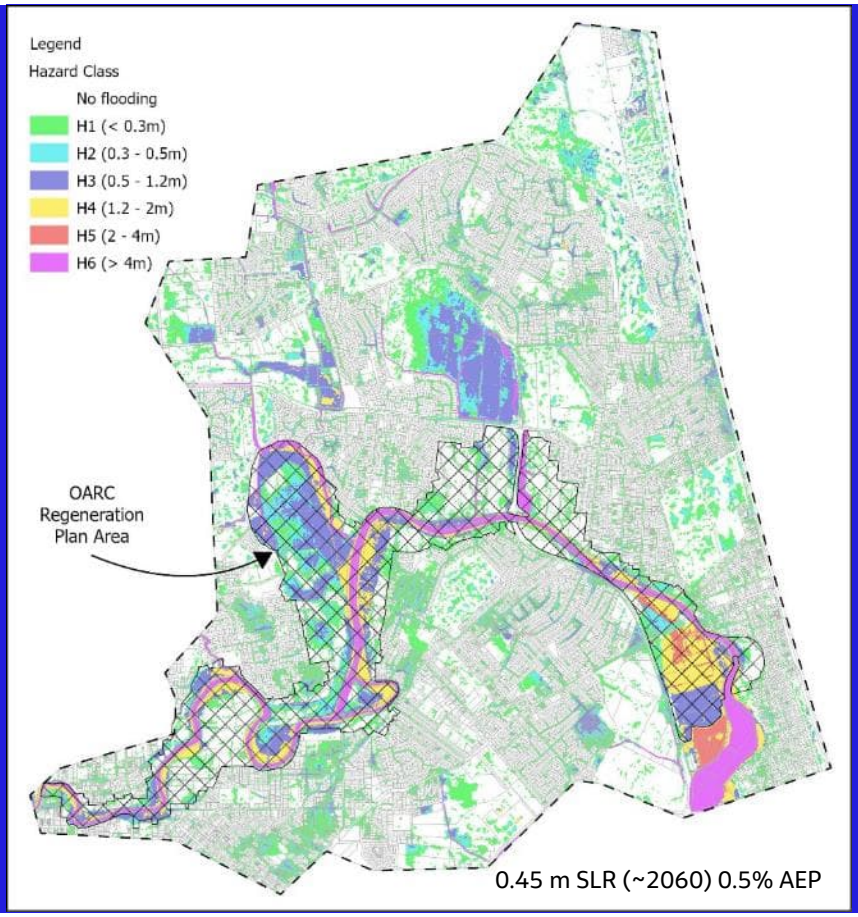
Christchurch City Council
LDRP97

Christchurch Multi-Hazards



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Executive summary

The Christchurch multi-hazards project has examined a broad range of natural hazards and assessed the relative consequence of each in exacerbating flooding in the tidally influenced river catchments of Christchurch city. The aim has been to identify which other natural hazards need to be considered when assessing flood hazards, provide a greater understanding of how these hazards interact with flooding, and so help inform the development of future investments in flood management and provide a sound technical basis for decision making by Christchurch City Council (Council).

Four study areas were initially defined for the project based on the estimated fluvial and pluvial floodplains of the major river catchments in Christchurch – the lower Pūharakekenui Styx, Ōtākaro Avon and Ōpāwaho Heathcote Rivers ('Lower Styx River', 'Avon River' and 'Heathcote River' study areas respectively) – and the coastal margins of Ihutai Avon Heathcote Estuary and Sumner ('Southshore and Estuary' study area).

Stage 1 of the study collated and analysed the best available information on the individual hazards impacting the study areas and identified gaps in the knowledge needed to produce robust adaptive flood management plans. Further studies were undertaken in Stage 2 of the project to address these gaps.

This report provides the results of Stage 3 of the project, a more detailed assessment of the effects of multi-hazards on flooding in the lower Ōtākaro Avon River catchment (the 'Avon River' study area), and the implications for the performance and long-term viability of the flood risk management measures currently being implemented by Council as part of the Ōtākaro Avon River Corridor Regeneration Plan – the 'OARC Scheme' (Figure ES-1).

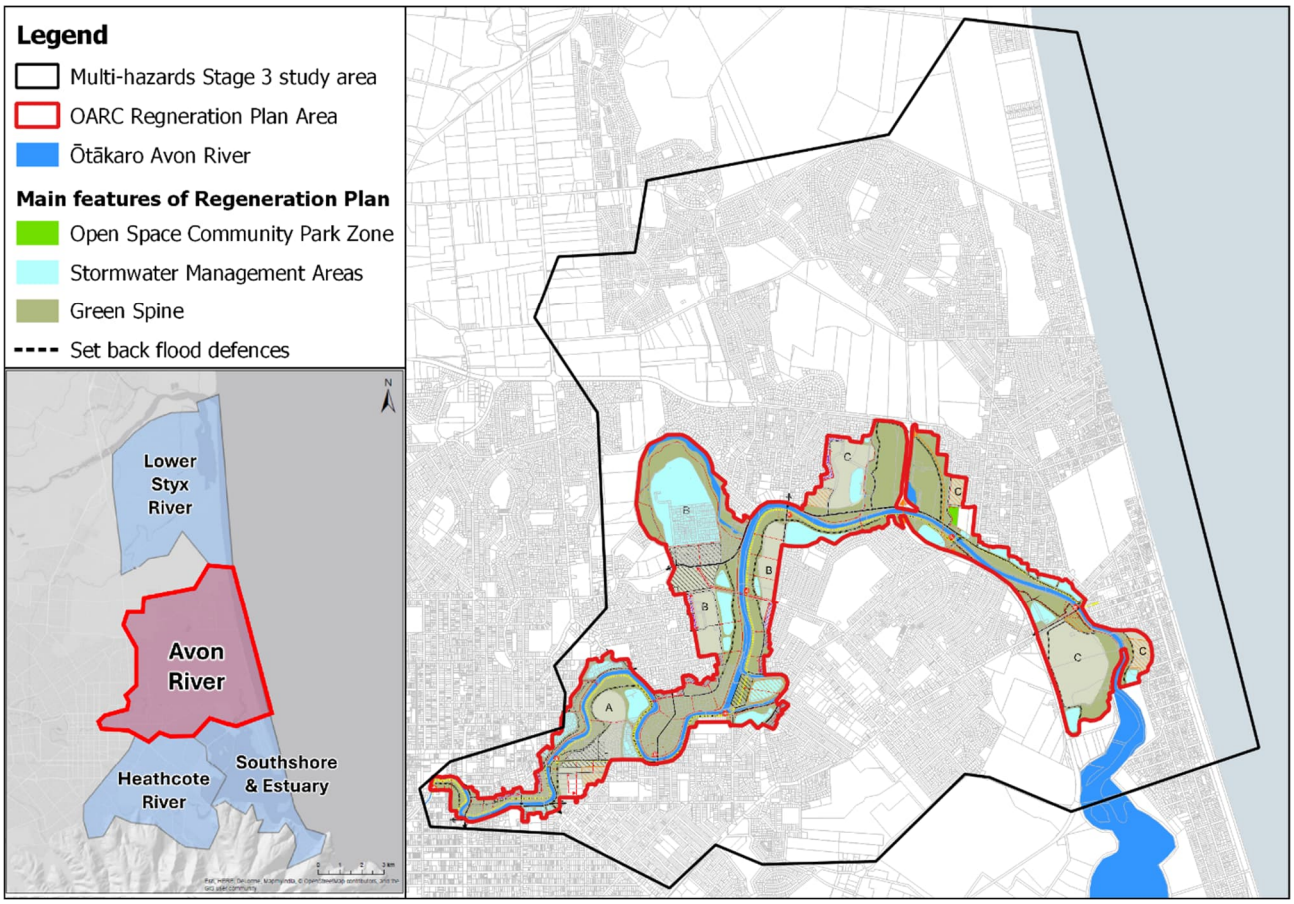

Figure ES-1: Location of the multi-hazards project study areas and indicative layout of the OARC Scheme.

The Stage 3 assessment shows that without new flood protection measures, an estimated 3,500 buildings in the lower Ōtākaro Avon catchment will be at a 0.5% Annual Exceedance Probability (AEP) chance of above floor flooding by 2060, increasing to 5,600 in 2100. The estimated present value of damage from flooding in the catchment from 2020 to 2060 is approximately $1 Billion, increasing to approximately $3 Billion by 2100.

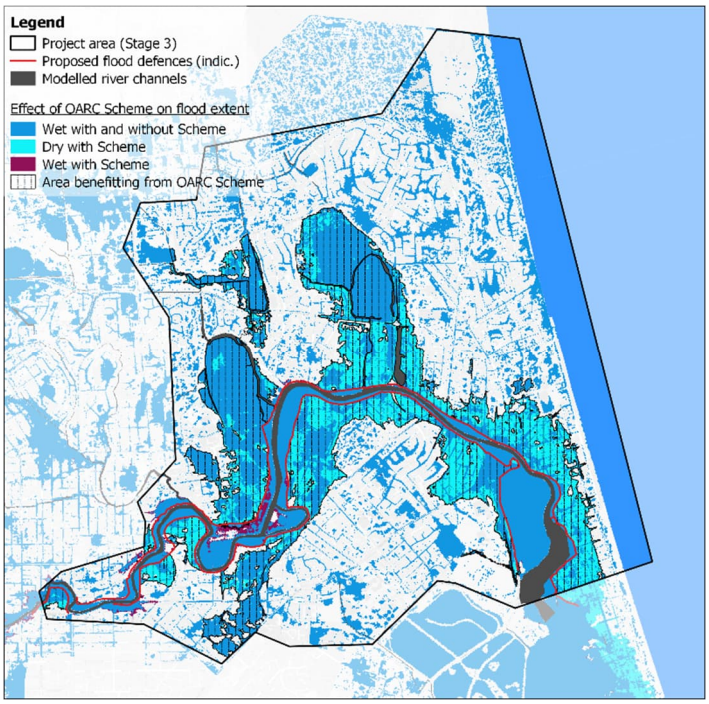

Figure ES-2: Effect of OARC Scheme on 0.5% AEP flood extent in approximately 2060 (0.45m sea level rise from 2020)

The OARC Scheme will reduce the risk of fluvially and tidally driven flooding from the lower Ōtākaro Avon River to a joint probability of least 1% AEP. This level of service is intended to be maintained over the lifetime of the scheme by allowing for the anticipated effects of climate change and vertical land movement in the design crest levels of the flood defences. Planned implementation of the OARC scheme is based on maintaining the level for service for 30 years. Consideration and decisions around providing for the design crest levels to be raised adaptively, if required, in the future would be made by Council's Coastal Hazards Adaption Planning (CHAP) process.

The Stage 3 assessment allows for the effects of climate change using New Zealand Ministry for the Environment guidance on changes in sea level and rainfall available at the time of the project. The potential timing of the flood hazards indicated in the assessment is based on the guidance for a single emissions scenario. The actual trajectory of future emissions and their effects on the sources of flooding is highly uncertain. This means that the reported flood hazards could occur sooner or later than the dates indicated in this assessment and this uncertainty will need to be considered in the OARC Scheme design and CHAP process.

In addition to preventing flooding where this is solely from the river, the OARC Scheme provides benefits to a broader area by reducing the overall maximum flood depths considering all sources of flooding – i.e., local pluvial flooding as well as fluvial and tidal river flooding (Figure ES-2).

The OARC Scheme is estimated to reduce the number of buildings at risk of above floor flooding in the study area in a 0.5% AEP event by around 2,200 buildings in 2060, and approximately 3,700 buildings in 2100.

The present value of flood damages avoided with the OARC Scheme is estimated to be $630 Million from 2020 to 2060, increasing to approximately $2.2 Billion by 2100.

Estimated cash costs for the new flood defences and pumpstations are around $580 Million to 2060 and $690 Million to 2100 (present values of around $380 Million and $420 Million respectively), noting that these are programme level estimates with an uncertainty of +/-50% potentially.

Flood levels along the Ōtākaro Avon River upstream of the OARC Scheme are expected to be higher than without any new downstream flood defences. For the scheme arrangement modelled in the Stage 3 assessment, this could expose additional buildings upstream of the OARC Scheme to above floor flooding.

The area benefiting from the OARC Scheme in terms of reduced flood depths, together with the wider Stage 3 study area of the lower Ōtākaro Avon catchment, is exposed to other natural hazards which the OARC Scheme is not designed to mitigate – principally residual pluvial and fluvial flooding from local drainage catchments, shallow groundwater, earthquakes and tsunami (Figure ES-3).

These other hazards may affect the performance of the OARC Scheme or the value of providing protection from river flooding to areas where the residual risk from other hazards is significant. These factors should be considered by Council when making decisions on the planned flood protection investment.

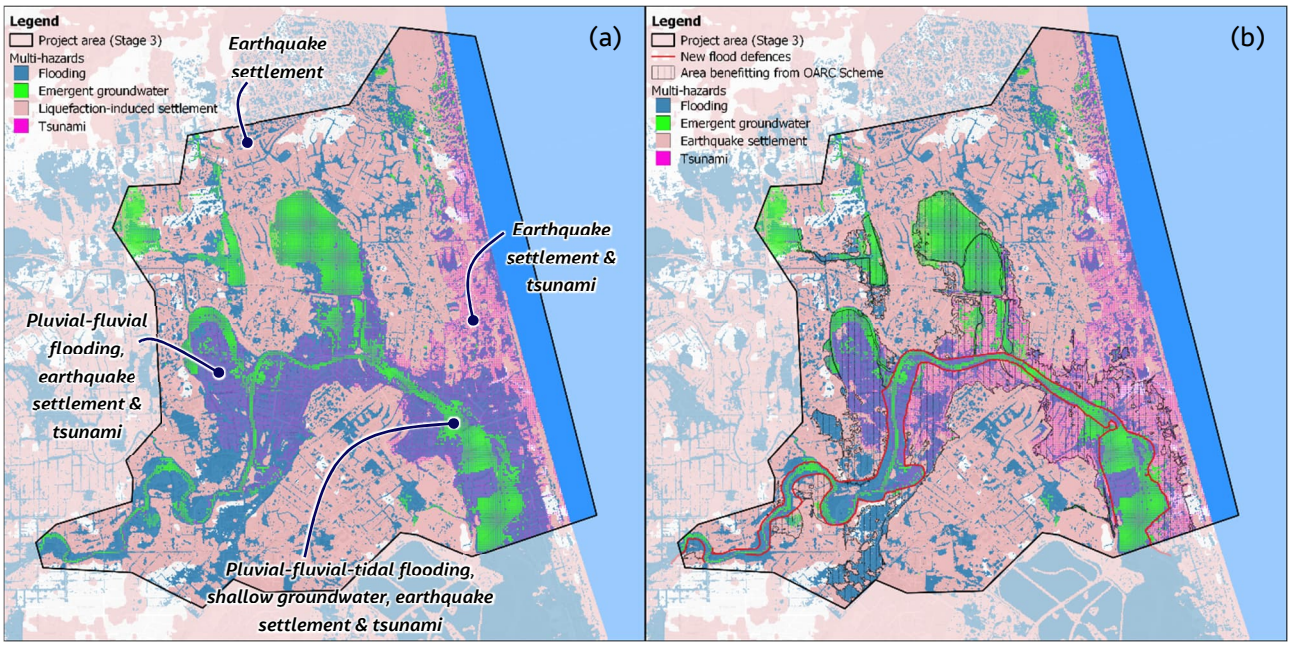

Figure ES-3: Distribution of pluvial, fluvial and tidal flooding[1], shallow groundwater[2], earthquake[3] and tsunami[4] hazards multi-hazards in the Stage 3 study area in approximately 2060 (0.45 m sea level rise from 2020): (a) without OARC Scheme; (b) with OARC Scheme, together with examples of the co-located hazards.

In particular:

- Within the area benefiting from the OARC Scheme, around 400 buildings are estimated to remain at a residual risk of above floor flooding in 2060 (1000 in 2100) due to pluvial flooding from the stormwater drainage networks. Outside this area around 900 buildings in the study area are estimated to be at risk of above floor flooding in 2060 and 2100. Council is currently investigating solutions to stormwater flooding more generally in the catchment, as a potential additional investment to the OARC Scheme.

- Groundwater levels in the catchment are high and are expected to rise further with climate change. The effect of groundwater on buildings and other infrastructure and assets in the floodplain – both within the area benefiting from the OARC Scheme and elsewhere in the catchment – could make existing land use within these areas less viable in the future if not managed. Combined with vertical land movement, shallow groundwater is considered likely to pose a hazard to around 25% of the buildings benefiting from the OARC Scheme by 2060 and around 42% of buildings by 2100.

- Initial consideration suggests it may be possible to manage the effect of shallow groundwater on buildings within the area benefiting from the OARC Scheme – through pumped drainage for example. However, the effectiveness and costs of such measures are uncertain. Based on available information,

[1] Mapped hazard is the areas where the 0.5% AEP surface water depths from all sources of flooding exceeds 50 mm

[2] Mapped hazard is where the 85th percentile groundwater level exceeds ground levels

[3] Mapped hazard is where the liquefaction-induced ground settlement in a hypothetical M6 earthquake (0.5g peak ground acceleration) exceeds 50 mm

[4] Mapped hazard is modelled area of inundation in a 0.2% AEP distant source earthquake event

the capital costs of providing a pumped management system could range from around $130 Million to over $300 Million for groundwater levels in 2060. The additional pumping requirements to manage levels in 2100 could result in total costs of $260 Million to over $600 Million. Extending such a system to manage the effects of groundwater on buildings in the wider Stage 3 study area could increase these costs by a further 25% to 30%. These costs are comparable to the costs of the new flood defences and pumpstations. Operational costs are excluded from these values and have not been estimated. Such a solution could have other effects including changes in the salinity of groundwater which would need to be investigated further together with the feasibility of obtaining planning consent for this method of managing groundwater since it may not be provided for under current planning policies.

- Future earthquakes are likely to damage flood infrastructure, primarily through lateral spreading, potentially increasing the risk of overtopping or breaching. The proposed alignment of the new flood defences intersects areas of higher lateral spreading risk in some locations and there could be value in considering alternative alignments. The costs of repairs in such events should be considered alongside the initial capital investment. Damage to the stormwater network could take longer to remediate and be more costly, resulting in an increase in pluvial flood risk in the area benefiting from the OARC Scheme.

- Ground level changes from future earthquakes may not alter the extents of fluvial flooding but are considered likely to increase depths of that flooding and redistribute flooding according to spatial variations in settlement. Provided the new flood defences are repaired after an earthquake, the OARC Scheme will continue to provide protection from inundation and reduce the additional potential flood damage following ground movements. Earthquake-induced land settlement will exacerbate the groundwater hazards and increase the costs of managing this hazard.

- The area benefiting from the OARC Scheme is potentially at risk from coastal inundation when SLR exceeds around 1 m. There is uncertainty in how shoreline levels and dune morphology will evolve over the life of the scheme and therefore the risk posed from this source. Based on present day ground levels, future inundation pathways are localised and there appears to be scope to limit the risk through appropriate management of the shoreline.

- Large distant source tsunami would likely inundate the area benefiting from the OARC Scheme through overtopping of the shoreline at New Brighton and North New Brighton as well as through the Ihutai Avon Heathcote estuary and overtopping of the Ōtākaro Avon flood defences downstream of Anzac Drive. Such events are much less likely (0.04% to 0.2% AEP, for example) than the design standard of the OARC Scheme which is unlikely to provide protection from fluvial or tidal events of a similar probability.

- Tsunami have the potential to damage the bridges and the flood defences along the Ōtākaro Avon River which could lead to breaching and uncontrolled inundation. If they are not breached, there is potential for the new higher flood defences to impound tsunami inundation in the floodplain to a deeper depth and for longer than the existing stopbanks. The communities in the area benefiting from protection from river flooding should be made aware that the flood defences will not provide protection from tsunami and that civil defence managed evacuation remains the primary means for managing this hazard.

ⓘ Important note about this report

The sole purpose of this report and the associated services performed by Jacobs is to assess the interaction of multiple hazards with the proposed flood management infrastructure outlined in the Ōtākaro Avon River Corridor Regeneration Plan in accordance with the scope of services set out in the contract between Jacobs and Christchurch City Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from information sourced from the Client (if any) and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

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1. Background

1.1 Christchurch multi-hazards project

In early 2017, Christchurch City Council ('Council') commissioned the Christchurch multi-hazards project with the original intention of developing adaptive flood management plans for the downstream, tidally influenced areas of the city. This Land Drainage Recovery Programme project (LDRP97) aims to:

- better understand the full natural hazard picture
- review flood management investment in light of other hazards
- project how flood risk could change with climate and hazard events
- develop adaptive engineering and policy flood management options and pathways
- develop a sound technical basis for decision making by Council

Four study areas were defined based on the estimated fluvial and pluvial floodplains of the three major river catchments in Christchurch – the lower catchments of the Pūharakekenui Styx, Ōtākaro Avon and Ōpāwaho Heathcote Rivers ('Lower Styx River', 'Avon River' and 'Heathcote River' study areas respectively) – and the coastal margins of Ihutai Avon Heathcote Estuary and Sumner ('Southshore and Estuary' study area) as shown in Figure 1. The landward limit of each of these areas was set by Council as the estimated upstream limit of coastal multi-hazard risk, taken at that stage to be the limit of tidal influence on flood levels.

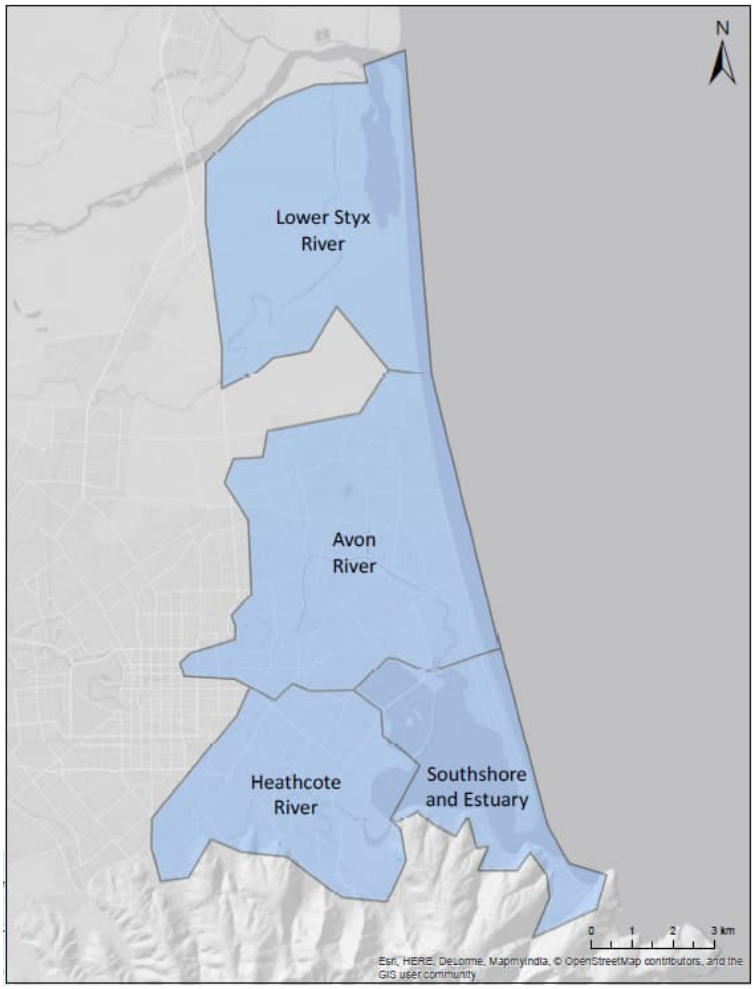


Figure 1. Boundaries of the original four multi-hazards project study areas.

The overall planned delivery structure of the project is shown in Figure 2. Stage 1 of the study collated and analysed the best available information on the individual hazards impacting the study areas. Within Stage 1, gaps were identified in the information required to produce robust adaptive flood management plans. Therefore, Council commissioned a series of further studies which were undertaken in Stage 2 of the project. Stage 3 of the project was expected to use that information and knowledge to identify a range of potential dynamic adaptive pathways for each of the four project study areas.

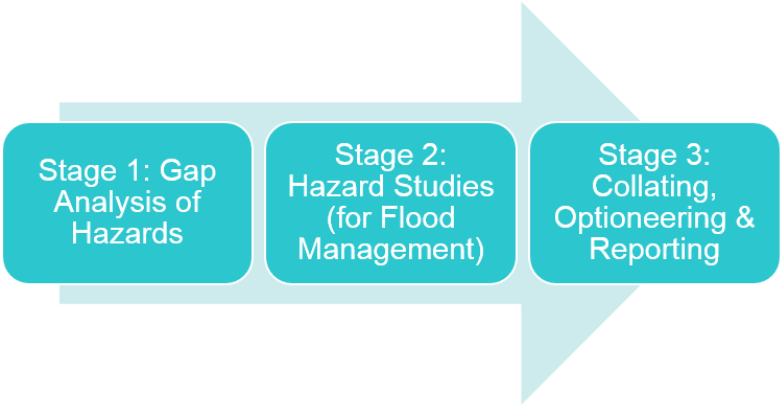


Figure 2. Christchurch multi-hazards project delivery structure.

1.2 Outcomes of previous stages

1.2.1 Stage 1 outcomes

Stage 1 of the project identified nine key gaps in the existing knowledge needed to assess multi-hazards in Christchurch as reported in the **Gap Analysis Report (IZ084400-NW-RP-0001) issued 11 July 2017**:

1. Coincidence of flooding, extreme weather, coastal erosion and coastal inundation
2. Council policy implementation options (managed retreat)
3. Detailed information for asset valuation
4. Definition of level of service for flooding
5. Effect of climate change and sediment budget change on coastal erosion and coastal inundation
6. Vertical land displacement due to liquefaction in a seismic event
7. Changes in groundwater levels with changes in the environment
8. Model simulations of tsunami with higher likelihoods of occurrence
9. Liquefaction risk to non-residential land.

Additional studies or investigations were commissioned by Council to address each of these knowledge gaps as part of Stage 2 of the project.

1.2.2 Stage 2 outcomes

The results of the Stage 2 studies were summarised in the **Stages 1 & 2 Summary Report (IZ084400-NW-RPT-003), prepared in September 2020**. These outputs are a key part of the data set used in Stage 3 of the project. The Stages 1 & 2 Summary Report also sets out a Delivery Plan for Stage 3 of the project.

In parallel with the multi-hazards project, Council are renewing the flood models of each of the city's river catchments. These models were expected to provide most of the data necessary for assessing flood risk in Stage 3 of the multi-hazards project. The first of these models, for the Ōtākaro Avon River catchment, was completed in mid-2022 and the **Multi-Hazards Stages 1 & 2 Summary Report was updated in November 2022** to include a summary of initial results from the model. No updates were made to other information relating to hazards that may have been developed independent of the project by Council or others since 2020.

As planned in 2020, the key questions which the delivery plan for Stage 3 of the project was designed to answer are:

> "Is the anticipated significant investment in flood management justified, given the other natural hazards to which the land is exposed?
>
> If so, what are the adaptive flood management pathways over time, and what are the significant residual risks?"

At that time, it was expected that Stage 3 would identify a range of potential Dynamic Adaptive Policy Pathways (DAPP) for each of the four project study areas shown in Figure 1, supported by relevant analysis and modelling. However, the project would not select a preferred pathway. That would be undertaken by Council in consultation with the communities, beyond the scope of the multi-hazards project. The DAPP process is a method used in climate change adaptation planning that seeks to deal with uncertainty and long timeframes. DAPP consists of a series of interlinked pathways that can be changed or switched between depending on the monitoring of indicators of change, such as frequency of flooding or rise in sea level.

The Stage 3 delivery plan prepared in Stage 2 of the project identified constraints to delivery of Stage 3 of the project. These included the need to develop flood models covering all four study areas for use in the study and the concurrent development of the Ōtākaro Avon River Corridor (OARC) Regeneration Plan and associated flood management infrastructure ('the OARC Scheme') in the Avon study area of the multi-hazards project.

Given the size of investment proposed in the OARC Scheme, the 2020 Stage 3 delivery plan prioritised the assessment of multi-hazards within the Ōtākaro Avon River study area and the development of the Avon flood model over the other study areas.

1.3 Scope of this report

This report documents the outcomes of Stage 3 of the multi-hazards project.

As described in Section 1.2.2 above, the scope of this stage of the project was refined in Stage 2 of the project to prioritise the detailed assessment of multi-hazards for the Ōtākaro Avon River study area and the development of the Avon flood model over the other three study areas.

Further revisions were made to the scope following completion of flood modelling for the Ōtākaro Avon River in 2022 to primarily assess the impacts of multi-hazards on the performance of the proposed Ōtākaro Avon River Corridor Regeneration Plan flood management scheme as set out in Sections 2.1 and 2.2 below. The OARC Scheme is planned to initially manage flooding over the medium term (i.e., 30 years) and the intention is to provide an adaptable system which is open to future decision making and so reduce the risk of maladaptation.

The Stage 3 assessment differs from a conventional DAPP process which would first consider a broad range of options to manage flood risk to identify preferred options for more detailed investigation. The revised Stage 3 scope primarily assesses the performance of a particular option – the Ōtākaro Avon River Corridor Scheme – under the range of multi-hazards considered in the wider project. However, the project scope was extended to consider and compare, at a high level, generic complementary options to the OARC Scheme

which could help inform the development of long term flood risk management measures under a future DAPP process.

Following completion of the Stage 3 assessment in the Avon study area, Council will decide how best to progress with assessing the remaining three catchments, either through similar studies or through the Council's Coastal Hazards Adaption Planning (CHAP) process. The DAPP process will be used as a tool within the CHAP programme to help establish adaptation pathways for Council infrastructure. The CHAP involves Council working with the community to develop adaptation plans for the coastal areas of the city. A 'Coastal Panel' of community representatives is responsible for making recommendations to Council for decision. The outcomes of the technical investigations completed under Stage 3 of the multi-hazards project will form one element of the information regarding hazards and the performance of possible adaptation options used to inform future CHAP processes. The geographic area of focus of subsequent CHAP processes is unlikely to reflect the full scope of this study. Specifically, it is unlikely to extend inland, instead focusing on coastal areas.

1.4 The Ōtākaro Avon River Corridor Regeneration Plan

The Ōtākaro Avon River Corridor (OARC) covers 602 hectares of land along the Ōtākaro Avon River from central Christchurch to Bexley in east Christchurch and lies wholly within the Avon study area of the multi-hazards project. More than 5,000 households previously lived in this area which experienced some of the worst effects of the Canterbury earthquake sequence of 2010-2011. Much of the land was classified 'Residential Red Zone' because it was so badly damaged that it was unlikely residential properties could be rebuilt on it in a timely or cost-effective manner.

The OARC is also highly susceptible to flood hazards. Figure 3 shows the location of the OARC and the known flood hazard areas identified in Stage 1 of the multi-hazards project. Much of the flood hazard in the Avon study area results from overflow of the Ōtākaro Avon River into its low-lying floodplain areas during high river flows or high tides in the Ihutai Avon-Heathcote Estuary.

A draft plan for the regeneration of the OARC – the Ōtākaro Avon River Corridor Regeneration Plan – was released in November 2018 and approved in August 2019. Developed by Regenerate Christchurch, the Regeneration Plan is intended to support the regeneration of the OARC, providing a vision and objectives for short, medium and long-term future land uses and opportunities in the area (Figure 4). The expected cost of implementing the entire plan is over $1 Billion.

Stormwater management areas, flood defences and transport corridors were considered to be critical to the achievement of the vision and foundational for regeneration of the Residential Red Zone. In terms of flood protection, a conceptual arrangement of continuous new set back flood defences along the Ōtākaro Avon River to replace the existing 'temporary' stopbanks (constructed following the 2010-2011 earthquakes) were included in the Regeneration Plan.

The new flood defences are intended to prevent flooding from the Ōtākaro Avon River, the primary source of flooding within the OARC, except in the most extreme of storm events (i.e., with less than a 1% chance of occurring each year). The flood defence design is intended to enable the flood defences to be raised higher over time, if required, to allow for the effects of climate change – sea level rise and increases in flood flows – on water levels in the river. New stormwater pumpstations are also proposed to improve the drainage of heavy rainfall from the areas protected from river flooding by the flood defences (Figure 5).

Council has since progressed a broad range of elements to progress the design of the regeneration plan, including:

- Investigative studies into values and issues associated with contaminated land, hydrogeology, existing services, geotechnical, archaeology, ecology and landscape
- Developing designs for and constructing community facility, parks and landscape land uses
- Working with community interests around planned works

- Planning asset relocations and removals (roading, three waters and utilities)
- Drafting resource consent applications for all Council elements (e.g., not the edge housing)
- Developing preferred hydraulic designs for the remaining proposed stormwater treatment facilities and establishing flood defence locations
- Designs for the stormwater treatment wetlands (Wainoni, Waitaki and Bexley) with some associated flood defence designs
- Construction of a new stopbank in the Waitaki Street area and stormwater treatment facilities

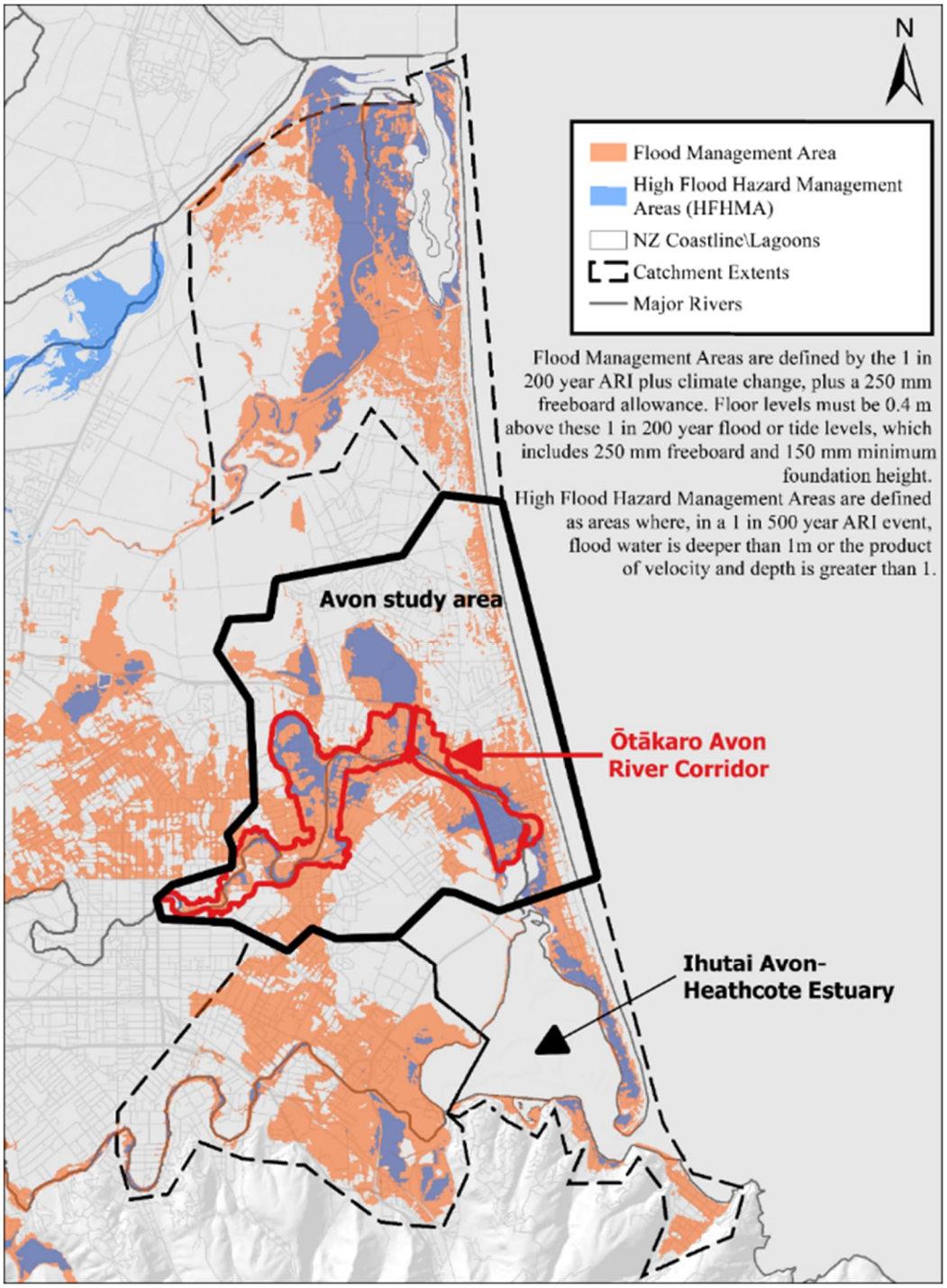


Figure 3. Map of known flood hazards developed in Stage 1 of the multi-hazards project and location of the Ōtākaro Avon River Corridor Regeneration Plan area in relation to the multi-hazards study areas.

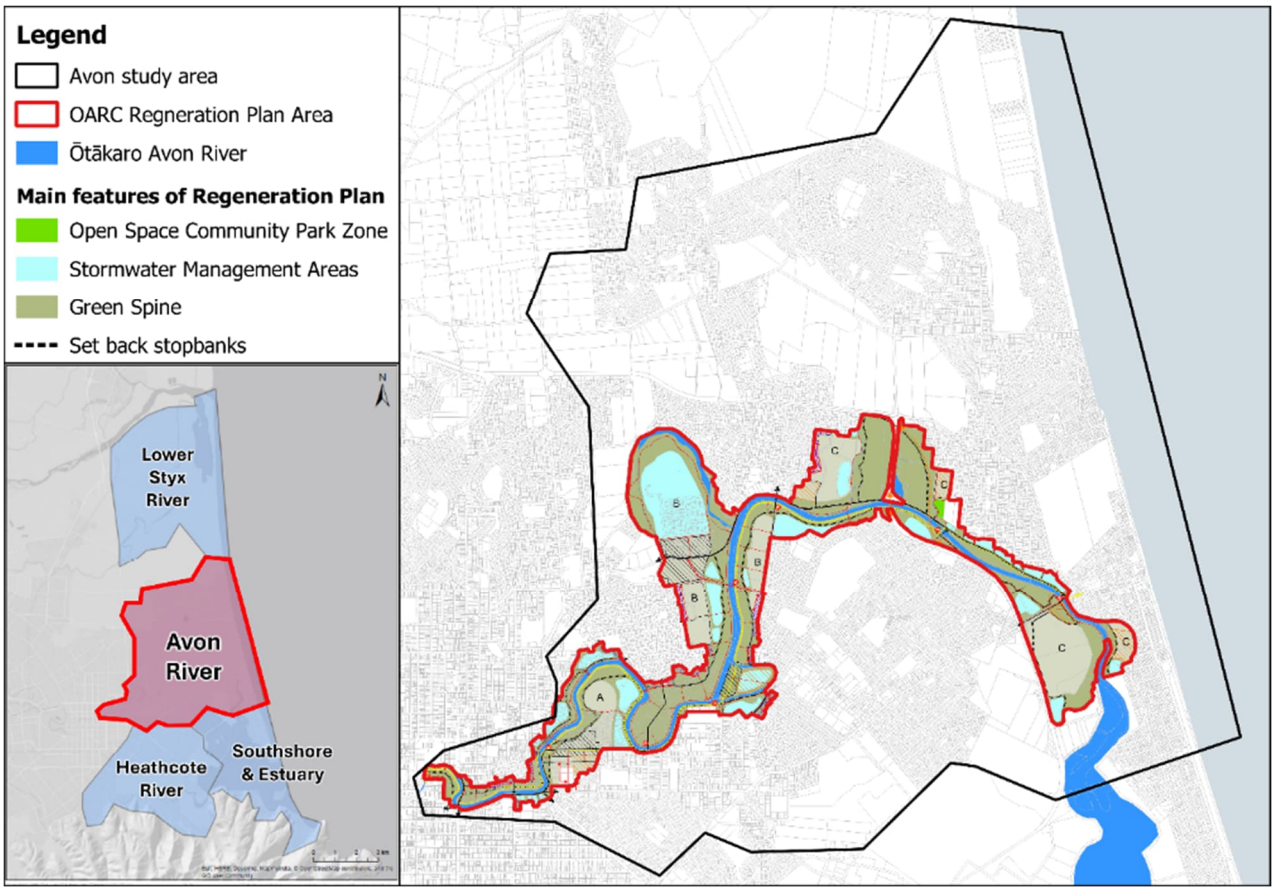


Figure 4. Indicative overview of main features of the Ōtākaro Avon River Corridor Regeneration Plan area.

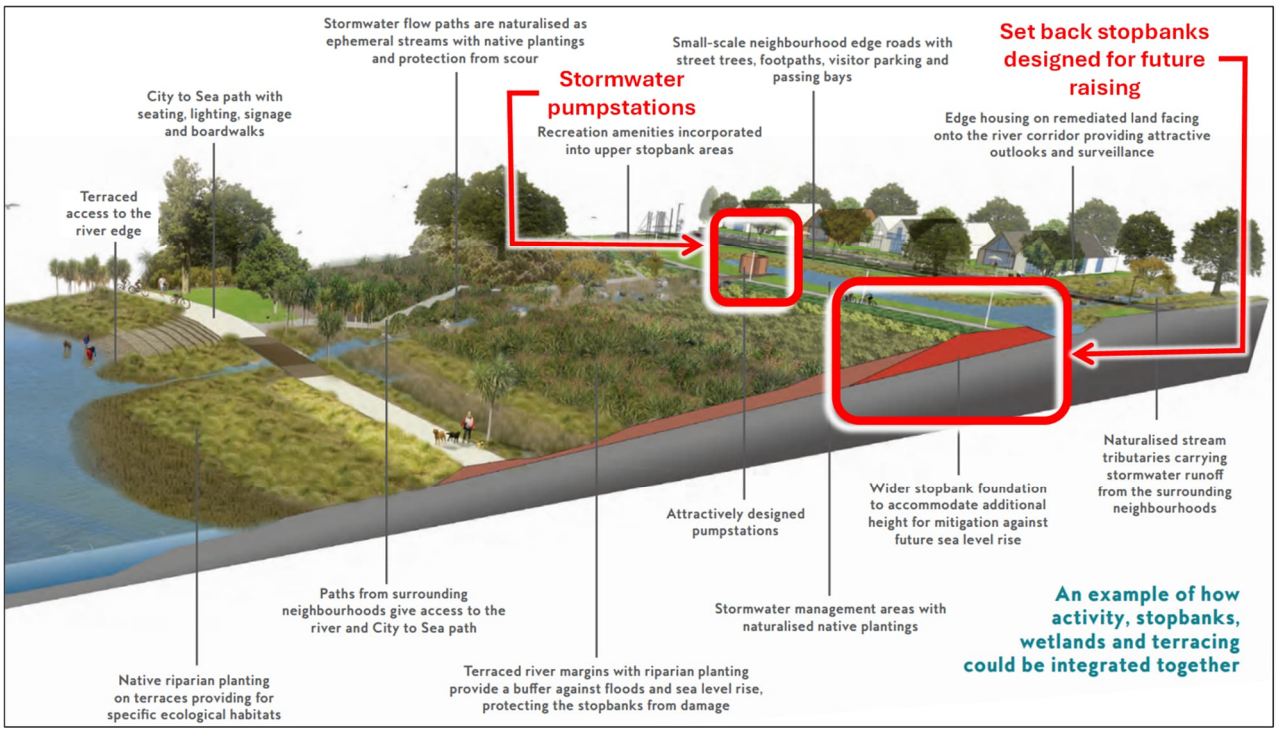


Figure 5. Indicative illustration of flood protection concept for the Ōtākaro Avon River Corridor Regeneration Plan and integrated land use features (Regenerate Christchurch, 2019).

2. Introduction to Stage 3

2.1 Development of scope for Stage 3

The scope of Stage 3 of the project was reviewed in mid-2022 following completion of the Avon flood model. Given the progress in planning the flood management infrastructure within the OARC Scheme, and the fact that models for the other study areas were still currently under development and not yet available for use, the scope of Stage 3 of the project was revised by Council to assess multi-hazards only for the Avon River study area, referred to as the 'project area' in this report. This would enable Council to better understand:

- the benefits of the proposed OARC Scheme
- how other hazards may impact land use in the areas protected from flooding by the OARC Scheme
- what other responses may be needed in this area

Figure 6 shows the boundary of the revised project area for Stage 3 of the project together with the overall extent of the Avon model.

The other three study areas – the Lower Styx River, Heathcote River, and Southshore and Estuary – will be considered separately by Council in the future.

In terms of study outcomes, the revised scope of Stage 3 of the project does not include identifying a range of management or intervention actions or pathways.

Instead, the aim is to:

- identify the specific issues that can lead to the new OARC Scheme flood management measures planned for the lower Ōtākaro Avon (consisting of new setback flood defences and new stormwater pump stations) becoming ineffective or requiring modification in the future because of other hazards
- identify where the OARC Scheme flood management measures may provide benefit in management of other hazards
- identify when the severity of these hazards may reach the point where a further management response or change in pathway may be needed

While intervention actions and pathways were not generally planned to be developed in Stage 3, the project did consider options and costs to apply an engineering solution to manage high groundwater levels. This hazard is recognised to potentially pose a significant risk to current land uses and is not currently addressed by the OARC Scheme. The project has outlined, at a high level, what an engineering management pathway of managing groundwater may entail in those areas which benefit from the proposed stormwater works. The options considered for managing groundwater are those identified for Council by Beca (2018)[5]. While it is noted that the approaches outlined by Beca (2018) are not the only groundwater management options available, and may not necessarily reflect the most effective options, the intent is to provide a high-level estimate of where groundwater may need to be managed and its cost. This will give Council an indication of the effort that may be required to manage groundwater rise, if needed. Council does not currently have any policy to mitigate groundwater risks. In identifying potential costs associated with managing groundwater in the future should not be interpreted as Council being willing or required to provide this infrastructure.

[5] Beca (2018) Earthquake Effects on Groundwater Levels - Case Study Options Report – Draft B Unpublished Client report for Christchurch City Council Dated 7th August 2018.

Methods for monitoring the sources of hazard to identify when a further response may be needed have also been considered.

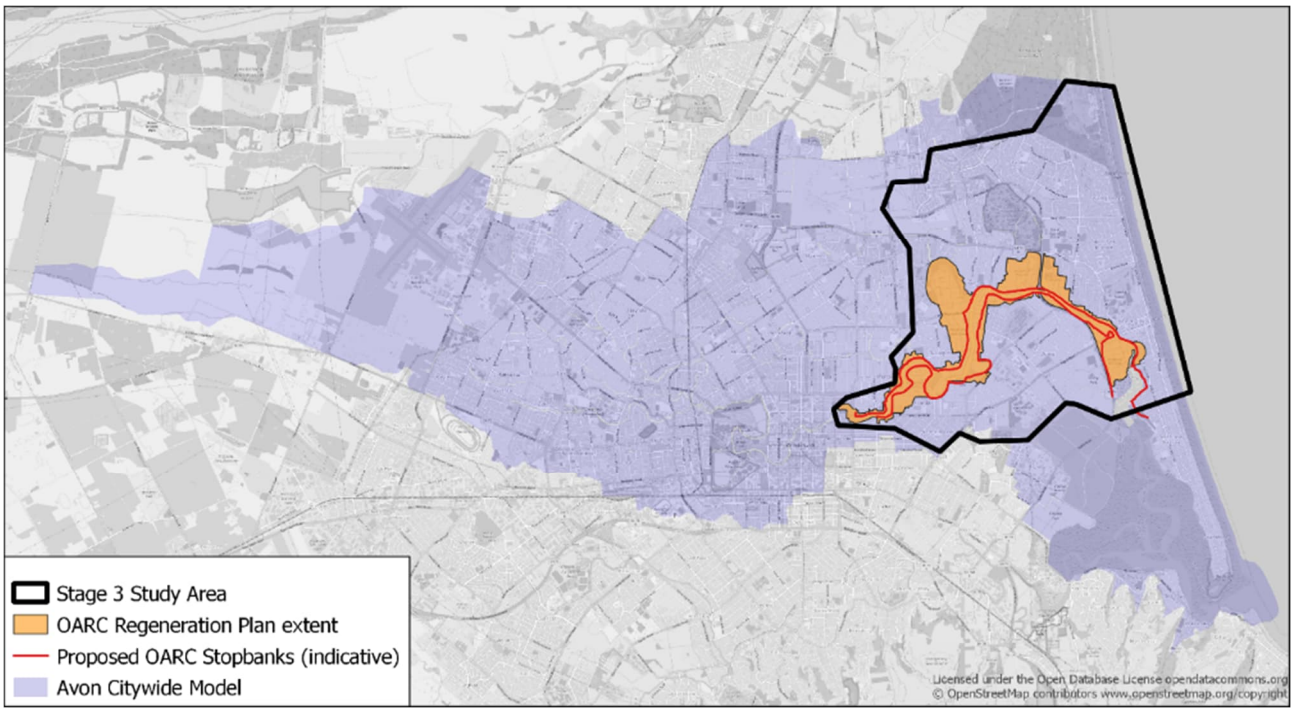


Figure 6. Boundary of the project area for Stage 3 of the multi-hazards project, extent of the Avon model and extent of the OARC Regeneration Plan area and proposed new flood defences.

2.2 Extension of scope

Following commencement of Stage 3 of the project, new data for ongoing vertical land movement (VLM) in Christchurch following the 2010-11 Canterbury Earthquake Sequence and the Valentine's Day and Kaikōura earthquakes in 2016 became available. The data indicate that the current, 'post-seismic', rates of VLM are up to an order of magnitude higher – around 10 mm per year in some places – than previous estimates of 'inter-seismic' rates of VLM from data collected between 2003 and 2011 (which exclude effects of local earthquakes). An additional task was included in the project scope to assess the potential impacts of this additional source of flood hazard (Appendix D of this report).

That task identified that there was reasonable confidence in the rates of ongoing VLM observed in the catchment which indicated that VLM was likely to impact on flooding and other hazards in the lower Ōtākaro Avon catchment. Therefore, the scope of Stage 3 of the project was extended to include additional model simulations incorporating projected changes in ground levels for selected future scenarios. The results of these simulations are reported together with the original simulations which had no allowance for VLM, which cover a wider range of future scenarios. This allows for a more detailed assessment of the effects of VLM on flooding as well as providing a more likely projection of future flood risk in the project area.

The revised scope of Stage 3 of the project provides for limited consideration of alternatives to the OARC Scheme concept for managing flood risk in the lower Ōtākaro Avon Catchment and of any future interventions that may be required to adapt to identified hazards over time. During Stage 3 an additional task was added to the project scope to consider and compare, at a high level, generic alternative options to the OARC Scheme. The results of that assessment are summarised in Section 8 with more details in Appendix I.

2.3 Approach to Stage 3

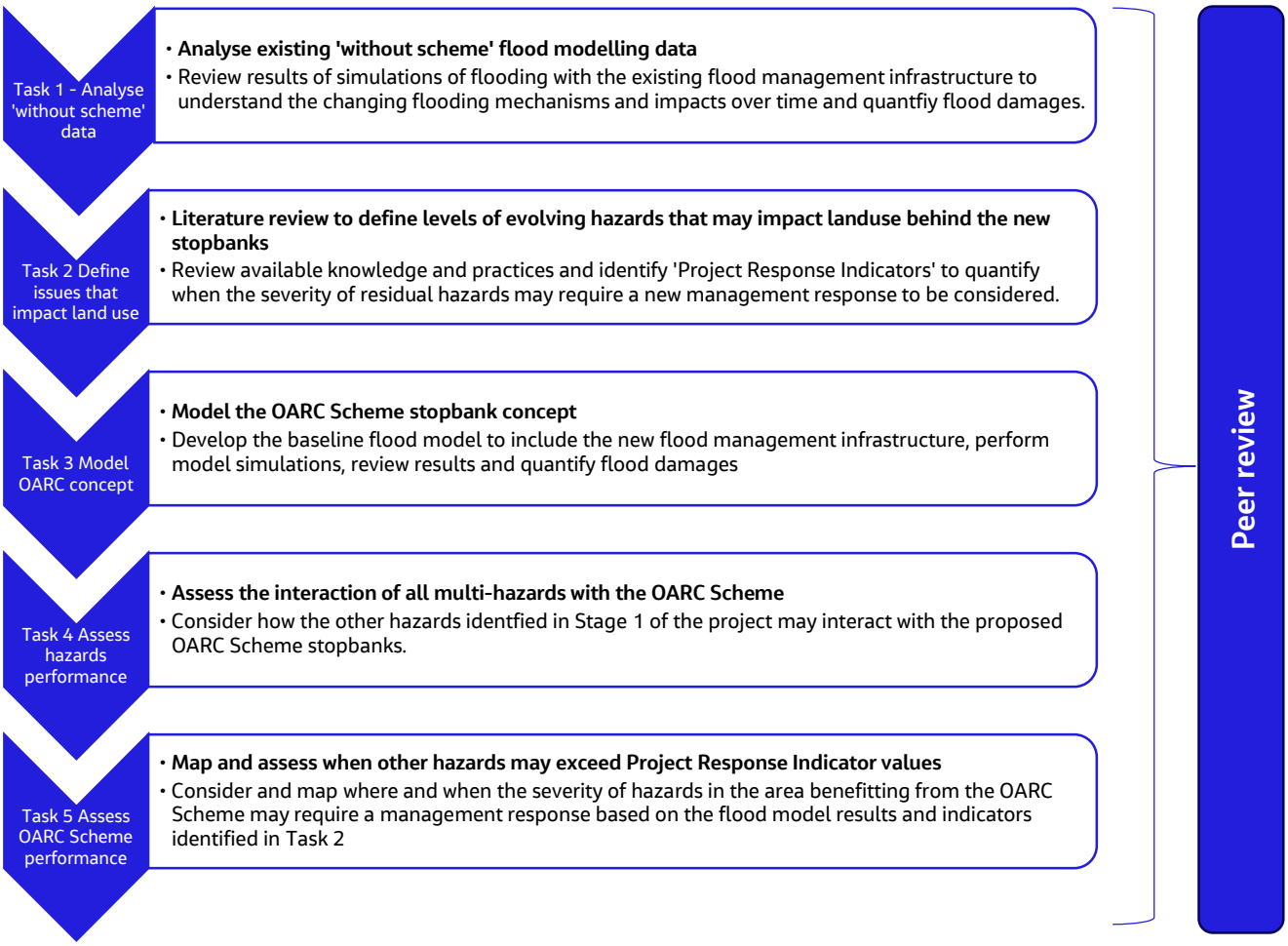
2.3.1 Objective

The objective of Stage 3 of the Multi-Hazards project is:

> "*to assess the performance, impacts and long term viability of the Ōtākaro Avon River Corridor Regeneration Area (the OARC) set back stopbanks along the Avon River*" with the view to identifying whether there are issues related to managing flooding and other hazards that would make existing land use untenable behind the flood defences, and when these issues may occur.

2.3.2 Method

Stage 3 undertook the following 5 tasks to answer this overall question. The scope and outcomes from these tasks, together with this Stage 3 report, were reviewed over the course of the project by the multi-hazards project Peer Review Panel appointed by Council.



2.3.3 Flood model

The primary means of assessing flood hazards and the performance of the OARC Scheme in Stage 3 of the project is the Avon model (Figure 6).

This model represents the current flood management infrastructure and was developed by GHD in parallel with Stage 2 of the multi-hazards project. The model includes the existing stopbanks along the lower Ōtākaro

Avon River. These stopbanks were reconstructed following the 2010-2011 earthquakes with a relatively short design life – 20 to 30 years – and are hence sometimes referred to as 'temporary' stopbanks. Given the short life of these stopbanks relative to some of the future scenarios modelled, a separate version of the model without the temporary stopbanks was also produced by GHD to represent a scenario where the temporary stopbanks are ineffective.

In Stage 3 of the project, Jacobs developed a third version of the model to include the flood management infrastructure proposed under the OARC Scheme – new flood defences and stormwater pump stations. In the OARC Scheme version of the model the existing stopbanks are removed and the new flood defences have been set at a sufficiently high level to contain all the flood events simulated so that the resulting river levels indicate the minimum required design crest levels to prevent flooding from the river.

Figure 7 shows the alignment of the new flood defences and the locations of new pumpstations adopted in the OARC Scheme version of the model for the purposes of the project, based on initial scheme layouts at the time of modelling. The arrangement of these elements is subject to change as design of the scheme progresses. However, the modelled effects of the flood defences on flooding in the project area is not considered to be sensitive to minor variations in their location.

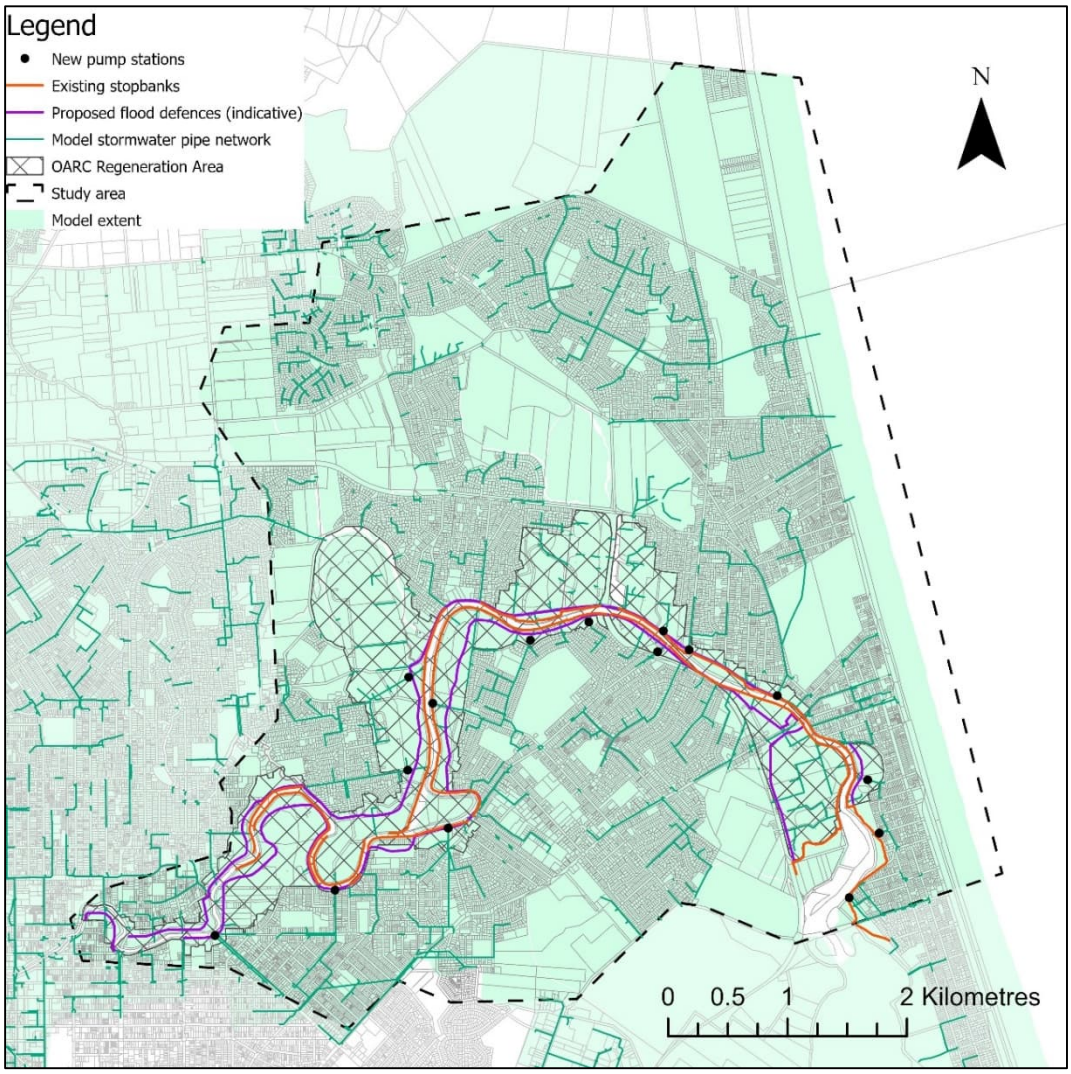


Figure 7. Location of new flood defences and pump stations adopted in the OARC Scheme version of the Avon model.

The Avon model was originally developed to simulate flooding with two alternative ground surfaces – surveyed ground levels in 2018 and a modified ground surface including allowances for modelled settlement

due to a hypothetical earthquake event. For the extended scope of modelling, to include the effects of VLM, additional versions of the ground surface and associated linkages to the flood model were developed for each future scenario of VLM, incorporating the corresponding projected changes in ground levels.

The main versions of the Avon model used in Stage 3 of the project are summarised in Table 1.

Table 1. Avon model versions.

Model version name	Configuration	Without VLM	With VLM
Existing stopbanks	Includes the existing 'temporary' stopbanks along the lower Ōtākaro Avon River and all other existing flood management infrastructure (stormwater network, drainage channels, pumpstations)	✓	✗
No stopbanks	No stopbanks along the lower Ōtākaro Avon River but other existing flood management infrastructure in place	✓	✓
OARC Scheme	Includes the planned new setback flood defences and stormwater pump stations along the lower Ōtākaro Avon River. Existing stopbanks removed but other existing flood management infrastructure in place	✓	✓

Detailed descriptions of the development of these versions of the model and the peer reviews undertaken of the models are provided in:

- Citywide Flood Modelling Model Status Report – Avon/Estuary – Rev 7 (GHD, July 2022)
- Task 3: Model Build Statement, LDRP97 Multi Hazards Stage 3, IZ084400-NW-MEM-0008 (Jacobs, May 2024) (included as Appendix H to this report).

The models appropriately simulate the flooding arising from the interaction of multiple, coincident, sources of flooding in modelled flood event in accordance with statistical analysis of past coincidence as follows:

- storm tide along the coastline
- fluvial flow in the Ōtākaro Avon River and its tributaries
- rainfall over the catchment
- groundwater levels (in terms of the effect on soil storage capacity and infiltration of rainfall).

Model boundary conditions for events with combined Annual Exceedance Probabilities (AEPs) of 10%, 2% and 0.5% have been developed for model simulations of flooding in a range of future climate scenarios, incorporating the projected effects of climate change on each source of flooding in the model.

Specific outputs from the studies undertaken in Stage 2 of the project and used in the model are:

- **Future land surface results (memo), Job No:1000273 (Tonkin + Taylor, 2019[6]).**

  The study developed a hypothetical surface of land settlement resulting from liquefaction through modelling an earthquake of similar shaking to the 2010-11 Canterbury Earthquake Sequence. This is used to develop the ground surface in the flood model for scenarios which include the effects of a 'shock' earthquake hazard on flooding.

[6] Tonkin + Taylor (2019) Future land surface model results memo, Unpublished client memo for Christchurch City Council dated 8th April 2019.

- **LDRP45: Impacts of earthquakes and sea level rise on shallow groundwater levels, Project number: C17054 (Aqualinc, 14 August 2020)**

  The study produced projected 50th percentile and 85th percentile groundwater level surfaces for present-day (~2020) mean sea level and for mean sea level rise values of 0.19 m, 0.4 m, 1 m, 1.88 m and 2.40 m. The surfaces are input to the flood model to define the available storage capacity for infiltration of rainfall above the water table in the computation of runoff.

  The groundwater surfaces have also been used directly in Stage 3 of the project to assess hazards from shallow groundwater (Section 5 of this report).

The scenarios simulated with the model are set out in Section 3 of this report. Summaries of the model results are provided in Section 4 of this report. Further details are provided in the memos in Appendix A and Appendix C of this report. The 2022 revision of the Multi-Hazards Stages 1 & 2 Summary Report[7] also provides further assessment of the 'existing stopbanks' and 'no stopbanks' model results.

2.3.4 Stage 3 outputs

The results of Tasks 1 to 3 of Stage 3 were delivered to Council as independent memos as the tasks were completed. The outcomes of these tasks are summarised in this report, and the detailed memos are provided as appendices to the report. Tasks 4 and 5 are presented in full in this report.

[7] IZ084400-NW-RPT-0003 Stages 1 & 2 Summary Report Draft A (Dated 15th Nov 2022)

2.4 Structure of this report

The contents of this report are structured as set out in Table 2.

Table 2. Structure of Stage 3 report.

Report Section	Task	Content
1 Background	-	Overview of the purpose and stages of the multi-hazards project
2 Introduction to Stage 3	-	Summarises the development of scope for Stage 3 of the project
3 Scenarios and for multi-hazards assessment	-	Defines the scenarios of future climate states, earthquake events and flood management infrastructure which we have used to assess flood hazard
4 Flood model results 4.1 Without OARC Scheme	Task 1	Summary of the results of assessment of flood hazards without the OARC Scheme and estimates of flood damages. *[Additional details provided in memo in Appendix A]*
4 Flood model results 4.2 With OARC Scheme	Task 3	Summary of the results of assessment of flood hazards with the OARC Scheme and estimates of flood damages. *[Additional details provided in memo in Appendix C]*
5 Project response indicators	Task 2	Summary of the principle and purpose of the project response indicators and the values identified. *[Full details provided in memo in Appendix B]*
6 Performance of OARC Scheme	Task 5	Identification of when and where responses to residual hazards may be needed, mapping of outputs and discussion of the scenarios. Consideration of how shock hazard (earthquake) affects the residual hazards. Approach to and cost of managing evolving groundwater hazards. Approaches to monitoring changing hazards or risks over time.
7 Interaction of OARC Scheme with other hazards	Task 4	Update of cascading hazards assessment from Stage 1 of project and assessment of interaction of multi-hazards (tsunami, earthquake, coastal hazards and vertical land movement) with the OARC Scheme. - Interaction of tsunami with the OARC Scheme - Performance of OARC Scheme for managing tsunami hazard - Interaction of future earthquake with the OARC Scheme – impact on the scheme and change in flood mechanisms and scheme performance - Management of coastal flooding change in flooding over time - Options to reduce cascading flood hazard risk from other hazards
8 Assessment of alternative options	-	High level screening assessment of a short list of generic alternative options to flood risk management in the project area. Simple assessment of potential flood management benefits of alternative options to allow Council to consider whether any alternatives to the OARC Scheme would merit further investigation.
9 Conclusions	-	Summary of key findings of Stage 3 of the multi-hazards project

2.5 Understanding the scope, purpose and limitations of this report

This report documents the outcomes of multiple technical investigations to explore how hazards in the lower Ōtākaro Avon River catchment may change over a period of more than 100 years into the future and how the OARC Scheme will perform in managing flood hazards. There is uncertainty in how the sources of hazard will change over such a period. For example, how the climate will change and how this will affect rainfall, sea level and groundwater levels, or when an earthquake may occur and how this would affect flooding. Land use may also change, driven by factors other than natural hazards, leading to changes in the consequences of flooding and other hazards in the future.

Rather than try to predict the future consequences of multi-hazards in the project area we therefore consider a set of plausible possible scenarios of future conditions in the project area, informed by current knowledge and, where available, recommended allowances for changes in the sources of hazard. We then investigate what the resulting hazards would be in these scenarios to provide an assessment of what *may* happen in the future and the implications for the OARC Scheme under these scenarios. We identify the simplifications and uncertainties inherent in these assessments and how these may affect the outcomes, and these limitations should be kept in mind when interpreting the results.

We are not assessing whether the OARC Scheme is the 'best' way to manage flood risk in the lower Ōtākaro Avon River catchment. Council is already developing the OARC Scheme, which consists of new setback flood defences, planned new stormwater pump stations and stormwater treatment and detention wetlands, as envisaged in the OARC Regeneration Plan. This project is assessing the performance of that OARC Scheme in a multi-hazards context. The project seeks to *identify the specific issues that can lead to the new flood management measures (proposed for the lower Ōtākaro Avon) becoming ineffective in the future because of other hazards*.

We have not considered alternative ways to manage flood risk in detail. Originally Stage 3 of the multi-hazards project was intended to consider all options to manage changing flood risk over time and incorporate them into a set of potential pathways using a conventional DAPP approach. The revised scope primarily provides a detailed assessment of a single option, the OARC Scheme, which includes adaptive elements such as provision for future raising of flood defence crest levels. During the project Council however requested a high-level assessment of complementary alternative options to manage flood risk – similar to that undertaken in a conventional DAPP but in less detail – in response to recommendations from the Peer Review Panel. The assessment considers a short list of alternative options, estimates potential costs, damages and reduction in damages for these options and qualitatively compares a limited set of other factors such as environmental impacts. It seeks only to identify if, in comparison to the OARC Scheme, any of the alternative options would be worthy of additional consideration by Council. This assessment is included in Section 8 of this Stage 3 report. In addition, a full DAPP process has not been advanced within this project as this could be inconsistent with Council's wider adaptation planning work through their Coastal Hazards Adaptation Planning Programme (CHAP).

Work is future focused and informed by assessment of specific scenarios that are not predictions of possible futures. We are looking well into the future to identify what *may* happen to hazards and what *may* happen once the OARC Scheme is in place. The outcomes should not be taken as a prediction of what *will* happen. In Stage 1 and Stage 2 of the multi-hazards project we developed a series of scenarios of *climate change (sea level rise and increasing rainfall intensity) and earthquake events* at six points of time in the future to test the performance of flood management measures. These scenarios form a set of *pathways* through time over which we have assessed the performance of existing or future flood management infrastructure in Stage 3.

We test the infrastructure using storm tide and rainfall event of three specific likelihoods of occurrence. The events range from smaller events which are more likely to occur, to larger events which will rarely occur. We describe the likelihood that these events will occur through their Annual Exceedance Probability (AEP), a standard statistical measurement commonly used to define the chance

of an event occurring in any given year. The events we have chosen (AEPs of 10%, 2% and 0.5%) are not the only floods that can occur but allow us to provide an understanding of the effects of events of different magnitudes and likelihoods over a range of events that might occur. Events greater than a 0.5% AEP event could occur at any time.

The current magnitudes of events of these likelihoods are estimated from historical records of tidal levels and rainfall depths. These records will not necessarily have captured more extreme events, particularly where the period of records is relatively short (much less than a century, for example). This may mean that the current magnitudes events of the selected likelihoods are underestimated – i.e., they may be more likely to occur than the stated AEP. Future climate change is expected to increase the magnitudes of events of a given probability. We have allowed for the anticipated effects of climate change on mean sea level and on the intensity of rainfall in extreme events using values of sea level rise, nominally from 2020, and the corresponding change in mean annual temperature, selected from those recommended by New Zealand planning guidance at the time the assessment scenarios were defined in Stage 2 of the project (Coastal Hazards and Climate Change guidance, 2017[8] and Climate Change Projections for New Zealand, 2018[9]). The timing of these climatic states is uncertain and depends on future global rates of emissions and how these affect sea level and temperature in New Zealand. In our assessments we primarily refer to these future states in terms of the values of sea level rise. Where the timing of the climate state is relevant, we use the indicative dates for these values under the RCP8.5 H+ emissions scenario in the 2017 and 2018 guidance. These dates are similar to those under the latest New Zealand climate change guidance[10] for scenario SSP5-8.5H+. These future climate states could occur earlier or later than the dates indicated in our assessment depending on the actual rates of emissions.

The number of scenarios we have developed for assessment has been purposefully limited. We have developed a set of scenarios for this project which are appropriate for understanding the performance of the OARC Scheme over a range of event magnitudes in an uncertain future. Various factors were considered when defining the scenarios, including the purpose of the study, availability of data, uncertainty in data, complexity of analysis and modelling and the time required to undertake the assessments. Together these factors limit the number of scenarios which can be assessed to provide results within a timeframe that allows them to usefully inform the development of the OARC Scheme.

Uncertainty in the data we have used and in our methods of assessment may influence the outcomes. In a study such as this, which uses a variety of analytical models, uncertainties in input data and the simplifications which are made in the analyses may affect the outcomes of the assessment. Not all data are of a similar level of development or confidence. The analytical methods adopted represent a balance between complexity, time and value in providing outputs to an appropriate level of confidence. We identify sources of data and where the potential uncertainties and limitations could be significant for the outcomes of the project so that Council can consider future work to improve certainty if needed.

Underlying data used in the assessment is fixed to a point in time, and may subsequently change. This study has been undertaken over a period of years, and various data sources have been used that have evolved over that period. Generally, data and inputs were fixed at a point in time to allow the project to progress. An example is the council building and floor level dataset. This dataset is used in both FloodFX analysis and the project response indicator assessment work within the study. The dataset represents buildings and floor levels from 2016. It is acknowledged that changes will have occurred since that time that may modify the outcomes slightly. Primarily this would be to remove houses at risk of overfloor flooding as any new builds would have floor levels elevated above the 0.5% AEP flood level as required by the District Plan. In addition, in the Knights Drain catchment Council has purchased 13

[8] MfE (2017) Ministry for the Environment 2017. Coastal Hazards and Climate Change. Guidance for Local Government. Wellington MfE

[9] MfE (2018) Ministry for the Environment 2018. Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment, 2nd Edition. Wellington: MfE.

[10] Ministry for the Environment. 2024. Coastal hazards and climate change guidance. Wellington: MfE

properties at risk of flooding to facilitate building a treatment wetland. Given the overall numbers of properties at risk of overfloor flooding, small changes to buildings and datasets are not expected to significantly change the overall scale of the outcomes of our assessment. Results at an individual property level should not be interpreted as being exact.

We recognise that land use and development may change in the study area over the future horizons considered in the project. However, we consider that current (and future) land use planning controls should avoid increasing the amount of development at risk of flooding through zoning and floor level controls for example, and this provides some basis for using the present-day development state in future scenarios, at least for flood hazard. We note that less control over development currently exists for some other hazards such as shallow groundwater.

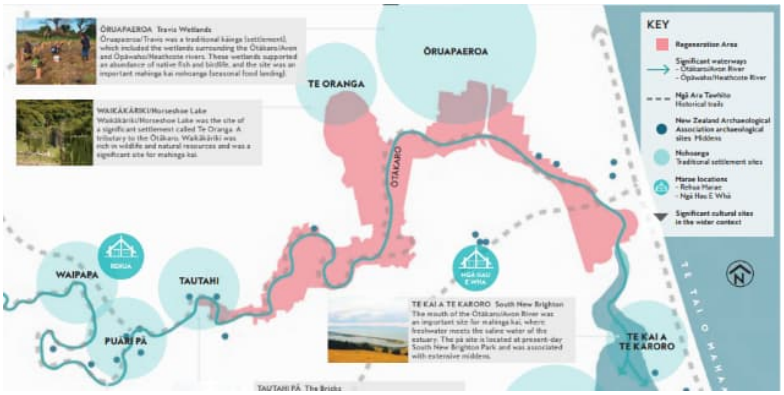
While the project seeks to *identify when the severity of hazards with the OARC Scheme in place may reach a point where a further management response or change in planning pathway may be needed*, it does not generally identify what these other responses or interventions may be. The revised scope of Stage 3 of the multi-hazards excludes development of DAPP and does not seek to identify what else Council could do to respond to these hazards. It seeks to identify where and when other management responses or interventions may be needed. This will provide part of the supporting knowledge for Council to co-develop DAPP with the community as part of Council's CHAP. An exception is that the project includes a high-level assessment to identify where hazards from high groundwater levels mean that these may need to be managed and the indicative costs of doing this through pumping. This provides Council with an order of magnitude estimate of the costs of such an approach if a solution were needed and if this approach were selected, recognising that other approaches could be chosen if needed. At present Council does not have a policy or a level of service for providing control of groundwater. As such inclusion of these findings should not be interpreted as Council planning on or needing to manage groundwater.

Future work is envisaged after this project. The OARC Scheme is a long-term programme of works, and this project provides an important and early part of the knowledge to support the design of these works. Understanding of the hazards we have assessed will continue to develop over the period of development of the OARC Scheme. Council's CHAP will enable the community to help develop a preferred approach to adapting to future hazards. There are therefore opportunities for Council to further refine the outcomes of this work in the future and address limitations, assumptions and uncertainties where necessary. This report includes recommendations for further work.

2.6 Terms and abbreviations used in this report

Table 3 defines the meaning of key terms as they are used in Stage 3 of the project and Table 4 defines abbreviations used in this report.

Table 3. Definition of key terms as used in Stage 3 of the project.

Term	Meaning within Stage 3 of Multi-Hazards project
Ōtākaro Avon River Corridor (OARC) Regeneration Plan area	The Ōtākaro Avon River Corridor (OARC) Regeneration Plan area is the 602 hectare area identified for regenerative development as specified in the Ōtākaro Avon River Corridor Regeneration Plan (Regenerate Christchurch, 2019)[11]. The map below shows the OARC Regeneration Area as shown in the OARC Regeneration Plan. 
OARC Scheme	The flood risk management infrastructure proposed under the OARC Regeneration Plan which has been included within the 'OARC Scheme' flood model, consisting of set-back flood defences along both banks of the Ōtākaro Avon River and new stormwater pump stations. Modifications to existing stormwater outlets and pipes that pass under the new flood defence alignment (sealed maintenance holes and non-return valves) are also included in the model. The model does not include a representation of any detention basins or stormwater treatment basins or any changes to the stormwater networks upstream of the proposed flood defences or new pump stations or other measures which may be needed to address localised flooding issues from pluvial sources. The OARC flood management scheme includes work outside of the OARC in order to provide a complete system, such that flood defences will not be outflanked as far downstream as Bridge Street.
Dynamic Adaptive Policy Pathways (DAPP)	Dynamic Adaptive Policy Pathways (DAPP) is a method used in climate change adaptation planning that seeks to deal with uncertainty and long timeframes. DAPP allows for a series of interlinked pathways that can be changed or switched between depending on the monitoring of indicators of change, such as frequency of flooding or rise in sea level. DAPP uses 'signals' to alert the decision maker of a pending 'trigger' to make a change before an 'adaptation threshold' is reached. *[Note that this stage of the multi-hazards project does not develop DAPP because multiple solutions to address flood risk are not considered. Instead, the performance of a single pathway (the OARC Scheme) in managing flood risk is*

[11] Regenerate Christchurch. (2019). Ōtākaro Avon River Corridor Regeneration Plan. https://dpmc.govt.nz/sites/default/files/201908/Otakaro%20Avon%20River%20Corridor%20Regeneration%20PlanReducedSize.pdf

Term	Meaning within Stage 3 of Multi-Hazards project
	assessed, including how it interacts with other hazards. Alternative, project-specific terminology is used to differentiate this approach to a DAPP process.]
Adaptation Threshold (AT)	Adaptation Threshold is a concept used within DAPP projects, as set out in Stephens et al (2018), and defined as: "an adaptation threshold occurs when the present pathway is no longer effective in meeting objectives and a new action or pathway is necessary. Adaptation thresholds are associated with performance of the system of concern, for example storm-tide flooding becoming too frequent for a viable community to function or, when beach nourishment or a sea wall is no longer effective due to technical, economic or social limitations." Adaptation thresholds can be related to extreme events, such as storm-tide flooding, or to gradual changes, such as sea-level rise. Adaptation thresholds can be identified through community engagement, modelling, or risk assessments.
Trigger	A decision-point that initiates the process to change the adaption pathway before an Adaption Threshold is reached.
Signal	A signal is an alert of an impending Trigger being reached.
Project Response Indicator (PRI)	Project Response Indicators (PRIs) have been developed specifically for Stage 3 of the multi-hazards project and are quantitative measures of flood hazard where the risk from a hazard may require a change in pathway. The PRIs (such as probability of flooding to a particular depth or annual average damage to an asset) can be compared to the outputs of flood models and provide an indication of when the magnitude of the hazard may have reached a level to require a response. The PRIs are developed solely as tool for this project and do not necessarily reflect Council policy or community risk tolerance. *[Note that this term is used as an alternative to 'adaptation threshold' to reflect the fact that whilst the technical principles are similar, the purpose of application differs, the derivation of the indicator is technical not community led and the use of the indicators in this project and to the modelled hazard data is distinguished from that of a detailed DAPP process.]*
Stopbanks down scenario	A modelled scenario without the present day stopbanks in place and without the proposed OARC stopbanks. It is intended to simulate a future scenario in which present day stopbanks are not maintained and either removed, breached or otherwise lose all functionality.
Direct damage	The financial damage caused to a building and its contents by flooding in terms of the cost of repairs and / or replacement.
Damage Ratio (DR)	The cost of flood damage to a building relative to the value of the building, as defined in the 'RiskScape' flood fragility methodology (NIWA, 2010)[12].
Damage State (DS)	Describes the level of flood damage to a building through classifying Damage Ratio into one of five categories ranging from DS0 (insignificant damage) to DS4 (collapse—structural integrity fails), as defined in the 'RiskScape' flood fragility methodology (NIWA, 2010).

[12] NIWA (2010), RiskScape: Flood fragility methodology. NIWA Technical Report WLG2010-45. Prepared for New Zealand Climate Change Research Institute Victoria University of Wellington. August 2010.

Term	Meaning within Stage 3 of Multi-Hazards project
Hazard Vulnerability Classification	A set of six categories of flood hazard defined by flood depth and velocity which characterise the vulnerability of the community when interacting with floodwaters as set out in Book 6 of the Australian Rainfall and Runoff Guidelines[13].
FloodFX	FloodFX is a council tool developed by Jacobs that quantifies the numbers of buildings exposed to flooding and the financial damages that may occur with that flooding. This tool uses flood modelling results as inputs to count properties potentially exposed to flooding in the modelled epochs and develop damages data and damages metrics over time.

Table 4. Abbreviations used in this report.

Abbreviation	Definition
AAD	Annual Average Damage
AEP	Annual Exceedance Probability
AR&R	Australian Rainfall and Runoff Guidelines
ARP	Average Return Period
AT	Adaptation Threshold
CCC	Christchurch City Council
CDD	Christchurch Drainage Datum
CES	Canterbury Earthquake Sequence 2010/2011
CPT	Cone Penetration Test
CHA	Coastal Hazard Assessment (Council's 2021 assessment of erosion and inundation hazards)
CHAP	Christchurch City Council's Coastal Hazards Adaption Planning Programme
CRPS	Canterbury Regional Policy Statement
DAPP	Dynamic Adaptive Policy Pathways
DR	Damage Ratio
DS	Damage State
FPF	Fluvial and Pluvial Flooding
LiDAR	Light Detection and Ranging
LDRP45	Land Drainage Recovery Project 45 (Rutter, 2020[14])
MBIE	Ministry of Business Innovation and Employment
mbgl	Meters Below Ground Level
MHWS	Mean High Water Springs
NIWA	National Institute of Water and Atmospheric Research (now Earth Sciences New Zealand)
NSHM	National Seismic Hazard Model

[13] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

[14] Rutter, H (2020). LDRP45: Impacts of Earthquakes and Sea Level Rise on Shallow Groundwater Levels. Christchurch City Council. Aqualinc Research Limited.

Abbreviation	Definition
NZBC	New Zealand Building Code
NZGS	New Zealand Geotechnical Society
NZVD	New Zealand Vertical Datum
OARC	Ōtākaro Avon River Corridor
PGA	Peak Ground Acceleration
PRI	Project Response Indicator
RSLR	Relative Sea Level Rise
RMA	Resource Management Act
SLR	Sea Level Rise
SLS	Serviceability Limit State
UI	Urban Intelligence
ULS	Ultimate Limit State
VLM	Vertical Land Movement

3. Scenarios for multi-hazards assessment

In Stage 1 and Stage 2 of the multi-hazards project we developed a set of future scenarios for assessing flood hazard in the project area. The scenarios include the main co-located hazards in the project area, informed by the hazard co-location assessment in Stage 1 and Stage 2 of the project summarised in Figure 8. The scenarios were defined at discrete points of time in the future and allow for the effects of both continuous ongoing climate change and of 'shock' earthquake events on hazard.

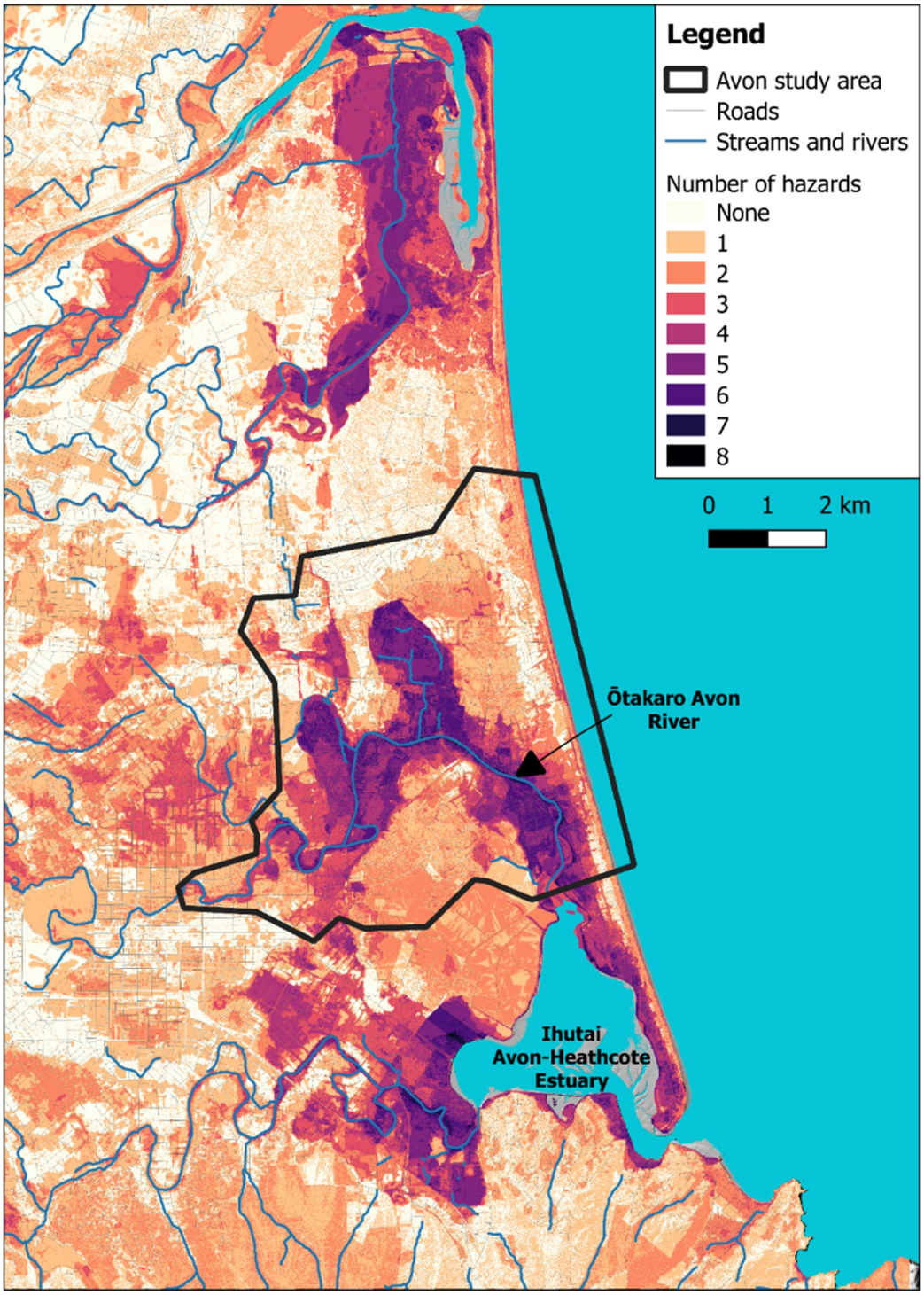


Figure 8. Summary of co-location of hazards identified in Stages 1 and 2 of the multi-hazards project.

In Stage 3 we assess the flood hazard in each of these scenarios for both the existing flood management infrastructure and the OARC Scheme. We also consider the performance of the infrastructure over a set of potential alternative hazard pathways in time through linking successive scenarios, as shown in Figure 9. Although these are shown as continuous pathways, in practice hazards may change at different rates between scenarios at tipping points such as when overtopping of flood defences starts to occur.

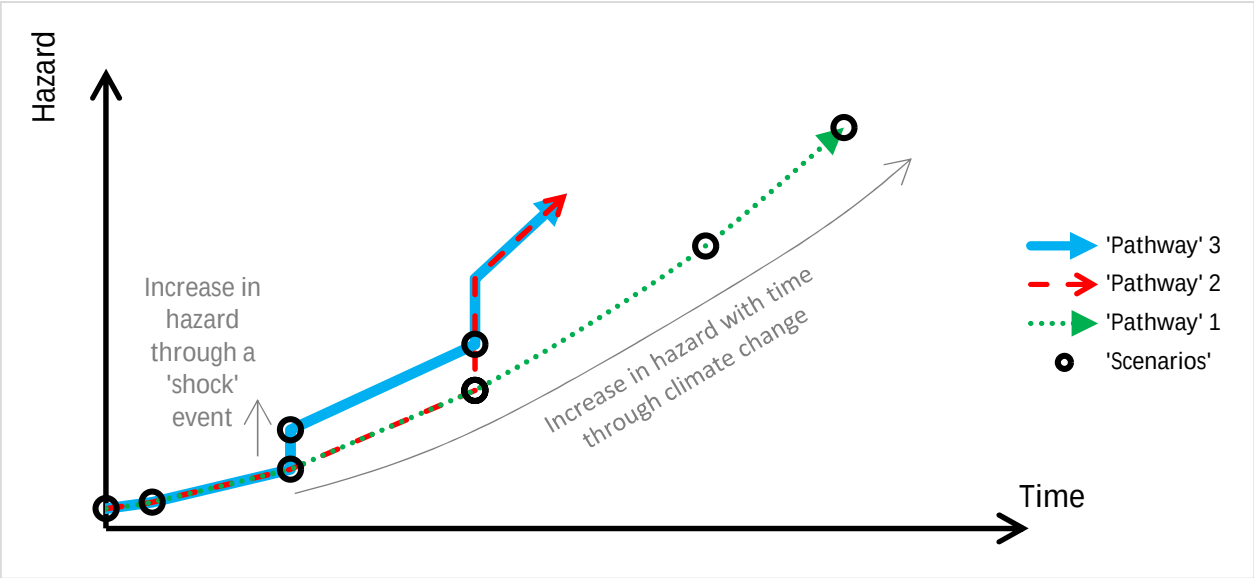


Figure 9. Diagrammatic illustration of increasing flood hazard with time in example future scenarios developed for the multi-hazards project and how these scenarios are combined to form alternative hazard pathways.

3.1 Scenarios

The scenarios developed in Stage 2 of the project are composed of plausible future climate states, informed by relevant planning policies, combined with hypothetical, liquefaction-induced settlement of ground levels from a seismic event, and alternative arrangements of flood protection infrastructure. The scenarios were developed to address the primary aims of the project: to consider how flood risk could change with climate and hazard events; and, to review flood management investment under multiple hazards.

In Stage 3 of the project, additional scenarios and pathways were developed which include ground level change scenarios in the project area due to ongoing VLM as well as climate change and settlement from a seismic event.

3.1.1 Future climate states

The future climate states allow for the anticipated effects of climate change on mean sea level (and the consequent effect on groundwater levels) and on the intensity of rainfall in extreme events (estimated from MfE climate change induced future temperature scenarios) at six future points in time up to approximately 2150. They are defined by a value of sea level rise, nominally from 2020, and a corresponding change in mean annual temperature as detailed in Table 5. The values were selected from those recommended by New Zealand planning guidance at the time of Stage 2 of the project[15,16] and indicative future dates for each state were specified based on the guidance. Table 5 indicates the approximate earliest date each selected climate

[15] Ministry for the Environment 2017. Coastal Hazards and Climate Change Guidance for Local Government. Wellington: Ministry for the Environment.

[16] Ministry for the Environment 2018. Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment, 2nd Edition. Wellington: Ministry for the Environment.

state could occur, based on sea level rise projections under New Zealand climate change scenario RCP8.5 H+, to help inform the required timing for flood protection development, and for the purposes of economic analysis of flood damages. It should be noted that the sea level rise values we have adopted refer to the eustatic[17] sea level rise rather than relative sea level rise, which is often used to allow for the effects of VLM on coastal flooding. In this project we assessed the effect of VLM explicitly, by changing the ground levels in the model for selected future scenarios. The future tidal boundary water levels in the model therefore only include the eustatic sea level rise.

Table 5. Future climate states in the multi-hazards scenarios.

Sea level rise from 2020	Increase in mean temperature from 2020 (used to estimate increase in rainfall depth)	Indicative earliest date (Stage 2 of the project in relation to emissions scenario RCP8.5 H+)	Indicative earliest date (in relation to emissions scenario SSP5-8.5H+ in 2024 guidance)
0 m	0 °C	2020	2020
0.19 m	0.3 °C	2030	2040 to 2050
0.45 m	1.4 °C	2060	2060 to 2070
1.06 m	2.8 °C	2100	2100 to 2110
1.88 m	4.6 °C	2150	2140 to 2150
2.4 m	5.0 °C	>2150	n/a

The actual timing of these climatic states is uncertain and depends on future global rates of emissions and how these affect sea level and temperature locally in New Zealand. Projections of sea level rise in New Zealand and guidance on recommended allowances for planning purposes have been updated[18,19] since the multi-hazards scenarios were developed in Stage 2 of the project. We have reviewed the latest guidance on sea level rise[6] (Appendix D of this report) and the equivalent dates for the closest corresponding emission scenario (SSP5-8.5H+) are included in Table 5 for comparison. The timing of the climate states under the current guidance is generally very similar, within a decade, to that specified in Stage 2 of the project except for the 0.19 m sea level rise state which could now be expected to occur between one to two decades later.

In our assessments we primarily refer to these climate states in terms of the values of sea level rise (SLR) adopted rather than a specific date. Where the timing of the climate state is relevant, such as when estimating present value flood damages, we use the Stage 2 (RCP8.5 H+) indicative earliest dates for consistency with the previous stages of the project, given the small differences in timing under the current guidance relative to the overall uncertainty in timing. If emissions were to follow a lesser scenario, these future climate states could occur several decades later than the dates adopted in our assessment.

3.1.2 Earthquake events

Liquefaction-induced, permanent, settlement of ground levels over the project area resulting from an earthquake 'shock' event have been combined with two of the future climate states – 0.45 m SLR (~2060) and 1.06 m SLR (~2100) – to assess the combined effects of these sources of hazard. The change in ground levels considered in these scenarios were developed in Stage 2 of the project through modelling of a magnitude 6 earthquake causing 0.5g peak ground acceleration (Tonkin + Taylor, 2019)[20].

Figure 10 illustrates the modelled change in in ground levels through liquefaction-induced settlement which we have considered in these scenarios. Within the project area, the modelled liquefaction-induced land

[17] Eustatic refers to changes in global sea level caused by variations in the volume of water in the oceans or changes in the shape of ocean basins.

[18] Ministry for the Environment. 2022. Interim guidance on the use of new sea-level rise projections. Wellington: MfE.

[19] Ministry for the Environment. 2024. Coastal hazards and climate change guidance. Wellington: MfE.

[20] Tonkin + Taylor (2019) Future land surface model results memo, Unpublished client memo for Christchurch City Council dated 8th April 2019.

settlement ranges from -300 mm to -9 mm with a median value of -118 mm. The changes in ground level are relatively variable over the project area with an interquartile range of -160 mm to -80 mm.

The model simulation encompasses the strength of shaking over much of Christchurch City over the course of the 2010-2011 Canterbury Earthquake Sequence. The model was based on a uniform intensity of ground shaking across the entire city which is unlikely to be the case in an actual earthquake event, where shaking will be stronger closer to the fault and therefore any settlement in an actual event will differ to that modelled. The model does not include tectonic movement, including for example Port Hills uplift. The model results are also influenced by noise artefacts in the aerial survey data used in the model, such as flight path lines and local extreme changes in elevation. These have been smoothed out to some degree but will also result in differences between the modelled settlement and any actual settlement.

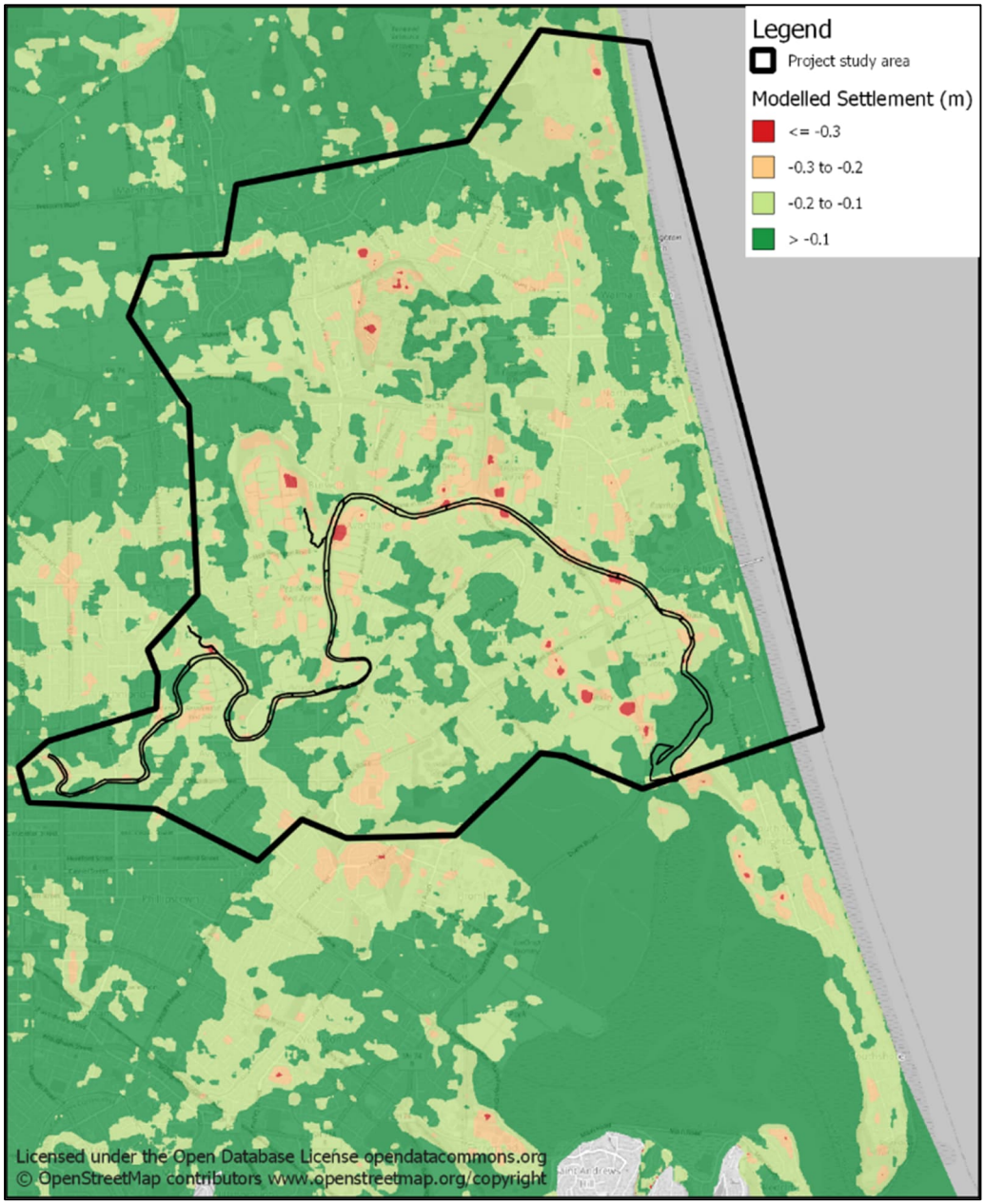


Figure 10. Potential change in ground levels due to liquefaction-induced settlement in an earthquake event as developed through modelling in Stage 2 of the multi-hazards project.

3.1.3 Vertical land movement (VLM)

Since the commencement of Stage 3 of the multi-hazards project, a greater understanding of the magnitudes of ongoing VLM in New Zealand and the potential effects of VLM on coastal flood hazards has emerged. In 2022, updated sea-level rise projections from the 2021 Intergovernmental Panel on Climate Change Sixth Assessment Report sea-level data, downscaled to Aotearoa New Zealand, were published by MfE and the NZ SeaRise Te Tai Pari O Aotearoa programme. NZ SeaRise also published estimates of local rates of ongoing vertical land movement (VLM) at 2 km intervals along the coastline of the country. The VLM rates were estimated from historic Envisat Synthetic Aperture Radar (SAR) satellite data acquired between 2003 and 2011. This period was chosen to exclude effects of local earthquakes around the country so that the rates therefore represent the ongoing 'inter-seismic' VLM at each location between individual seismic events.

Measurements in Christchurch[21] following the 2010-11 Canterbury Earthquake Sequence and the Valentine's Day and Kaikōura earthquakes in 2016 indicate a higher rate of ongoing VLM than the NZ SeaRise inter-seismic data. To better understand this 'post-seismic' VLM, Council commissioned additional analysis by GNS (now Earth Science New Zealand)[22] of recent satellite data to quantify the magnitude and spatial variation of VLM in the city. Figure 11 compares the current (2025) NZ SeaRise inter-seismic VLM values and GNS post-seismic VLM data over the extent of the Avon model.

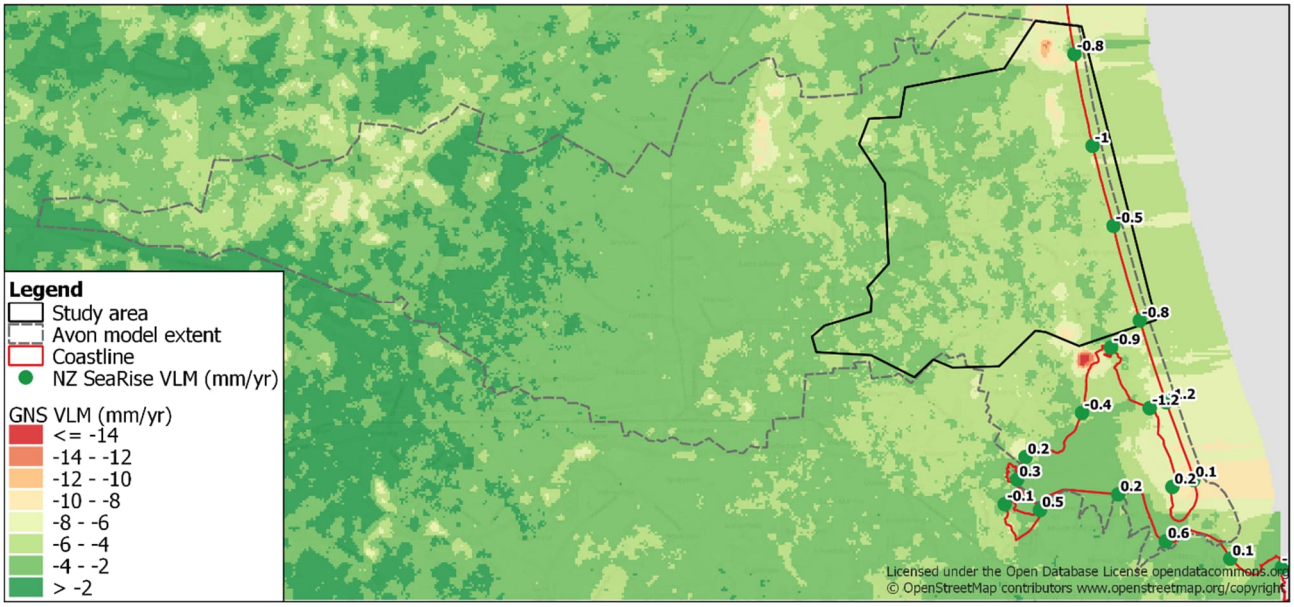


Figure 11. NZ SeaRise inter-seismic VLM values (2025) and post-seismic VLM rates derived by GNS

Around the boundary of the project area, the estimated inter-seismic VLM rates range from -1.0 mm/year to -0.5 mm/year with a median value of -0.8 mm/year. Inter-seismic VLM rates within the wider project area are not readily available. Within the project area, the estimated post-seismic VLM rates range from -13.4 mm/year to -2.2 mm/year with a median value of -4.1 mm/year. The rate of VLM is relatively uniform over the project area with an interquartile range of -4.6 mm/year to -3.7 mm/year.

VLM rates are expected to return to the inter-seismic rates in the future but the actual period over which the post-seismic rates will persist is unknown. Current data do not indicate any reduction in VLM rates at present and the GNS study indicates that it is more likely that the post-seismic rates will continue for several decades than cease in the near future.

[21] School of Surveying, Otago University (2022). Christchurch City Ground Height Monitoring. Vertical land motion in Eastern Christchurch. Report to Environment Canterbury.

[22] Inter-seismic, co-seismic and post-seismic rates of vertical land movement in the Christchurch district and implications for future changes in sea level. IJ Hamling J Kearse, GNS Science Consultancy Report 2023/81 October 2023 (Addendum report in 2024)

To understand the effects of long term VLM on flooding and the effects of uncertainty in how VLM may change in the future, the scope of Stage 3 of the multi-hazards project was extended to include assessment of flood hazards for three plausible scenarios of VLM as illustrated diagrammatically in Figure 12.

VLM Scenario 1: Post-seismic VLM for 10 years (2020 to 2030) followed by inter-seismic VLM thereafter (considered a less likely scenario)

VLM Scenario 2: Post-seismic VLM for 30 years (2020 to 2050) followed by inter-seismic VLM thereafter (considered a more likely scenario)

VLM Scenario 3: Earthquake "shock" scenario with long term VLM: post-seismic VLM for 30 years (2020 to 2050) followed by inter-seismic VLM from 2050 to 2060; 'instantaneous' liquefaction induced settlement from a seismic event at 2060; post-seismic VLM for 30 years after that event (2060 to 2090) followed by inter-seismic VLM

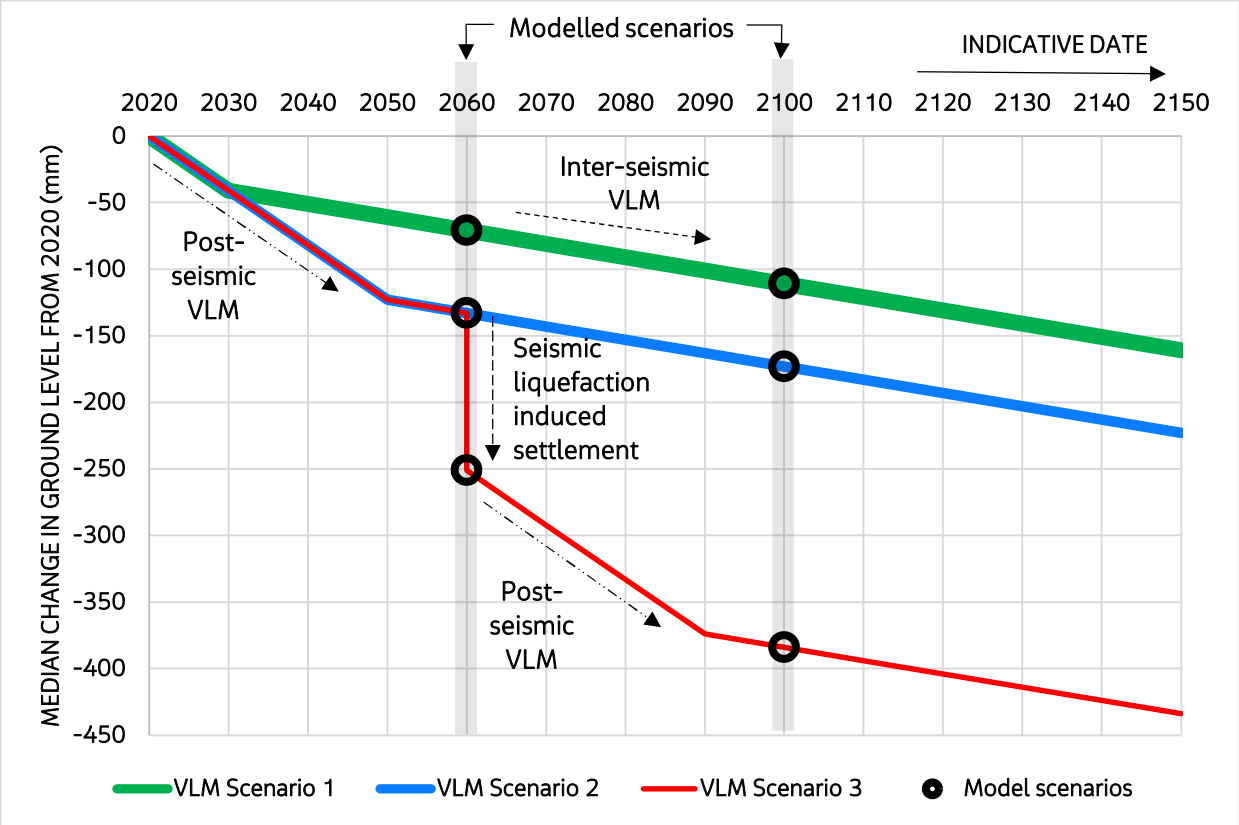


Figure 12. Diagrammatic illustration of the three scenarios of future VLM considered in Stage 3 of the project[23].

For post-seismic VLM we have used the spatially varying estimates of current rates of VLM following the 2010-11 and 2016 earthquake sequence as estimated by GNS (Figure 11).

For inter-seismic VLM we have adopted a uniform rate of -1 mm/year over the whole Avon model and project area based on the NZ SeaRise estimates of ongoing VLM, excluding the effects of seismic events (Figure 11).

[23] Post-seismic VLM varies spatially over the project area (see Figure 11) and has been applied accordingly in the model. Figure 12 depicts VLM using the median post-seismic rate over the project area of -4.1 mm/year and an inter-seismic rate of -1 mm/year.

For liquefaction induced settlement we have used the same estimated ground settlement in an earthquake event as for the other model scenarios (without VLM), as derived by T+T in Stage 2 of the Multi-Hazards project (Figure 10).

The terrain data used in the Avon model and for the other hazard assessments in Stage 3 of the study is derived from LiDAR survey captured in 2018 and so is considered representative of ground levels in 2020, the initial climate state adopted in the multi-hazards project, at the start of the modelled VLM scenarios.

For each VLM scenario we have assessed hazards and simulated flooding using the Avon model in two of the future climate states considered in the project (Table 5) as shown in Figure 12:

- Approximate date of 2060 (0.45 m SLR from 2020)
- Approximate date of 2100 (1.06 m SLR from 2020)

For each combination of VLM scenario and future climate state we have simulated flooding with two of the Avon model versions (refer to Table 1) – 'no stopbanks' and 'OARC Scheme' – for the same three AEPs as the other model scenarios (10%, 2% and 0.5%).

3.1.4 Flood protection infrastructure

As detailed in Table 1, three alternative arrangements of flood protection infrastructure are combined with the future climate states and earthquake events to define the scenarios for assessing flood hazard.

Existing stopbanks

The existing 'temporary' stopbanks along the lower Ōtākaro Avon River together with all other existing flood management infrastructure (stormwater drains and pumpstations).

This arrangement is only modelled for climate states up to and including 0.45 m SLR, corresponding to a date of approximately 2060. This corresponds to the end of the functional life of these stopbanks as envisaged at the time of Stage 2 of the project. Beyond this date the stopbanks may remain in place but cannot be relied on to contain water levels in the river and their presence is completely excluded in modelling scenarios further in the future.

No stopbanks

No stopbanks along the lower Ōtākaro Avon River but other existing flood management infrastructure (stormwater drains and pumpstations) in place.

OARC Scheme

The planned new setback flood defences and stormwater pump stations along the lower Ōtākaro Avon River. The existing stopbanks are removed but other existing flood management infrastructure in place.

3.1.5 Groundwater levels

Using groundwater monitoring data, present day groundwater level statistics have been interpolated across the study area to create a groundwater level surface. This surface is then used to calculate the depth to the water table below ground level. The depth data is put into the flood model to determine infiltration and runoff from the simulated pluvial events. The 85th percentile groundwater levels developed by Aqualinc in Stage 2 of the project are used in each of the scenarios. These levels allow for the estimated effects of sea level rise in each scenario on the water table. For the climate state of 1.06 m SLR, an additional scenario with 50th percentile groundwater levels was defined to understand the sensitivity of flooding to the adopted groundwater levels.

Groundwater levels (i.e., above vertical level datum) are taken to be unchanged by VLM. However, the lowering of ground surface levels due to VLM will reduce the depth to the water table from the ground surface and vadose zone storage capacity. For model scenarios which include VLM, this effect is allowed for by reducing the surfaces of depth to water table used in the model.

3.1.6 Summary

The full set of scenarios for which flood hazard has been assessed in Stage 3 are listed in Table 6.

Table 6. Scenarios for assessment of flood hazard.

Indicative date	Sea level rise from 2020	Increase in mean temperature from 2020 (to estimate increase in rainfall depth)	VLM	Land settlement from earthquake	Flood protection infrastructure	Groundwater levels
2020	0 m	0 °C	None	no	Existing stopbanks	85th %ile
				no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
2030	0.19 m	0.3 °C	None	no	Existing stopbanks	85th %ile
				no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
2060	0.45 m	1.4 °C	None	no	Existing stopbanks	85th %ile
				no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
				yes	Existing stopbanks	85th %ile
				yes	No stopbanks	85th %ile
				yes	OARC Scheme	85th %ile
			VLM S1	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
			VLM S2	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
			VLM S3	yes	No stopbanks	85th %ile
				yes	OARC Scheme	85th %ile
2100	1.06 m	2.8 °C	None	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
				yes	No stopbanks	85th %ile
				yes	OARC Scheme	85th %ile
				no	No stopbanks	50th %ile
			VLM S1	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
			VLM S2	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
			VLM S3	yes	No stopbanks	85th %ile
				yes	OARC Scheme	85th %ile
2150	1.88 m	4.6 °C	None	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile
>2150	2.4 m	5.0 °C	None	no	No stopbanks	85th %ile
				no	OARC Scheme	85th %ile

3.2 Flood events

For each future scenario, flood hazards have been assessed through model simulations of flood events using the Avon flood model. The modelled flood events are each a combination of coincident tide and rainfall events with overall joint AEPs of 10%, 2% and 0.5%. The combinations of tide and rainfall AEPs for each overall event AEP were selected using a "two-point" rule[24]. A pair of interchangeable probabilities are applied to each source of flooding resulting in two types of event with approximately the same overall probability: a "pluvially dominated event" in which the probability of the pluvial event is lower and therefore more extreme and likely to be the main source of flooding; and a "tidally dominated", event in which the probability of the tide is lower and likely to be the main source of flooding.

For pluvially-dominated events, a range of storm durations were selected for each AEP. In this way, five to six individual combinations of tide and rainfall events were simulated in the flood model for each overall AEP, as detailed in Table 7. The maximum depth and extent of flooding over all the events simulated for each joint AEP was then determined from the model results.

Table 7. Flood events simulated with the Avon model for each joint AEP.

Joint AEP	Event type	Rainfall	Tide
10%	Pluvially dominated	10% AEP 3-hour duration 10% AEP 9-hour duration 10% AEP 18-hour duration 10% AEP 36-hour duration (10% AEP 1-hour duration also simulated for 2020 and 2060 defences up scenarios with no earthquake)	39% AEP
2%	Pluvially dominated	2% AEP 3-hour duration (2% AEP 1-hour duration also simulated for 2020 and 2060 defences up scenarios with no earthquake)	18% AEP
		2% AEP 9-hour duration 2% AEP 18-hour duration 2% AEP 36-hour duration	14% AEP
	Tidally dominated	14% AEP 18-hour duration	2% AEP
0.5%	Pluvially dominated	0.5% AEP 3-hour duration	14% AEP
		0.5% AEP 9-hour duration 0.5% AEP 18-hour duration 0.5% AEP 36-hour duration	7% AEP
	Tidally dominated	7% AEP 18-hour duration	0.5% AEP

3.3 Design exceedance events

The OARC flood defence crest levels will be designed to contain river levels and prevent flooding from the river for storm events of 1% AEP with freeboard and for larger, less likely events – e.g., 0.5% AEP – with reduced freeboard. Given the uncertainty in estimating the magnitudes of rainfall and sea levels in these relatively extreme design events, and the potential for more extreme events to occur, additional simulations have been performed using rainfall and storm tide events that exceed the design events in order to understand residual risks. Simulations have been performed for the 0.45 m and 1.06 m future climate

[24] GHD/HKV (2021) LDRP97 Multi-Hazard baseline modelling. Joint Risks of Pluvial and Tidal Flooding. Rev 0. February 2021.

scenarios to provide an indication of the likely residual flood hazards from extreme events with the OARC Scheme in place.

The OARC Scheme version of the Avon model with VLM Scenario 2 was used to simulate the design exceedance events for each of the two future climate states. The flood defence crest levels in the model were set to the anticipated actual crest levels at these dates on the basis of the Christchurch City Council's Ōtākaro Avon River Stopbanks Design Standards (Table 8). The standards specify an initial construction crest level equal to the 1% AEP water level in the river, a freeboard of either 200 mm or 300 mm depending on the potential for wave action along each reach of stopbank and allowances for SLR and VLM over the design life of the stopbank. Since the 1% AEP event is not included in the scenarios modelled with the OARC Scheme (Table 7), the 0.5% AEP water levels from the OARC Scheme model simulations have been used to set the crest levels.

Table 8: OARC Stopbank Standards and values adopted for design exceedance event simulations

Factor	Adopted value for design exceedance events
Flood containment level	0.5% AEP water levels from model simulations of the OARC Scheme and VLM Scenario 2.
Freeboard	200mm or 300mm depending on location (proximity of stopbanks to main river channel).
Future allowance (effect of sea level rise on water levels)	Included in model water levels used to set crest levels.
Vertical Land Movement	Not included in model stopbank crest level. It is expected that VLM will be addressed by constructing the crest level higher than the required future level to allow for the expected total lowering of the stopbank due to VLM over the design life. For the simulations the crest is taken to have lowered to the minimum design level by the time of the future state simulated.
Construction and survey tolerance	Not included in model crest level.

Two types of design exceedance events were simulated for each future scenario.

Extreme pluvial flood event

This scenario uses a rainfall depth of double that of the 0.5% AEP 18-hour duration storm adopted for the model simulations. This represents an event more extreme than a '1 in 10,000 year' event based on a simple extrapolation of design rainfall data[25] in the project area and is approximately double the maximum 24-hour rainfall recorded at the Christchurch Gardens since 1874. A 7.7% AEP tidal boundary condition, as adopted for the 0.5% AEP pluvial event in the rest of the model simulations, was applied in combination with this extreme rainfall event.

Extreme tidal flood event

This scenario uses the 0.5% AEP storm tide boundary condition adopted for the rest of the model simulations with an additional height of 0.4 m applied over the whole tide cycle. Research[26] suggests that potential extreme storm tides in New Zealand could be 7% to 20% higher than current estimates of extreme levels (e.g., 1% AEP) derived from purely statistical analysis of tidal water level records due to historic data not including fully coincident surge and astronomical tides. The additional tide height of 0.4 m adopted in the design exceedance event scenario corresponds to approximately 20% of the 0.5% AEP storm tide adopted in the multi-hazards modelling. The resulting tide level would correspond to an event more extreme than a '1 in

[25] NIWA High Intensity Rainfall Design System Version 4 (https://hirds.niwa.co.nz/)

[26] Spatial and temporal analysis of extreme storm-tide and skew-surge events around the coastline of New Zealand, Scott A. Stephens, Robert G. Bell, and Ivan D. Haigh, Nat. Hazards Earth Syst. Sci., 20, 783–796, 2020 (https://doi.org/10.5194/nhess-20-783-2020)

10,000 year' event based on a simple extrapolation of storm tides at Sumner Head[27]. Design rainfall data for the 7.7% AEP 18-hour duration rainfall boundary, as adopted for the other simulations of the 0.5% AEP tidal event, was used in combination with the extreme tide.

Table 9: Summary of design exceedance events

Exceedance event	SLR	Indicative date	Event Type	Rainfall	Tide
1	0.45 m	2060	Pluvial	[0.5% AEP 18-hour duration] x 2	7.7% AEP
2	0.45 m	2060	Tidal	7.7% AEP 18-hour duration	[0.5% AEP] + 0.4m
3	1.06 m	2100	Pluvial	[0.5% AEP 18-hour duration] x 2	7.7% AEP
4	1.06 m	2100	Tidal	7.7% AEP 18-hour duration	[0.5% AEP] + 0.4m

[27] GHD/HKV (2021) LDRP97 Multi-Hazard baseline modelling. Joint Risks of Pluvial and Tidal Flooding. Rev 0. February 2021.

3.4 Hazard pathways

To assess the overall effects of the three alternative flood protection infrastructure arrangements on flood damages, we have defined a set of potential "hazard pathways" in time. The pathways are set out in Table 10 and have primarily been used to compare the present value of flood damages in each pathway.

Table 10. Pathways considered for assessing flood damages.

<table>
<tr><th>Pathway</th><th>2020</th><th>2030</th><th>2060</th><th>2100</th><th>2120+</th></tr>
<tr><td>Up1</td><td colspan="3">Existing Stopbanks</td><td colspan="2">No Stopbanks</td></tr>
<tr><td>Up2</td><td colspan="3">Existing Stopbanks</td><td colspan="2">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Up3</td><td colspan="2">Existing Stopbanks</td><td>Existing Stopbanks Earthquake settlement</td><td colspan="2">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Down1</td><td colspan="5" rowspan="3">No Stopbanks</td></tr>
<tr><td>Down-VLMS1#</td></tr>
<tr><td>Down-VLMS2#</td></tr>
<tr><td>Down2</td><td colspan="3">No Stopbanks</td><td colspan="2">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Down3</td><td colspan="2">No Stopbanks</td><td colspan="3">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Down-VLMS3#</td><td colspan="2">No Stopbanks</td><td colspan="3">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>OARC1</td><td colspan="5" rowspan="2">OARC Scheme</td></tr>
<tr><td>OARC-VLMS1#</td></tr>
<tr><td>OARC-VLMS2#</td><td colspan="5">OARC Scheme</td></tr>
<tr><td>OARC2</td><td colspan="3">OARC Scheme</td><td colspan="2">OARC Scheme [Earthquake settlement]</td></tr>
<tr><td>OARC3</td><td colspan="2">OARC Scheme</td><td colspan="3">OARC Scheme [Earthquake settlement]</td></tr>
<tr><td>OARC-VLMS3#</td><td colspan="2">OARC Scheme</td><td colspan="3">OARC Scheme [Earthquake settlement]</td></tr>
</table>

flooding not simulated in VLM scenarios at 2020 (no change in ground levels) or 2030. Damages for non-VLM scenarios in 2030 adopted in pathways which include VLM as an approximation (short period of VLM).

4. Flood model results

The extent and depth of flooding in the Avon project area in all the future scenarios listed in Table 6 has been assessed through simulation of these scenarios using the Avon flood model. The results of the simulations provide further understanding of the flood mechanisms in the project area and the input data for quantitative assessment of the effects of flooding in terms of the number of properties affected by flooding and the approximate financial cost of flood damage.

Section 4.1 provides a summary of the model results for scenarios with the existing stopbanks and with no stopbanks. Section 4.2 provides a summary of results for scenarios with the OARC Scheme. The model results are presented and discussed in more detail in the 2022 revision of the Multi-Hazards Stages 1 & 2 Summary Report, and in the Task 1 and Task 3 memos in Appendix A and Appendix C of this report.

For each future scenario, flooding was simulated for up to six combinations of tide and rainfall with a joint AEP of 10%, 2% and 0.5%, as detailed in Table 7, and the overall maximum depth and extent of flooding for each joint AEP was then determined from the results.

The number of properties flooded and the financial flood damages in each modelled scenario have been calculated using the 'FloodFX' tool[28]. The Annual Average Damage (AAD) has been estimated for each individual model scenario from the flood model results for the three AEPs.

The AAD varies between each scenario due to variations in climate change, flood management infrastructure and ground level changes at each point in time. The individual scenarios have been combined to form a series of potential future pathways (Table 10) of climate change, earthquake-induced land settlement and VLM over a 100-year period to approximately 2120. This allows the total present-day value ('present value') of flood damages over the 100-year period to be estimated and compared for each potential future pathway.

It is important to note that the purpose of this damage assessment is to enable a comparison of the relative performance – e.g., 'better' or 'worse' – of the existing and proposed flood protection infrastructure in the selected future scenarios. The results of the damage calculations are sensitive to the method and parameter values adopted for several key aspects of flood damage in the FloodFX tool. The tool is based on comprehensive research undertaken at the time of its development. However, it is acknowledged that considerable uncertainty remains in some aspects of the calculations and some values adopted are subject to change for economic reasons. Further details of the limitations are provided in the memo in Appendix A.

4.1 With and without existing stopbanks

Table 11 lists the scenarios simulated with and without the existing stopbanks. The scenarios consider the potential effects of climate change on flood hazard over the next 130 years.

For the scenarios which exclude ongoing VLM, the effects of land settlement from an earthquake on flood hazard are simulated in two of the future climate states (0.45 m and 1.06 m SLR). For scenarios including VLM, land settlement from an earthquake is included in VLM Scenario 3. As explained in Section 3.1.3 (and illustrated in Figure 12), in this scenario the earthquake settlement is applied at 0.45 m SLR and is included, together with additional post-seismic VLM, in the 1.06 m SLR climate state. For 1.06 m SLR, a sensitivity test on the effect of groundwater levels is included in the scenarios (50th %ile instead of 85th%ile).

[28] FloodFX is a Christchurch City Council tool (developed by Jacobs) that identifies impact of flooding on building assets. It utilises flood modelling outputs and a database of house floor levels and types to identify properties at risk of flooding and estimate damages (based on intangible and tangible factors).

Table 11. Scenarios simulated with existing stopbanks and with no stopbanks

SLR Approximate timing	0 m 2020	0.19 m 2030	0.45 m 2060	1.06 m 2100	1.88 m 2150	2.4 m > 2150
Existing stopbanks	✓	✓	✓			
+ earthquake			✓			
No stopbanks	✓	✓	✓	✓	✓	✓
+ 85%ile groundwater	✓	✓	✓	✓	✓	✓
+ 50%ile groundwater				✓		
+ earthquake			✓	✓		
+ VLM S1			✓	✓		
+ VLM S2			✓	✓		
+ VLM S3 (inc. earthquake)			✓	✓		

4.1.1 Flood extent

Figure 13 and Figure 14 show the model flood extents for the three modelled AEPs for 0.45 m SLR (with existing stopbanks) and 1.06 m, 1.88 m and 2.4 m SLR (no stopbanks), without any land settlement from earthquake or VLM. The model results indicate four main mechanisms of flooding over the project area:

- Overtopping of the existing stopbanks (or overflow of the riverbanks for the 'no stopbanks' scenarios) resulting in relatively deep flooding within the OARC Regeneration Plan area and suburbs immediately adjacent – particularly for more extreme events and in higher sea level rise scenarios – in areas such as Avondale, Bexley and New Brighton.
- Ponding of runoff in stormwater catchments draining into the Ōtākaro Avon River, even in more frequent rainfall and lower sea level rise scenarios – due to runoff exceeding the stormwater drainage network capacity or restricted discharge at the outfalls due to elevated river levels – in areas such as North Linwood and Dallington.
- Ponding of runoff in stormwater catchments draining into tributaries of the Ōtākaro Avon River or into the sea – due to runoff exceeding the drainage network capacity – in areas such as Parklands.
- Inundation from the sea through low points in the dunes along the shoreline[29] of the project area in scenarios with sea level rise greater than 1.06 m – at the North New Brighton surf club and, at higher sea levels, New Brighton beachfront – contributing to flooding in New Brighton and further inland.

Figure 15 shows the modelled flood extent for the 0.45 m SLR (with existing stopbanks) and 1.06 m SLR (no stopbanks) SLR scenarios including the effect of land settlement from an earthquake. For 0.45 m SLR with existing stopbanks – Figure 13(a) and Figure 15(a) – the effect of land settlement is greatest for the smallest event simulated (10% AEP) in the low-lying land along the Ōtākaro Avon River corridor. The main source of flooding in this area is from the river and the existing stopbanks provide some protection from small events and lower values of SLR. The reduction in crest levels through settlement results in more overtopping in such events. For larger events (2% and 0.5% AEP) and for small events with higher SLR (1.06 m), the existing stopbanks are overtopped without earthquake settlement and so the reduction in crest level has less effect on overall flood extent.

Figure 16 shows the modelled flood extent without stopbanks for the 10% AEP, with and without VLM, for 0.45 m SLR and 1.06 m SLR. Figure 17 shows the corresponding extents for the 0.5% AEP. The model results show that the extent of flooding generally increases with VLM but, for all three scenarios considered, the

[29] The present day dune crest elevation and position has been used as the key parameters in this model. It is noted that this dune is mobile and will change in elevation and position over the short term with storms, and in the future with the impacts of sea level rise. This is explored further in Section 7.6.

effect of VLM on maximum flood extent is relatively small. The change in flood extent is greatest for VLM Scenario 3 which includes the effect of earthquake land settlement and increased post-seismic VLM following the earthquake settlement. The results indicate that the reduction in ground levels along the New Brighton shoreline results in inundation from the sea will occur at a lower value of SLR than without VLM.

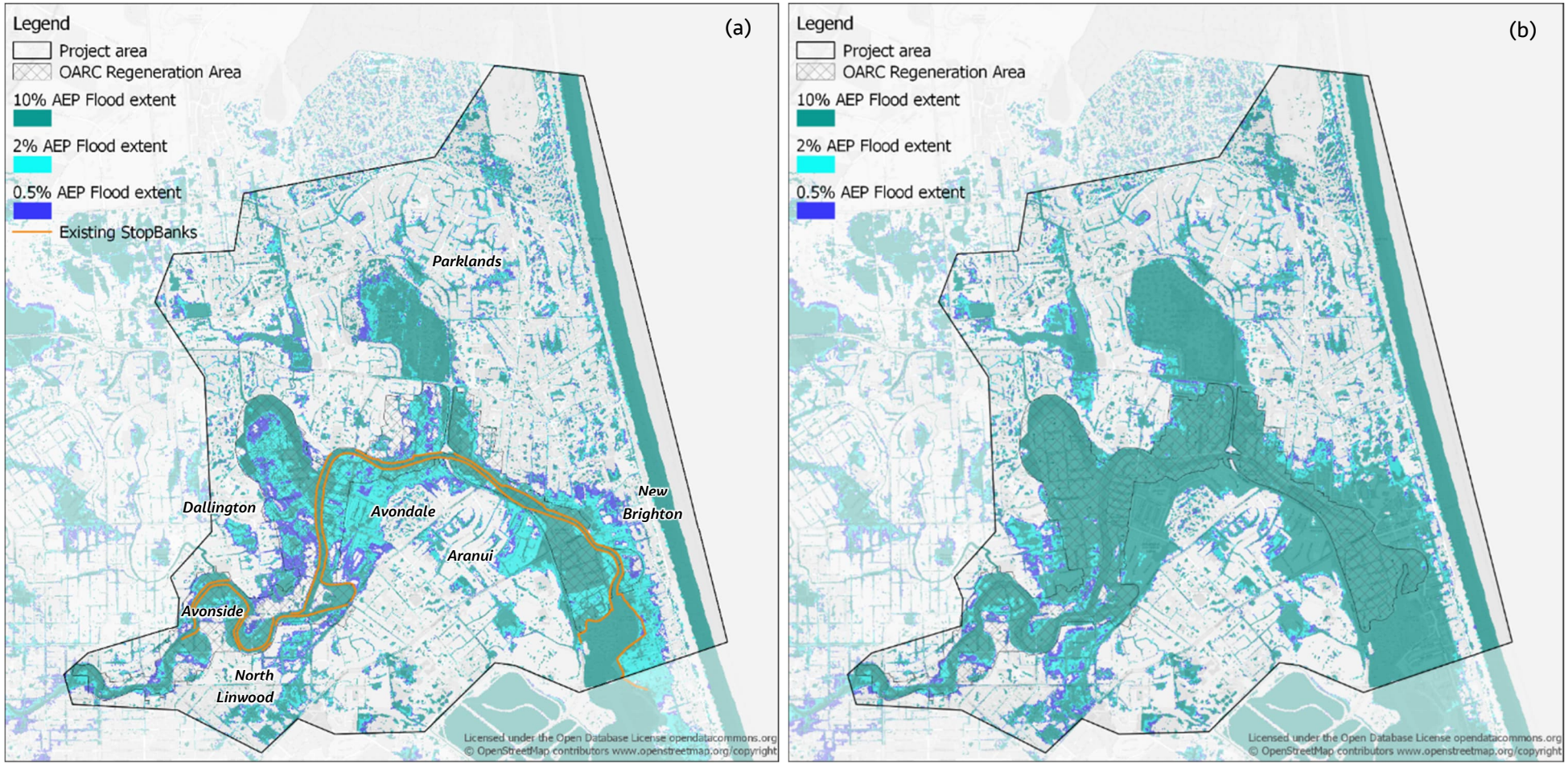


Figure 13. Modelled flood extents <u>without earthquake</u> settlement and <u>without VLM</u> (a) 0.45 m SLR with existing stopbanks; (b) 1.06 m SLR with no stopbanks.

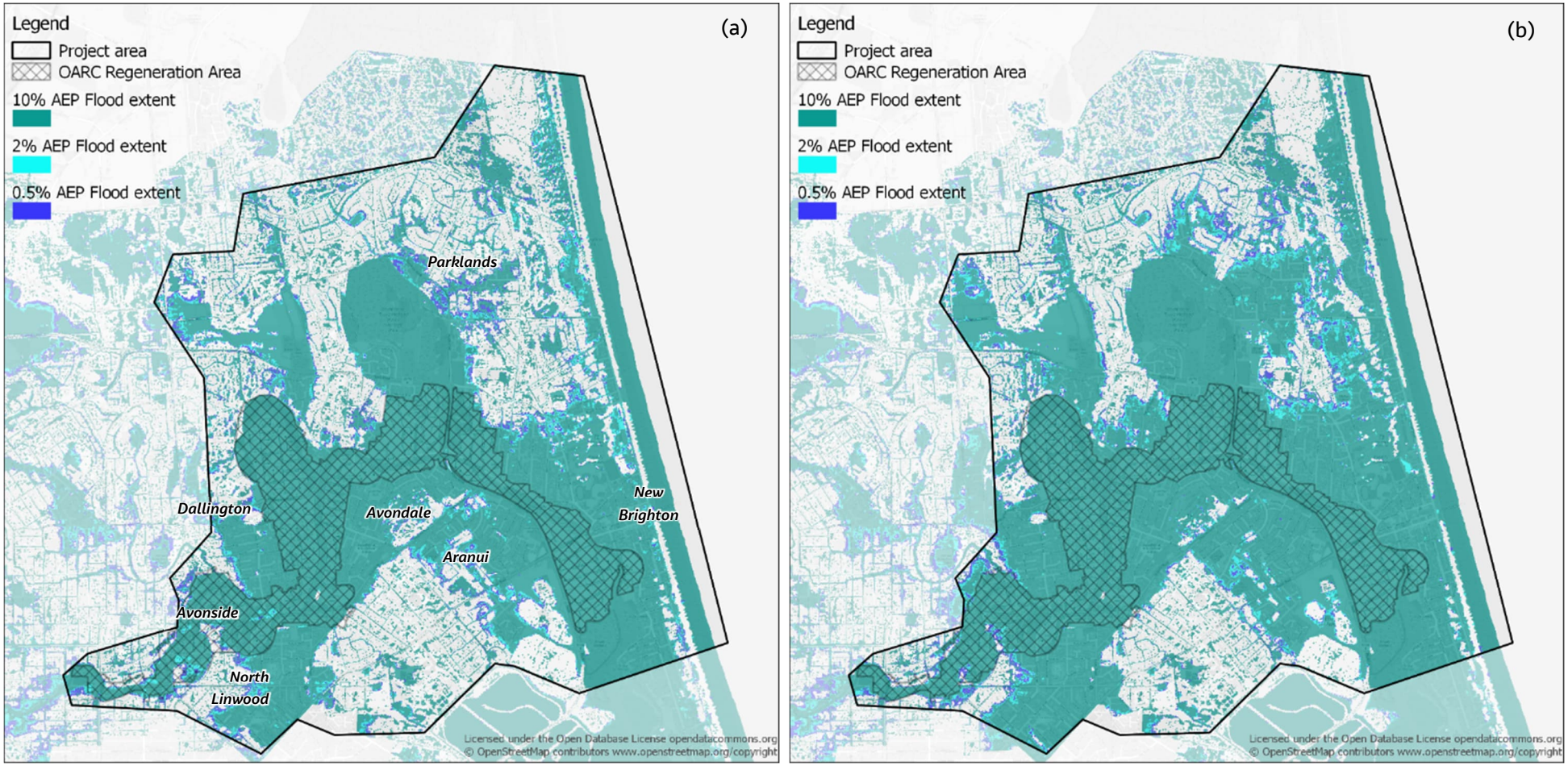


Figure 14. Modelled flood extents without earthquake, without VLM and with no stopbanks (a) 1.88 m SLR; (b) 2.4 m SLR.

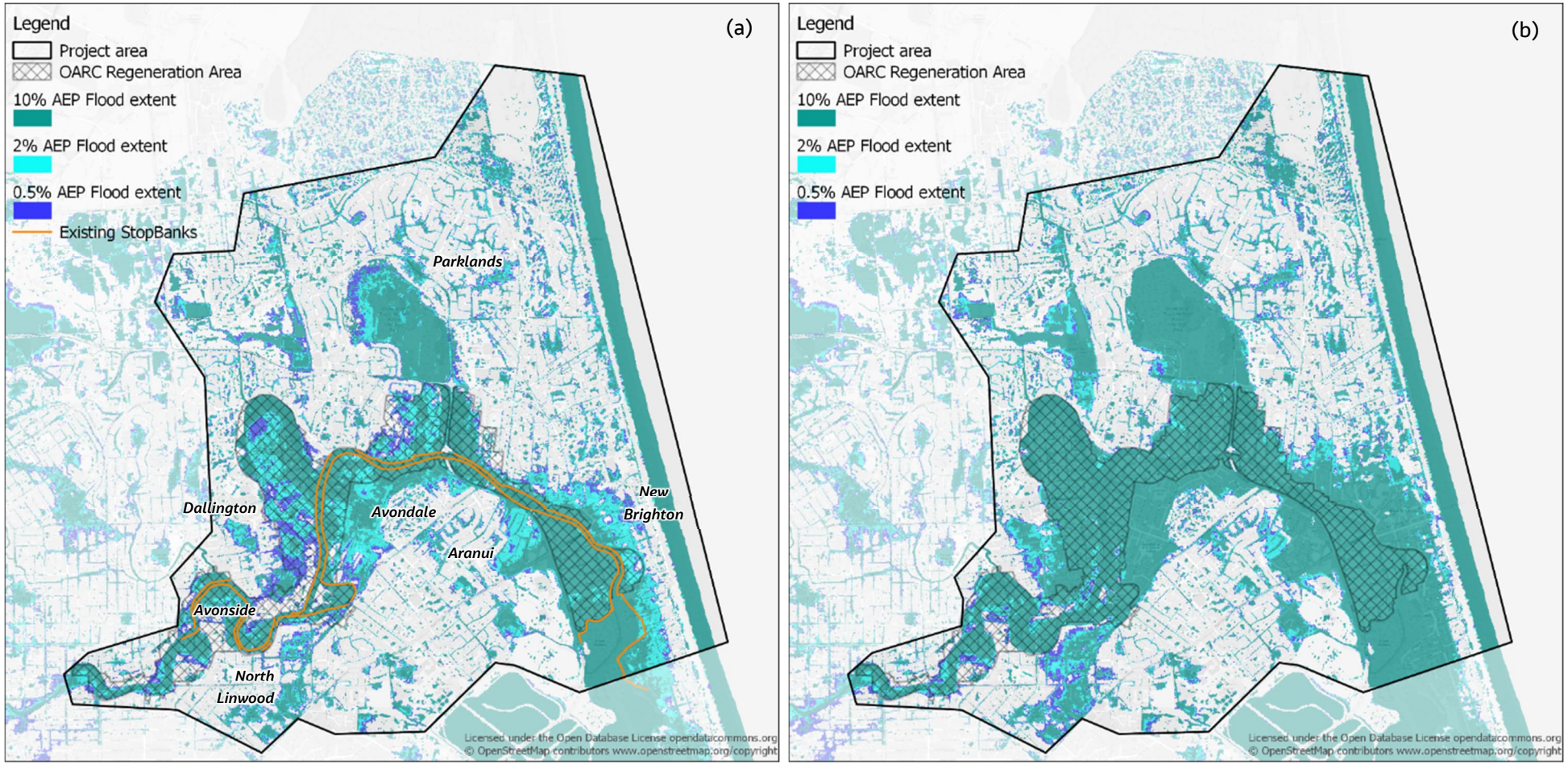


Figure 15. Modelled flood extents with earthquake settlement but without VLM (a) 0.45 m SLR with existing stopbanks; (b) 1.06 m SLR with no stopbanks.

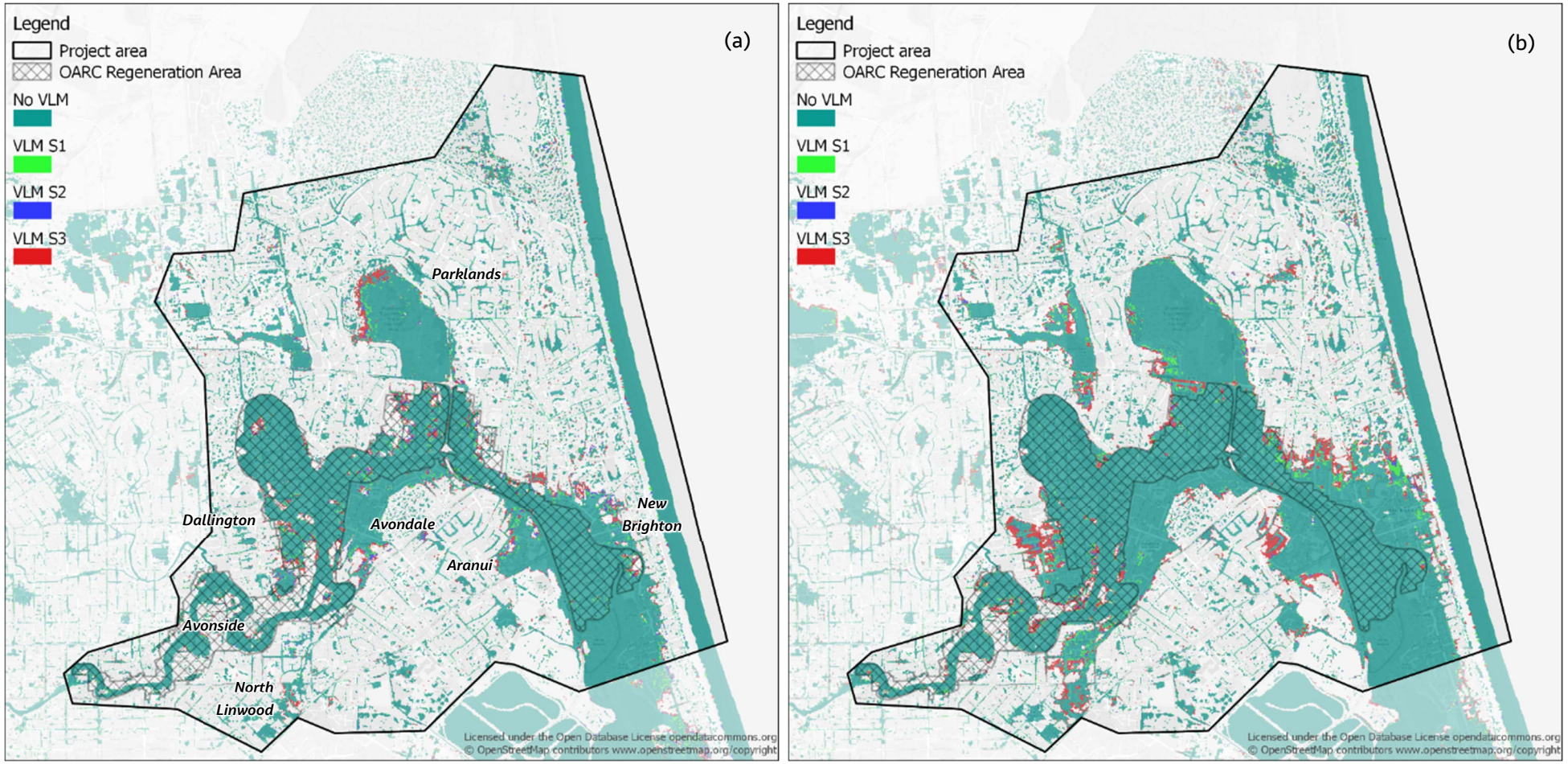


Figure 16. Modelled 10% AEP flood extents with and without VLM (a) 0.45 m SLR without stopbanks; (b) 1.06 m SLR without stopbanks.

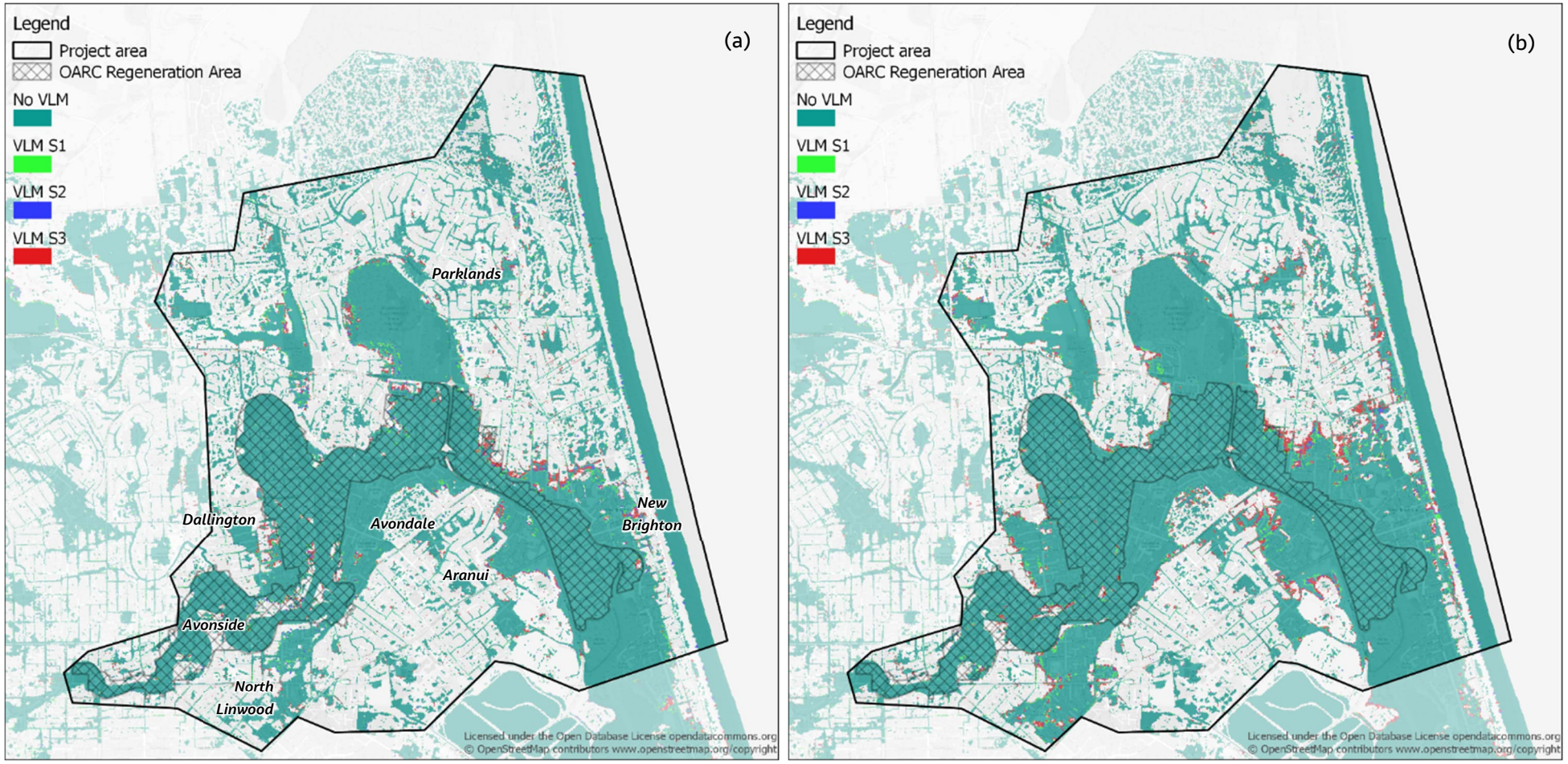


Figure 17. Modelled 0.5% AEP flood extents with and without VLM (a) 0.45 m SLR without stopbanks; (b) 1.06 m SLR without stopbanks.

4.1.2 Properties flooded

Figure 18(a) and Figure 18(b) show, for the 10% AEP and 0.5% AEP respectively, the number of buildings with 'under floor flooding' and 'above floor flooding' based on the model results for each of the scenarios in Table 11, excluding VLM. 'Under floor flooding' is defined as any building footprint which intersects the modelled flood extent and 'above floor flooding' is defined as any building intersecting the modelled flood extent for which the freeboard from the flood level to the floor level is less than 100 mm[30]. The building counts for all AEPs are tabulated in Table 12.

- For the 10% AEP, with the existing stopbanks there is little increase in the number of buildings affected for sea level rise up to 0.45 m. The existing stopbanks largely prevent flooding from the river over this range of climate states and the residual ponding from surface water runoff does not increase significantly over this period. With no stopbanks, the number of buildings affected increases more rapidly because flood levels are more directly affected by sea level rise.
- For the 0.5% AEP, the existing stopbanks overtop under the present-day climate state. This outcome is expected from the modelling as the existing stopbanks were only designed to contain the present day 1% AEP event. Overtopping increases further with sea level rise resulting in a higher number of affected buildings.

The results for the sensitivity test scenario for groundwater levels show that there is very little difference (less than 1%) in the number of buildings affected in the results for the 1.06 m SLR scenario with 50th percentile groundwater levels and those with the 85th percentile groundwater levels. The differences in modelled flood depths are also generally very small – less than 10 mm over much of the project area and only exceeding 50 mm in small areas of lower lying ground. These results justify use of a single frequency of groundwater levels in the model for simulating flooding in the project area.

Figure 18(c) and Figure 18(d) show the effect of VLM on the number of buildings flooded without stopbanks and with 0.45 m SLR and 1.06 m SLR. For all VLM scenarios there is only a small increase – around 10% or less – in the total number of buildings with under floor flooding for 0.45 m SLR. For VLM Scenario 3, which also includes earthquake-induced settlement, there is a somewhat larger increase in under floor flooding for 1.06 m SLR (up to around 20%).

VLM has a greater effect on the number of buildings with above floor flooding in both SLR scenarios, particularly for VLM Scenario 3 where the number of buildings at risk increases by around 60% to 100% in this scenario. This is comparable to, but a little greater than, the effect of earthquake settlement without VLM. The differences in building counts between the 'more likely' VLM Scenario 2 and 'less likely' VLM Scenario 1 are generally small.

These results reflect the fact that, without stopbanks, the modelled VLM does not significantly change the extent of flooding (ref. Figure 16 and Figure 17) – which determines total number of buildings affected – but does change the depth of flooding – which determines the proportion of buildings with above floor flooding. Figure 19 shows the effect of VLM on the 10% AEP flood depths (without stopbanks) over the project area in the 0.45 m SLR scenario (~2060). Along the Ōtākaro Avon River, where flood depths are determined mainly by water level in the river and ground level, the increase in flood depth is similar to the total amount of VLM since river levels are not significantly affected by VLM. Elsewhere in the project area, the changes in flood depth are generally small. Much of the area where flood depths are increased by VLM lies within the OARC Regeneration area and Travis Wetland. However, a significant number of buildings are also affected.

[30] A freeboard of 100mm below reported floor levels has been used to indicate when houses may be at risk of above floor flooding. This freeboard amount is intended to allow for unmodelled actions or processes that risk water rising above floors such as bow waves from cars and capillary action raising water up structures among others.

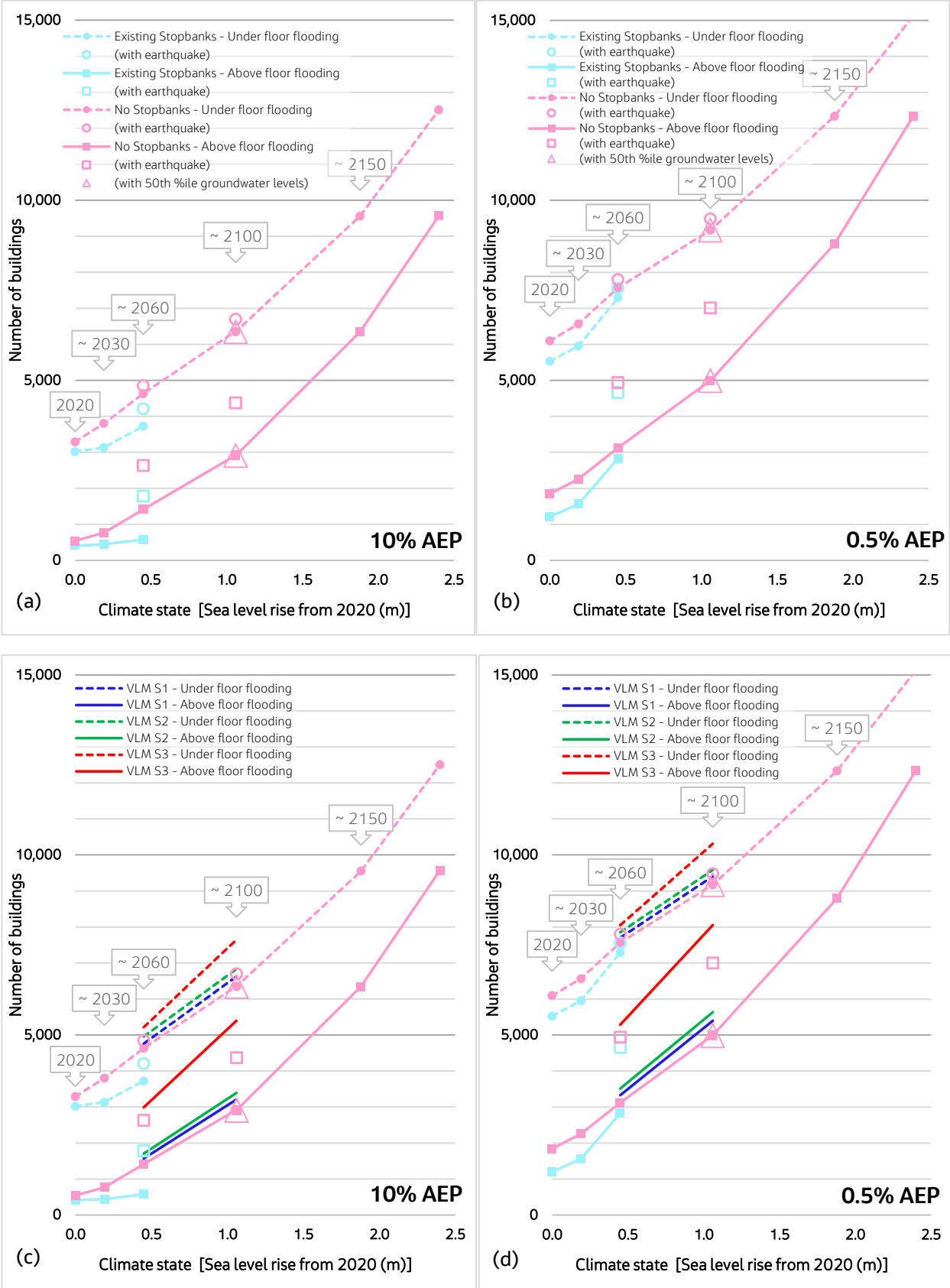


Figure 18. Model results for number of buildings with under floor and above floor flooding in: (a) 10% AEP and (b) 0.5% AEP, without VLM; (c) 10% AEP and (d) 0.5% AEP, with VLM.

Table 12. Approximate number of buildings subject to flooding under each scenario.

					Total building footprints intersecting modelled flood extent			Buildings where flood level within 100 mm of floor level			Buildings where flood level above floor level		
SLR and indicative timing	VLM	Land settlement from earthquake	Stopbanks	Groundwater levels	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP
0 m SLR (2020)	None	no	Existing	85th percentile	3018	4375	5528	410	693	1203	112	217	458
			None	85th percentile	3291	4978	6092	539	1186	1840	203	533	1075
0.19 m SLR (2030)	None	no	Existing	85th percentile	3133	4559	5954	441	764	1560	114	267	809
			None	85th percentile	3800	5419	6567	766	1627	2256	319	943	1464
0.45 m SLR (2060)	None	no	Existing	85th percentile	3725	6014	7291	576	1862	2827	180	1116	1915
		no	None	85th percentile	4629	6333	7565	1410	2296	3118	836	1574	2175
		yes	Existing	85th percentile	4210	6295	7561	1782	3621	4657	888	2461	3378
		yes	None	85th percentile	4851	6560	7800	2631	3902	4941	1700	2741	3652
	S1	no	None	85th percentile	4759	6450	7701	1569	2447	3334	1005	1742	2392
	S2	no	None	85th percentile	4955	6614	7851	1703	2631	3514	1156	1904	2573
	S3	yes	None	85th percentile	5215	6873	8052	2989	4217	5289	2057	3101	4012
1.06 m SLR (2100)	None	no	None	85th percentile	6358	8011	9177	2921	4030	4993	2303	3239	4042
		yes	None	85th percentile	6699	8351	9480	4372	5832	7007	3445	4655	5733
		no	None	50th percentile	6344	8002	9171	2904	4023	4985	2287	3230	4036
	S1	no	None	85th percentile	6624	8303	9403	3203	4356	5395	2577	3576	4425
	S2	no	None	85th percentile	6832	8489	9585	3390	4590	5635	2755	3761	4651
	S3	yes	None	85th percentile	7644	9193	10308	5396	6919	8058	4401	5762	6852
1.88 m SLR (2150)	None	no	None	85th percentile	9556	11153	12336	6341	7828	8790	5559	6938	7894
2.4 m SLR (>2150)	None	no	None	85th percentile	12506	14144	15121	9570	11237	12341	8733	10387	11453

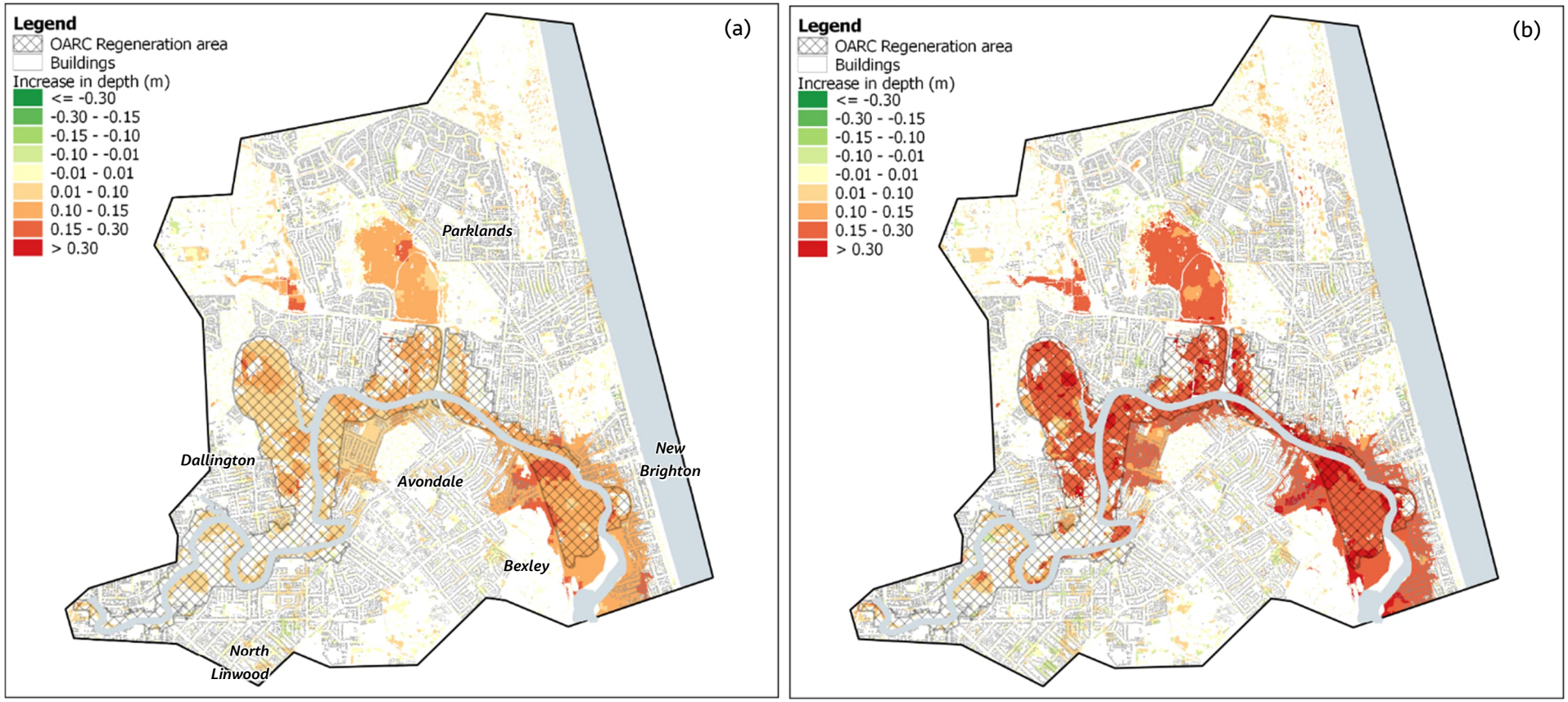


Figure 19. Increase in modelled 10% AEP flood depths (without stopbanks) due to VLM with 0.45 m SLR (~2060) (a) VLM Scenario 2; (b) VLM Scenario 3.

4.1.3 Flood damages

Average Annual Damage (AAD)

Figure 20 shows the Average Annual Damage (AAD) from flooding for each of the scenarios in Table 11, calculated from the model results using FloodFX.

The effect of earthquake induced land settlement on AAD is relatively significant for both the existing stopbanks and no stopbanks cases – AAD for the 0.45 m SLR scenario are approximately doubled and for the 1.06 m scenario AAD are increased by around 50% through land settlement. This is due to increased overflow from the river through settlement of the stopbanks or riverbanks and deep ponding of water in areas of greater settlement in the floodplain. The difference in AAD for the 1.06 m SLR with 50th percentile and 85th percentile groundwater levels is very small, around 0.5% of the total damages.

The effect of VLM on AAD is relatively small for VLM Scenario 1 and Scenario 2 due to the relatively small increase in number of flooded properties and flood depth these scenarios. However, for VLM Scenario 3, AAD is approximately doubled for both 0.45 m SLR and 1.06 m SLR due to both the increase in number of properties flooded and the depth of flooding. The AADs are greater than the scenarios with earthquake settlement without VLM due to the combined effects of earthquake settlement and post-seismic VLM.

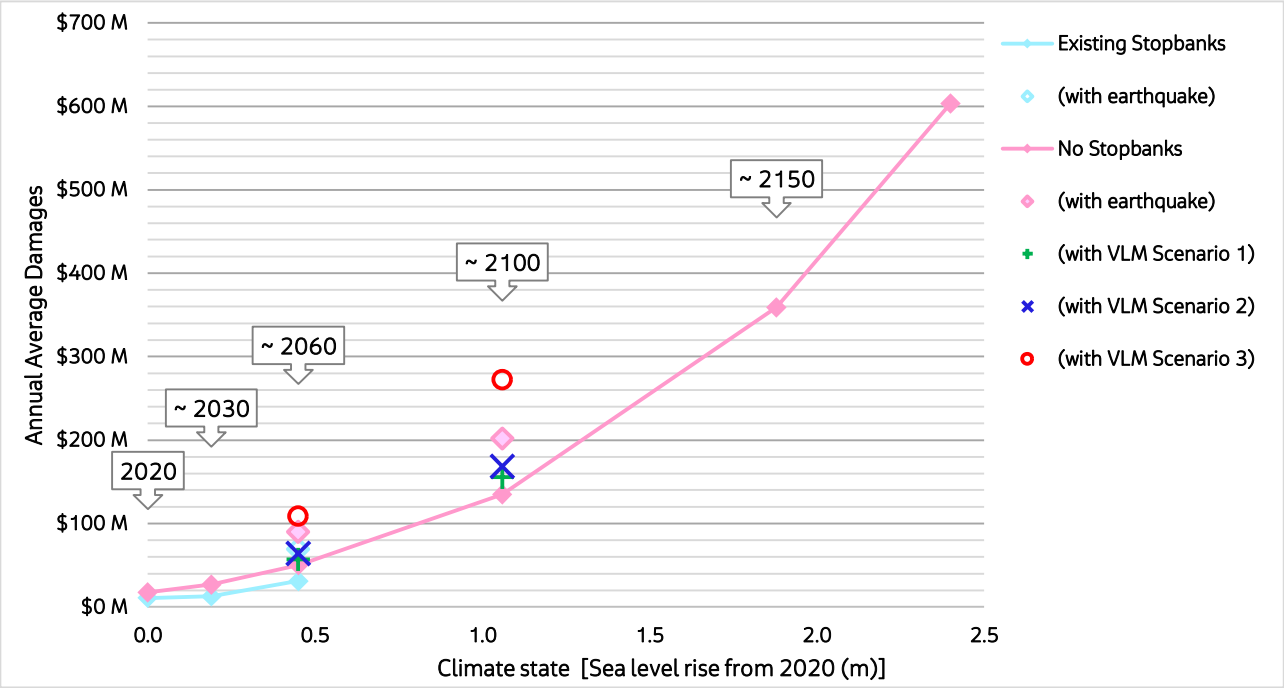


Figure 20. Annual Average Damage from flooding in the project area with and without existing stopbanks.

Present value cumulative damages

The cumulative value of flood damages over the period from 2020 to ~2100 (1.06 m SLR) has been calculated from the AADs for nine potential future pathways of climate change, earthquake-induced land settlement and VLM as shown in Table 13. The AAD value for each year in the pathways has been linearly interpolated from the values shown in Figure 20. For the VLM scenarios, AAD in 2020 is the same as without VLM and AAD in 2030 has been interpolated from the 2020 scenario without VLM and the 2060 scenario with VLM. Not all scenarios have been simulated beyond 2100. To illustrate the general future trend, indicative total damages beyond this date have been estimated using the AAD values at 2100.

Table 13. Pathways for assessing cumulative flood damages (existing stopbanks and without stopbanks).

<table>
<tr><th>Pathway</th><th>2020</th><th>2030</th><th>2060</th><th>2100+</th></tr>
<tr><td>Up1</td><td colspan="2">Existing Stopbanks</td><td colspan="2">No Stopbanks</td></tr>
<tr><td>Up2</td><td colspan="2">Existing Stopbanks</td><td colspan="2">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Up3</td><td colspan="2">Existing Stopbanks</td><td>Existing Stopbanks [Earthquake settlement]</td><td>No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Down1</td><td colspan="4" rowspan="3">No Stopbanks</td></tr>
<tr><td>Down-VLMS1</td></tr>
<tr><td>Down-VLMS2</td></tr>
<tr><td>Down2</td><td colspan="3">No Stopbanks</td><td>No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Down3</td><td colspan="2">No Stopbanks</td><td colspan="2">No Stopbanks [Earthquake settlement]</td></tr>
<tr><td>Down-VLMS3</td><td colspan="2">No Stopbanks</td><td colspan="2">No Stopbanks [Earthquake settlement]</td></tr>
</table>

Flood damage in each future year has been calculated as the 'present value' of the damage by reducing the damage by the discount rates set out in current New Zealand Treasury guidance[31] for public sector non-commercial proposals – i.e., a discount rate of 2% for years 1 to 30 and a rate of 1.5% for years 31 to 100. Damages have also been calculated using a constant discount rate of 8% as recommended by New Zealand Treasury for sensitivity testing purposes.

Figure 21 and Figure 22 show the cumulative present value damages due to flooding for these two discount rates.

For pathways which include earthquake shock events, the effect of earthquake induced settlement on present value damages is less than on the AAD due to discounting of future AAD. Present value damages for these pathways would be higher if the settlement occurred sooner.

Cumulative present value damages to 2100 using current Treasury discount rates ($1.8 billion to $4.2 billion) are around ten times higher than those using the higher fixed rate of 8% ($0.2 billion to $0.5 billion).

It should be noted that whilst the estimates of AAD relate to a particular climate state of sea level rise and increase in rainfall intensity from the present day, the calculation of cumulative present value damages requires the approximate future date at which the AADs and climate state occur. As explained in Section 3.1.1, the actual timing of these climatic states is uncertain and depends on future global rates of emissions and how these affect sea level and temperature locally in New Zealand. The present value flood damages for the pathways in Table 13 have been calculated using the indicative earliest dates for each state under the RCP8.5 H+ climate change scenario. If emissions were to follow a lesser scenario, these future climate states could occur several decades later than the dates adopted in our assessment. This would result in a reduction in the cumulative present value flood damages to a particular future date.

[31] https://www.treasury.govt.nz/information-and-services/public-sector-leadership/guidance/reporting-financial/discount-rates

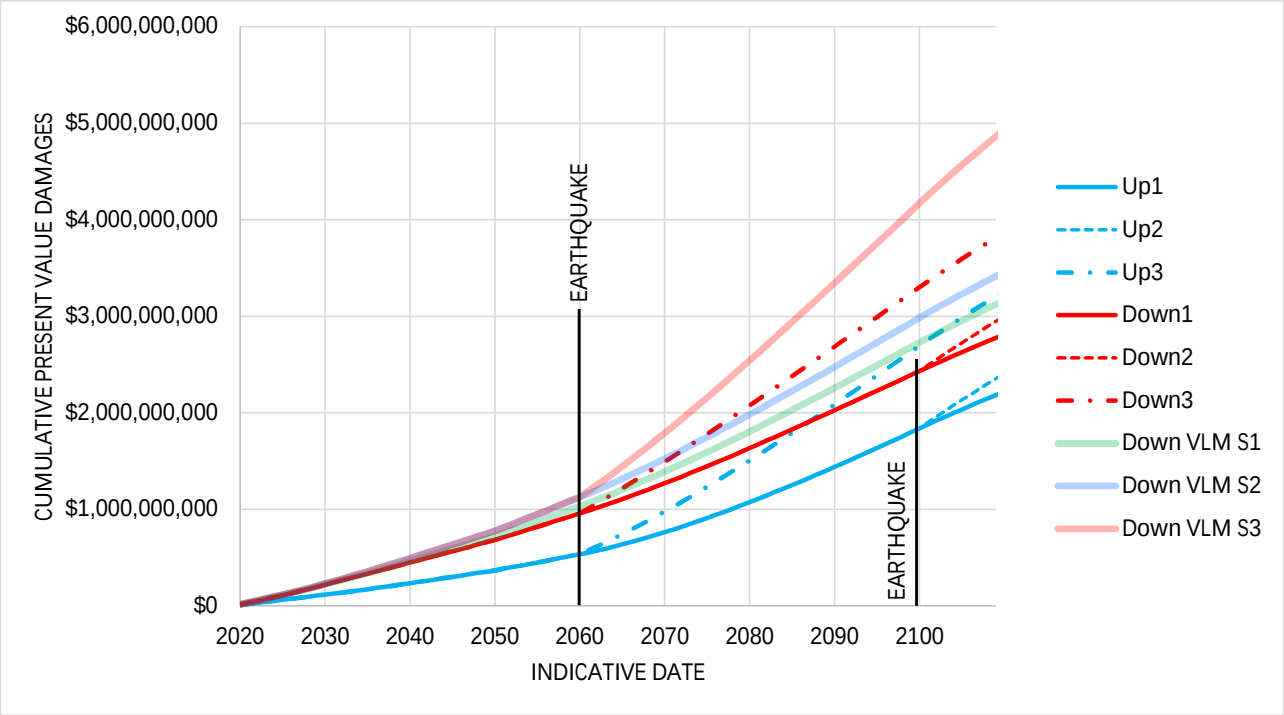


Figure 21. Cumulative present value damages from ~2020 for future pathways with and without existing stopbanks using New Zealand Treasury variable discount rate (2% for the first 30 years and 1.5% thereafter).

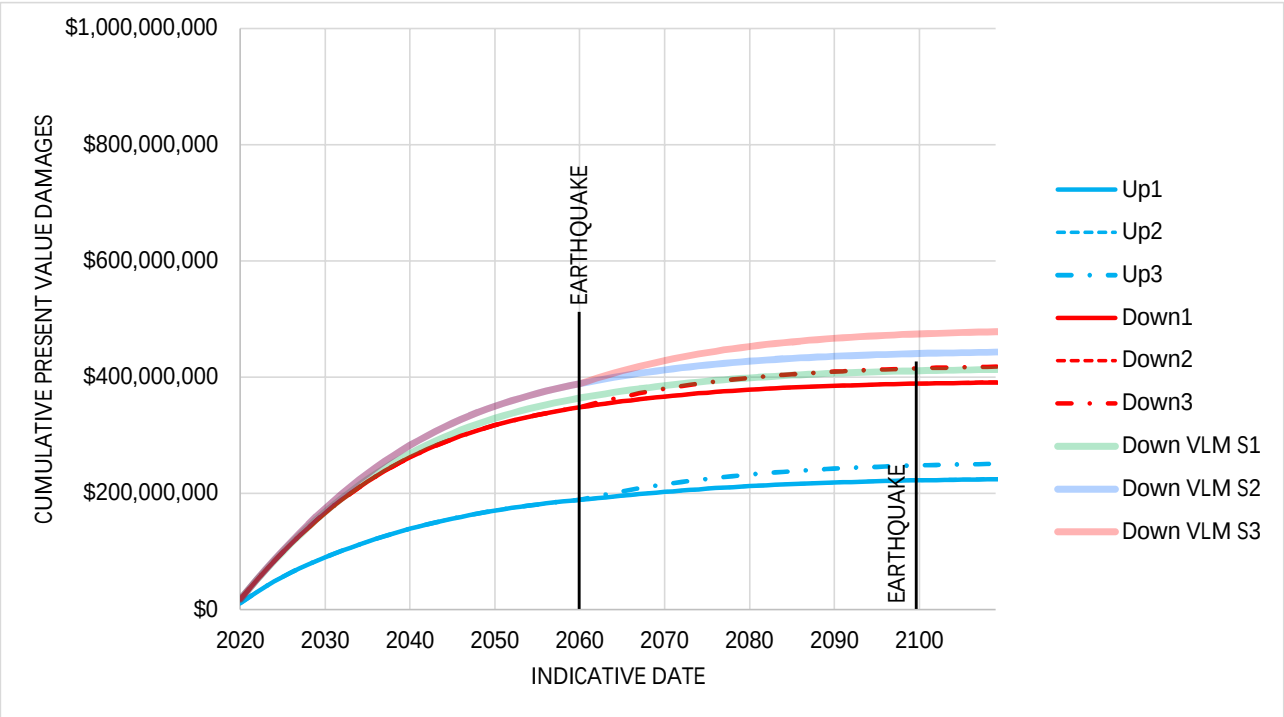


Figure 22. Cumulative present value damages from ~2020 for future pathways with and without existing stopbanks using a fixed discount rate of 8%.

4.2 With OARC Scheme

The effects of the new flood defences and pump stations proposed in the OARC Scheme have been assessed using a new version of the Avon model – the 'OARC Scheme model'. The arrangement of the new flood defences and pump stations represented in the model is as shown in Figure 7. Table 14 lists the scenarios simulated for the OARC Scheme.

Table 14. Scenarios simulated with OARC Scheme

SLR Approximate timing	0 m 2020	0.19 m 2030	0.45 m 2060	1.06 m 2100	1.88 m 2150	2.4 m > 2150
OARC Scheme	✓	✓	✓	✓	✓	✓
+ earthquake			✓	✓		
+ VLM S1			✓	✓		
+ VLM S2			✓	✓		
+ VLM S3 (inc. earthquake)			✓	✓		

The OARC Scheme model is based on the 'no stopbanks' version of the Avon flood model on the expectation that the existing stopbanks will either be demolished or breached as part of the scheme[32]. In the model, the crest level of the new flood defences is set at a sufficient level to contain water levels in the river corridor in all the modelled scenarios. In this way, the resulting model water levels in the river allow the required crest levels of the flood defences to be determined. Flood defence alignments are based on indicative alignments shown in the OARC Regeneration Plan. Minor adjustments to the alignments have been made where necessary to suit the model schematisation. Additional sections of raised flood defences have been included at the upstream and downstream ends of the OARC Regeneration Plan area – e.g., in South New Brighton – either as new flood defences or to replace existing stopbanks and prevent flooding from outside the Plan area outflanking the new OARC flood defences. These works will need further consideration to ensure that the proposed scheme is fully effective.

Stormwater pump stations are represented in the pipe network model at existing stormwater pipe outfalls. The model pump capacities are set sufficiently high to maintain free discharge in the pipes at the outfalls in all the scenarios modelled. Additional pumps to extract surface water at the vicinity of outfalls are included as point 'sinks' in the model. New non-return valves and sealed access chamber covers have also been included in the stormwater network model where necessary to prevent water in the river bypassing the setback flood defences. Further details on the model construction and peer review of the modelling are provided in the Model Build Statement in Appendix H.

It should be noted that the arrangement of the flood defences and pumpstations is subject to change as design of the scheme progresses and will be subject to further modelling as part of other Council projects.

For the scenarios which exclude ongoing VLM, the additional effects of land settlement from earthquake on flood hazard are considered in two of the future climate states (0.45 m and 1.06 m SLR). The combined effects of VLM and land settlement from an earthquake in the 0.45 m SLR climate state are considered in VLM Scenario 3.

4.2.1 Flood extent

Figure 23 and Figure 24 show the OARC Scheme model flood extents for the three AEPs simulated for 0.45 m, 1.06 m, 1.88 m and 2.4 m SLR, without earthquake settlement or VLM.

[32] It should be noted that Council do not have the relevant resource consents at this stage to either demolish or breach the existing stopbanks but would intend to do so and hence this is allowed for in the modelled arrangement.

Figure 25 shows the model flood extents for the same events with earthquake settlement (but without VLM) for 0.45 m and 1.06 m SLR. Figure 26 shows the change in 10% and 0.5% AEP flood depths following the modelled earthquake settlement with 0.45 m SLR, including allowance for VLM up to 2060 (Scenario 2).

Figure 27 shows the modelled flood extent with the OARC Scheme for the 10% AEP, with and without VLM, for 0.45 m SLR and 1.06 m SLR. Figure 28 shows the corresponding extents for the 0.5% AEP.

The model results show that:

- Both with and without earthquake settlement, **the largest changes in flood depths over the future scenarios simulated are within the river corridor, the OARC Regeneration Plan area and Horseshoe Lake/Waikākāriki and, for SLR greater than 1 m, in New Brighton and along the coastline as a result of coastal inundation.** Outside these areas there is a more gradual increase in flooding from pluvial flooding with future climate change.
- **For the scenarios including earthquake-induced land settlement, flood depths are increased in some areas and reduced in other areas**. This reflects the modelled spatial variation in settlement with increased depth of flooding tending to occur in areas of greater land settlement through ponding of runoff from areas of less settlement where flood depths are reduced.
- The model results show that **the extent of flooding generally increases with VLM but, for all three scenarios considered, the effect of VLM on maximum flood extent is relatively small.** The change in flood extent is greatest for VLM Scenario 3 which includes the effect of earthquake land settlement and increased post-seismic VLM following the earthquake settlement.

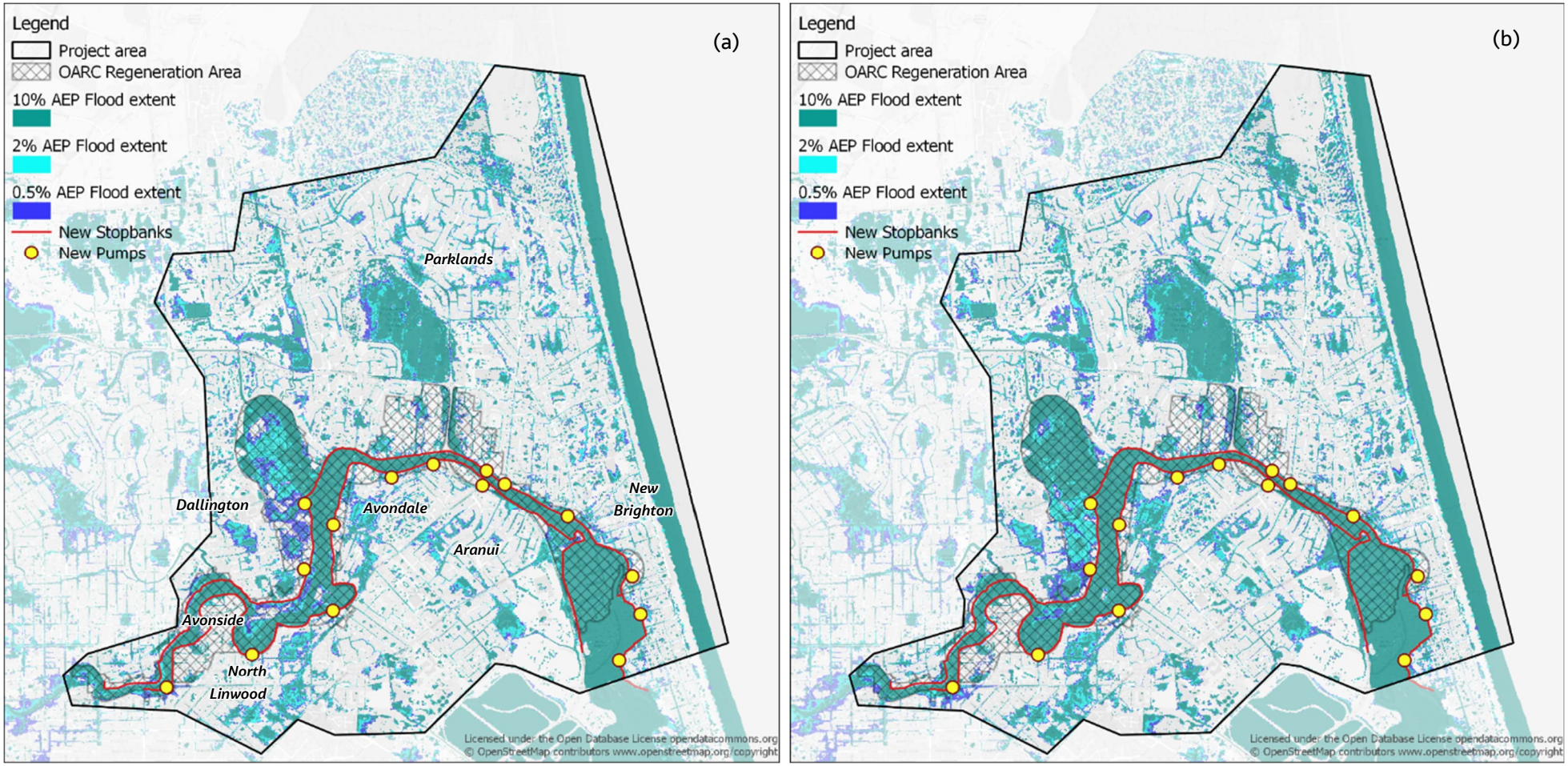


Figure 23. Modelled flood extents with OARC Scheme (without earthquake settlement or VLM): (a) 0.45 m SLR; (b) 1.06 m SLR.

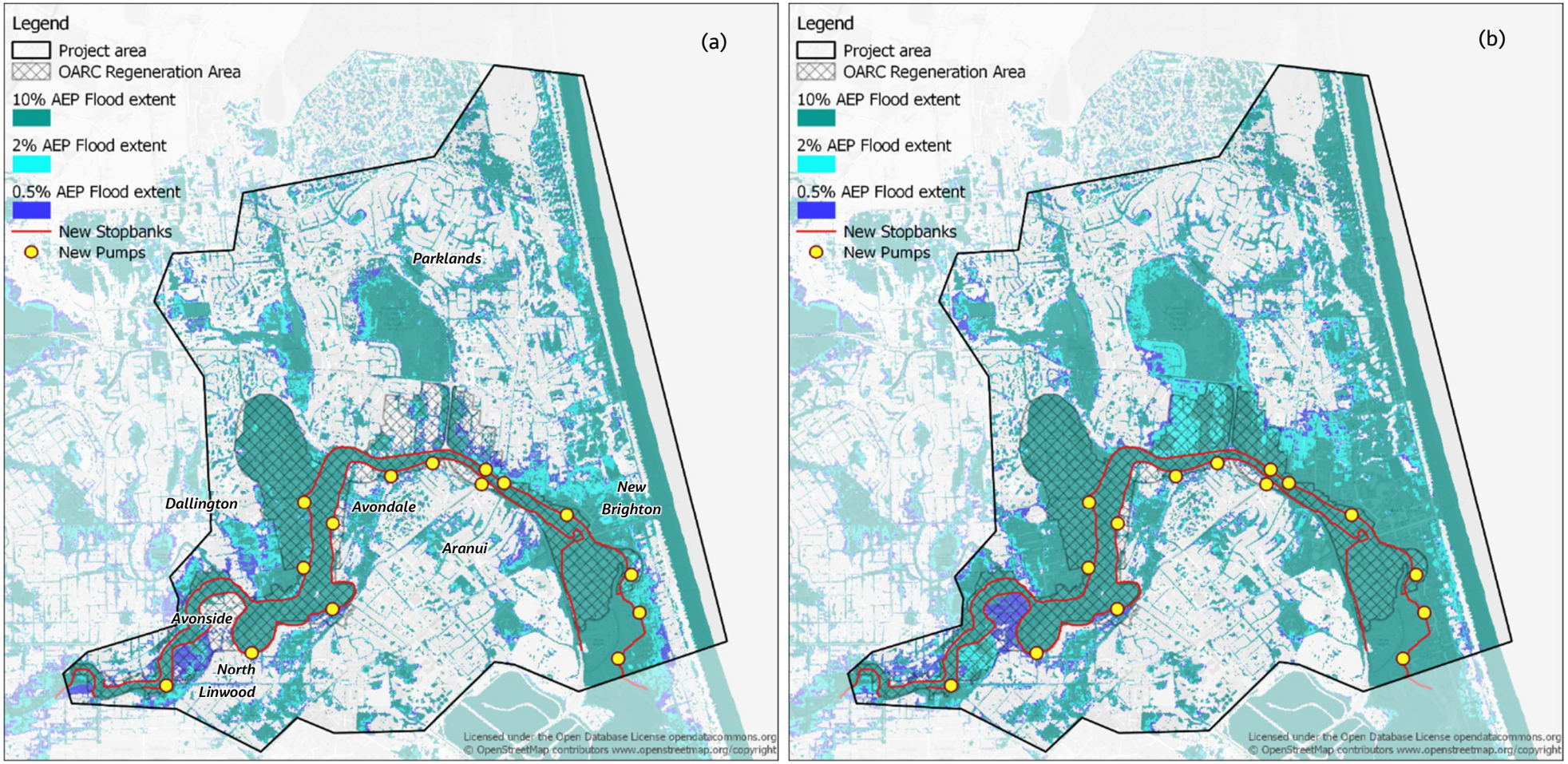


Figure 24. Modelled flood extents with OARC Scheme (without earthquake settlement or VLM): (a) 1.88 m SLR; (b) 2.4 m SLR.

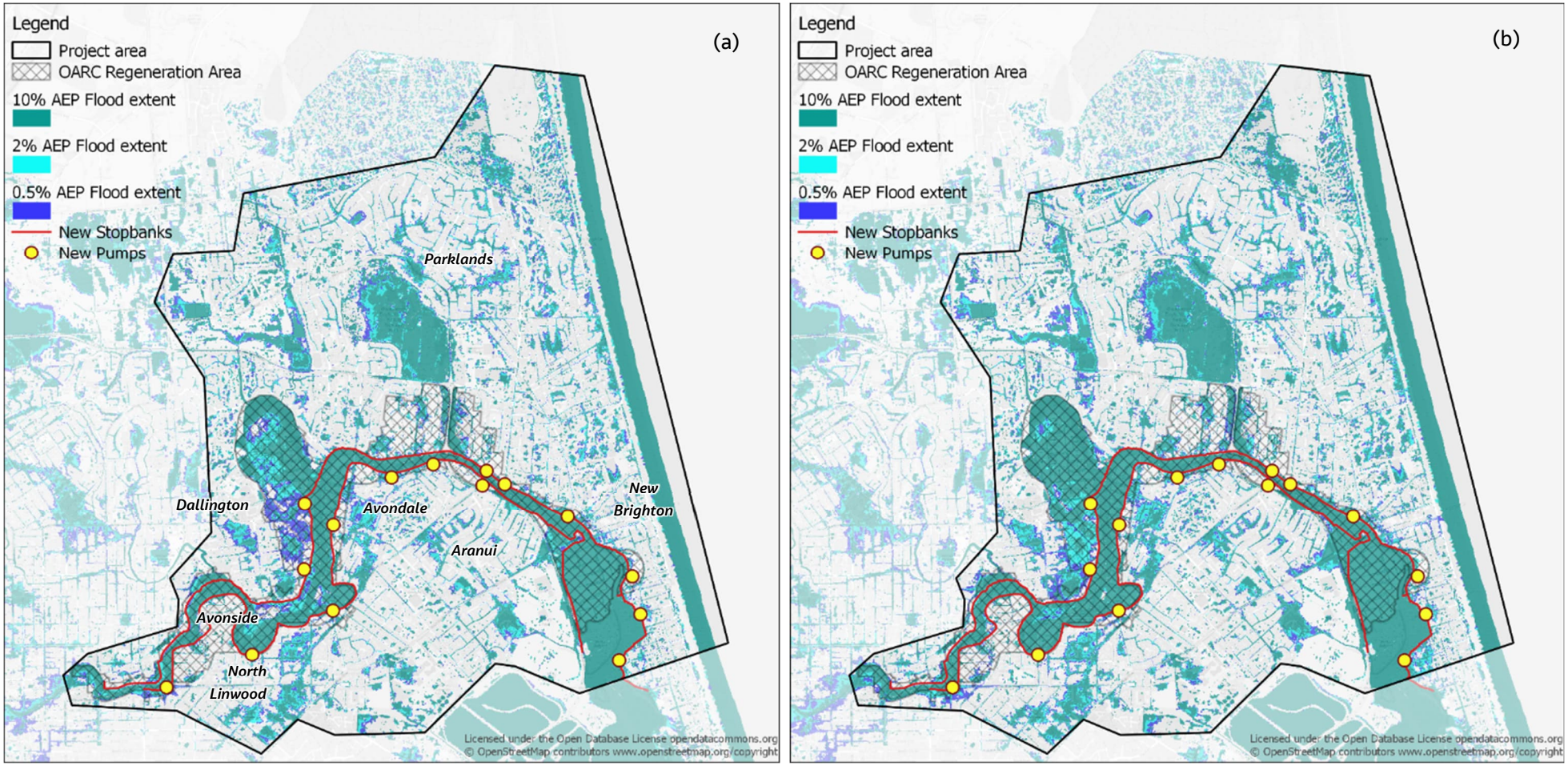


Figure 25. Modelled flood extents with OARC Scheme with earthquake settlement (without VLM): (a) 0.45 m SLR; (b) 1.06 m SLR.

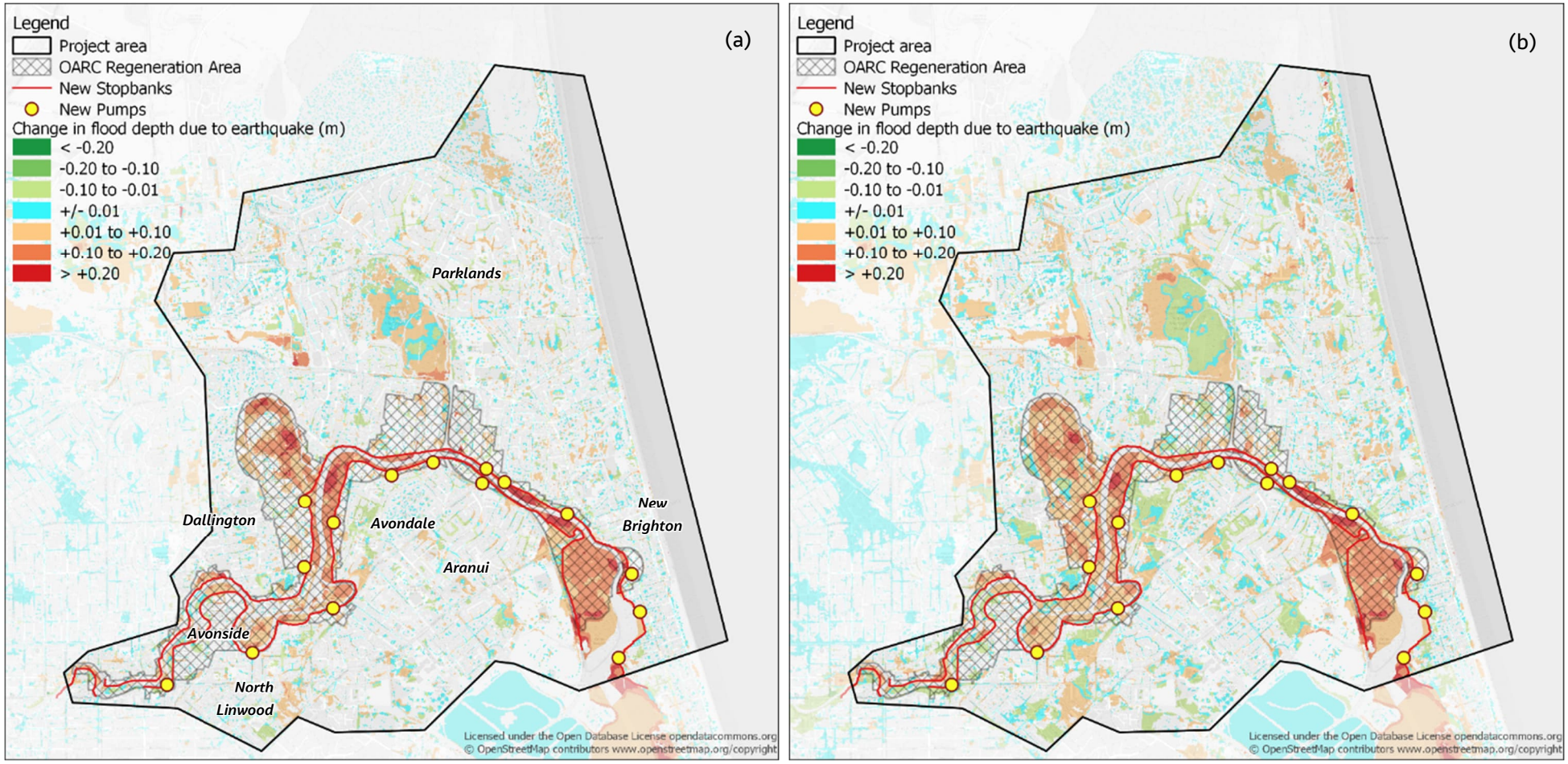


Figure 26. Change in modelled flood depths due to earthquake-induced land settlement (with VLM) for 0.45 m SLR: (a) 10% AEP; (b) 0.5% AEP.

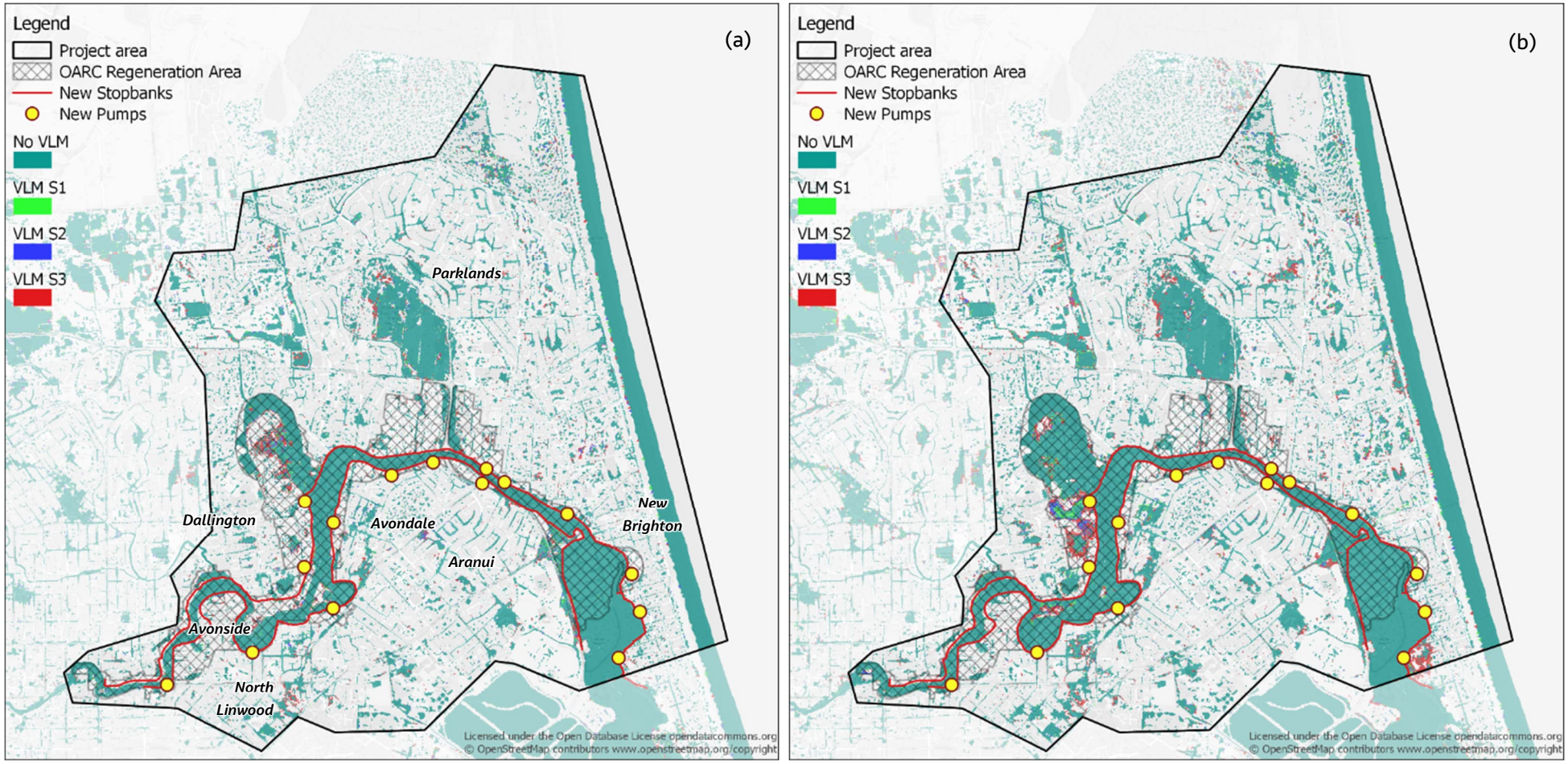


Figure 27. Modelled 10% AEP flood extents with OARC Scheme, with and without VLM (a) 0.45 m SLR; (b) 1.06 m SLR.

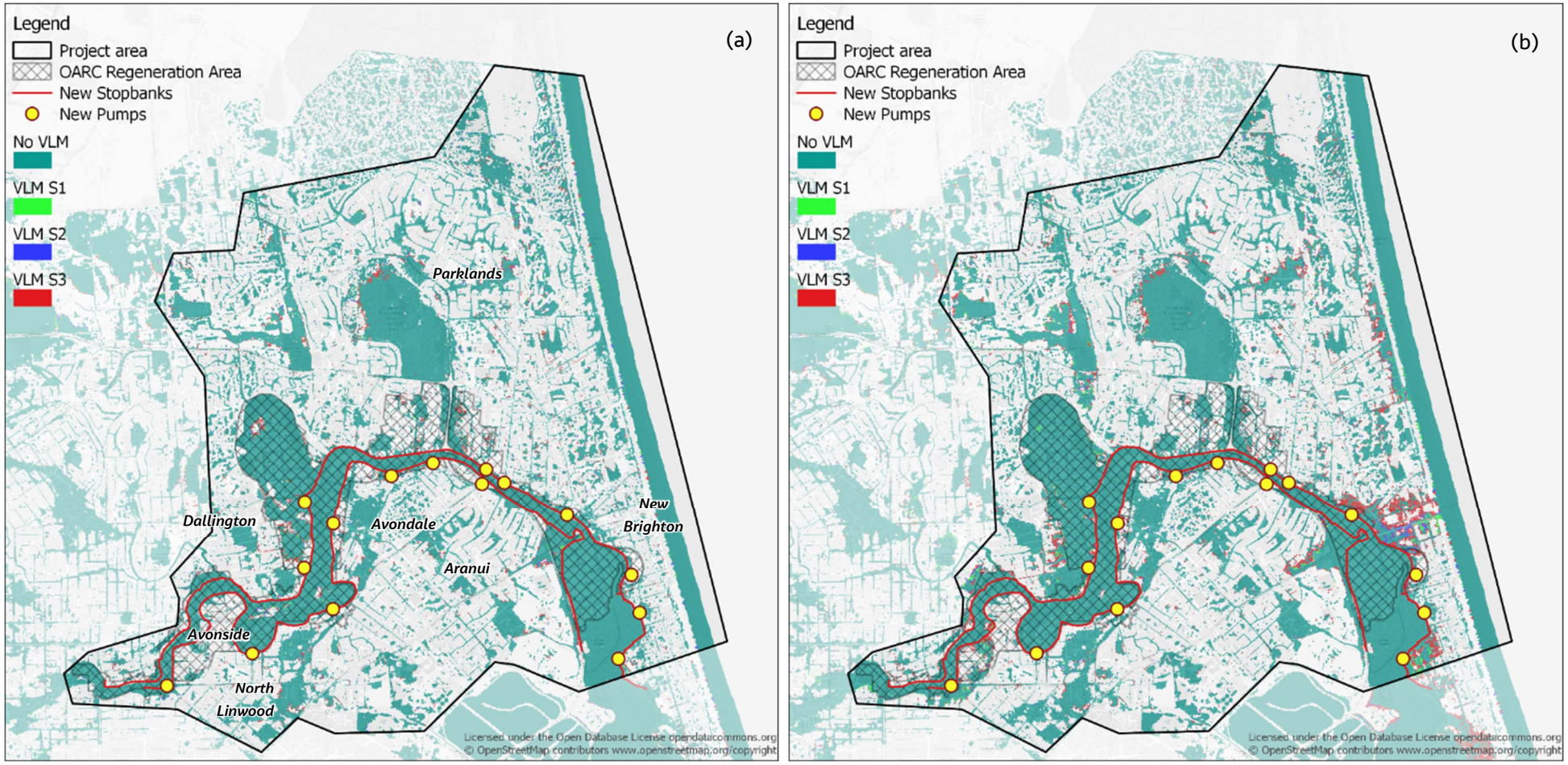


Figure 28. Modelled 0.5% AEP flood extents with OARC Scheme, with and without VLM (a) 0.45 m SLR; (b) 1.06 m SLR.

4.2.2 OARC Scheme performance

Flood extents and depths

Figure 29 compares the modelled 10% and 0.5% AEP flood OARC Scheme flood extents to those with the existing stopbanks for 0.19 m SLR, i.e., in approximately 2030, at which time the existing stopbanks will be approaching the end of their functional life. The model results do not include VLM but the amount of settlement at this time compared to the present day and its effect on flooding is expected to be very small. The results show that **in the short term, flooding with the OARC Scheme for more likely flood events (10% AEP) is very similar to that with the existing stopbanks**. In these scenarios the existing stopbanks are generally high enough to prevent flooding from the Ōtākaro Avon River and flood hazard outside the stopbanks is primarily due to rainfall over the catchments draining to the river. The new pump stations in the OARC Scheme model reduce the flooding from the stormwater network to some degree in this AEP but the difference in flood extent is very small.

For less likely events (0.5% AEP) in the same timescale, flood extent along the river corridor outside the new flood defences is more significantly reduced by the OARC Scheme model, particularly in the Avondale, Aranui and New Brighton areas where, without the scheme, flooding is a combination of overtopping of the stopbanks and rainfall. Further away from the river, where flooding is due primarily to rainfall and is beyond the influence of the new pump stations, the OARC Scheme has little effect on flooding.

Although the OARC Scheme has been modelled as fully in place in the near future (~2030) it must be noted that the lead time to construct the flood defences and pump stations will be relatively long due to their complexity and cost. Therefore, **it will be necessary to progress design and construction promptly to have the scheme in place and operational to achieve the modelled benefits.**

Figure 30 and Figure 31 compare the modelled flood extent with the OARC Scheme in place to the flooding without any stopbanks for VLM scenario 2 in future scenarios of 0.45 m SLR (~2060) and 1.06 m (~2100) respectively, beyond the expected functional life of the existing stopbanks. **The area protected from flooding by the OARC Scheme increases substantially with future climate change, particularly for more likely events (10% AEP)** in which large areas of the river corridor are exposed to tidally influenced river flooding with increasing SLR, but pluvial flooding is less extensive**. For less likely events (0.5% AEP) pluvial flooding in the area protected from river flooding by the scheme is more significant**.

Figure 32(a) shows the reduction in flood depths with the OARC Scheme for the 0.5% AEP with 0.45 m SLR and the corresponding "area benefitting from the OARC Scheme" in which the flood depths are smaller than without any stopbanks or new pumpstations. Figure 32(b) shows how **the area benefitting from the OARC Scheme is limited to the lowest lying part of the project area, in the corridor along the Ōtākaro Avon River corridor.** Pluvial flooding on higher ground outside the corridor is unaffected by the Scheme.

As shown in Figure 32(a), compared to flooding without any stopbanks, flood depths are generally reduced by the OARC Scheme outside the new flood defences. However, river levels are higher with the OARC Scheme as a result of confining flow within the new flood defences and so flood depths within the defences are increased. Although the new flood defences will be designed to contain the expected river levels, the results indicate that **the OARC Scheme will increase river levels upstream and downstream of the OARC Scheme flood defences resulting in higher flood levels in these areas than if there were no stopbanks.** Flood risk in these areas and any potential impacts of the OARC Scheme should be considered further by Council.

Figure 33 shows the area benefitting from the OARC Scheme for 0.45 m SLR (~2060) in relation to land use in the project area. On the true left bank of the river, upstream of New Brighton almost all the area benefiting from the OARC Scheme lies within the Regeneration Plan area or existing wetlands (Travis Park) while along the true right bank of the river, more substantial areas of existing residential and non-residential development in Aranui, Avondale and Linwood benefit. This suggests that **there may be opportunities to**

prioritise sections of flood defences according to benefits or possibly consider a less continuous arrangement combined with local defences depending on planned uses of the Regeneration Plan area.

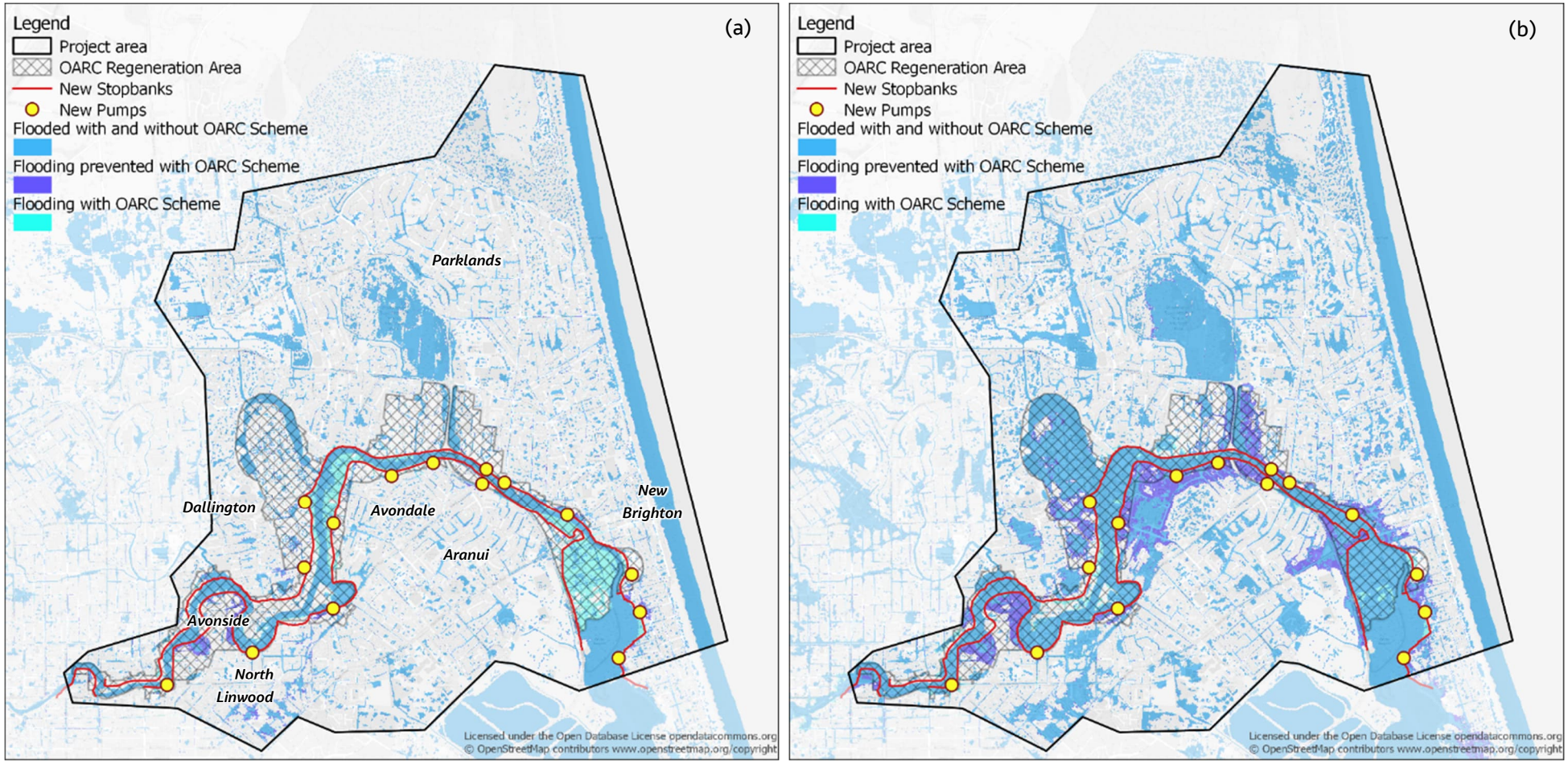


Figure 29. Modelled flood extents with and without the OARC Scheme with 0.19 m SLR (~2030) with no VLM: (a) 10% AEP; (b) 0.5% AEP.

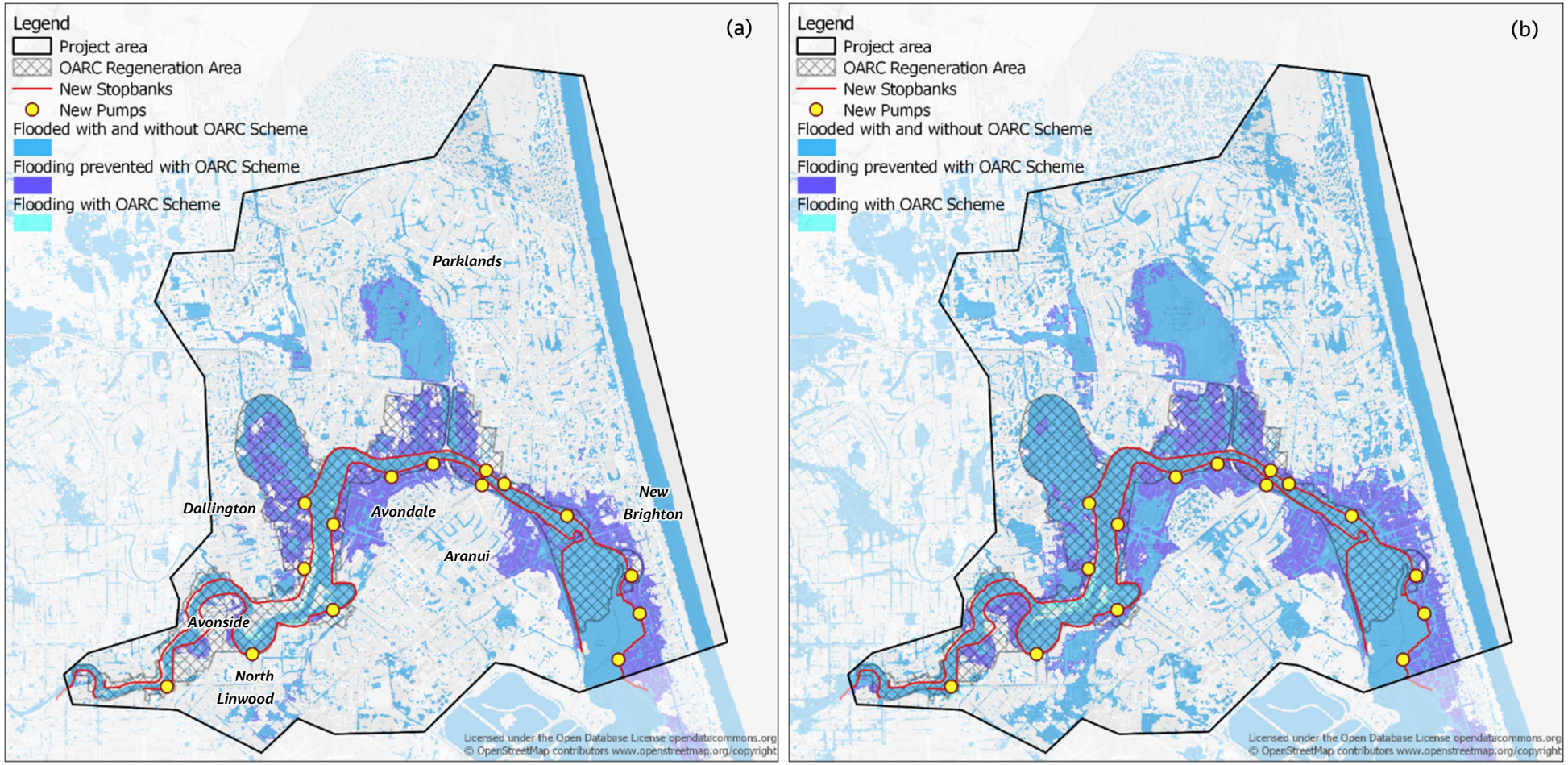


Figure 30. Modelled flood extents with and without the OARC Scheme with 0.45 m SLR (~2060) with VLM Scenario 2: (a) 10% AEP; (b) 0.5% AEP.

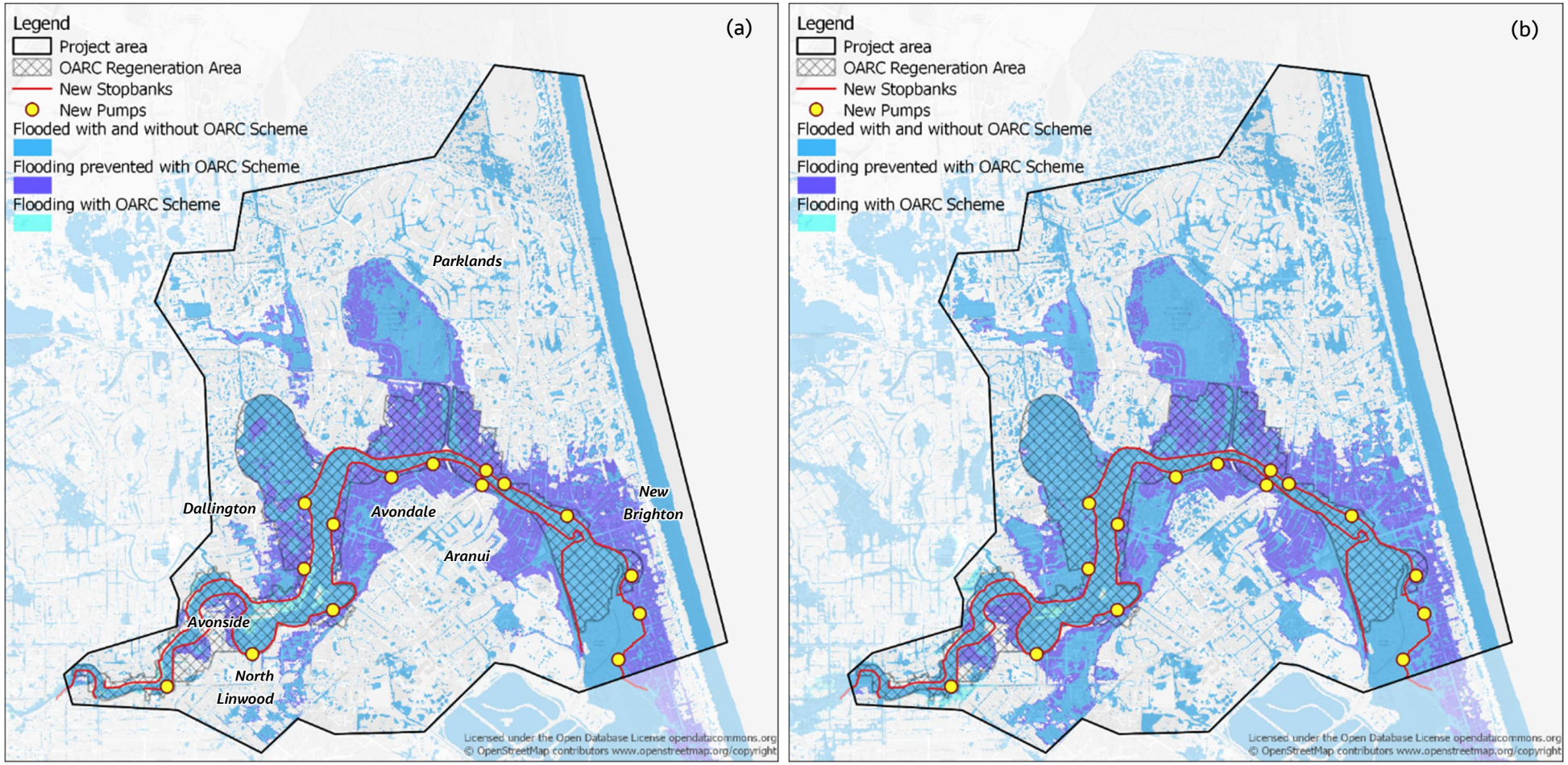


Figure 31. Modelled flood extents with and without the OARC Scheme with 1.06 m SLR (~2100) with VLM Scenario 2: (a) 10% AEP; (b) 0.5% AEP.

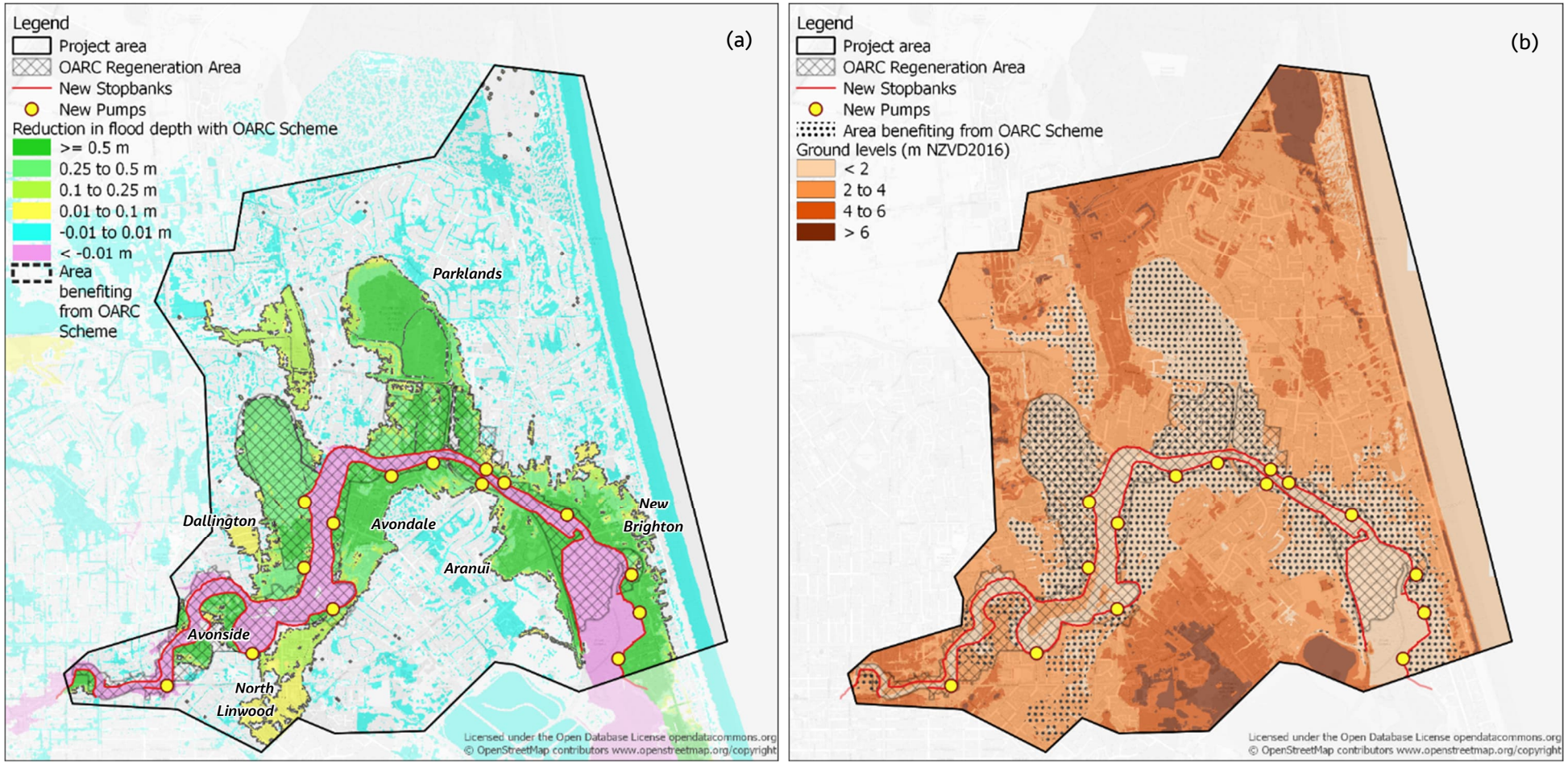


Figure 32. (a) reductions in model flood depths with OARC Scheme for 0.5% AEP and 0.45 m SLR (VLM Scenario 2); (b) area benefiting from the OARC Scheme in relation to topography of the project area.

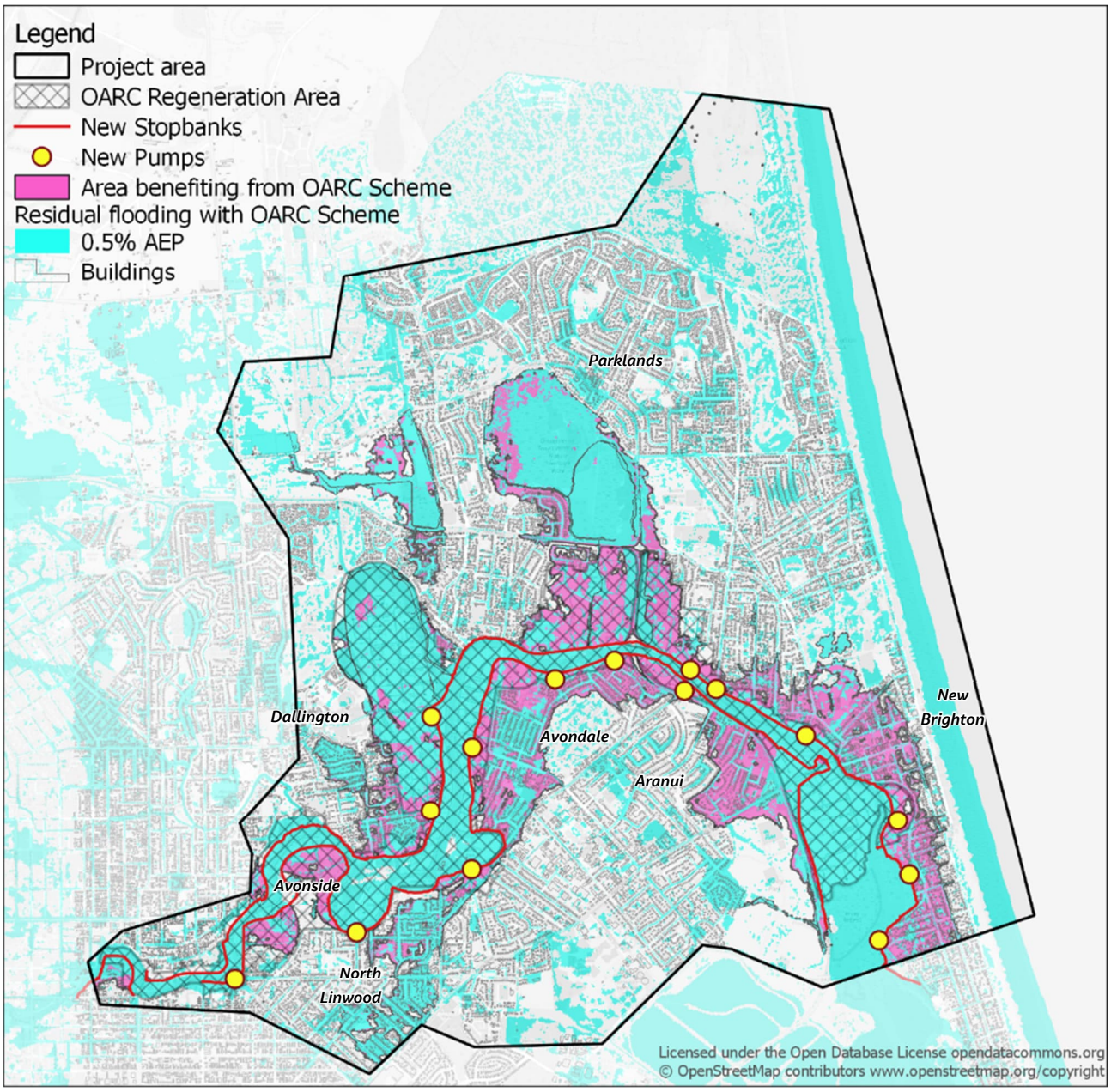


Figure 33. Area benefiting from the OARC Scheme (0.45 m SLR, VLM Scenario 2) in relation to developed land in the project area.

Pumpstations and stormwater drainage

For most of the new pump stations the maximum pumped flow rate does not increase substantially with future climate change although the rainfall over the catchments does increase. For example, for 10 of the new pump stations the difference in peak flow between the 0.19 m SLR and 1.06 m SLR scenarios is less than around 10% of the 0.19 m SLR flow. In the model, the available pump capacity is larger than the simulated pumped flows, so pumped flow is not constrained by pump capacity flow. This suggests that for these pump stations the flow reaching the pumps is limited by the inletting and conveyance capacity of the pipe network serving the pump station, as represented in the model, rather than the catchment runoff. At the remaining new pump stations the increase in maximum flow is larger, indicating fewer constraints to the flow paths for surface water to the pumpstations or greater capacity in the drainage networks to these pump stations.

Although the maximum pumped flow does not vary significantly at most of the new pump stations, **the total volume pumped, and the duration of pumping, does increase over the future scenarios**, reflecting the increases in total rainfall depth, runoff volume in the catchments and tailwater levels preventing gravity discharge of the stormwater network. In future scenarios which include the earthquake-induced land settlement values derived for the project (which vary over the project area) the modelled pump flows are generally very similar to the scenarios without land settlement. The actual changes in flow reaching the pumps could vary according to the spatial distribution of settlement.

4.2.3 River water levels

Figure 34 shows the maximum modelled water levels in the Ōtākaro Avon River for the 0.5% AEP with 0.19 m to 1.88 m SLR, without any allowance for VLM and provide an indication of the required flood defence crest levels in each future scenario. Maximum water levels are tidally dominated as far upstream as around the Avondale Road bridge.

Figure 35 compares the 0.5% AEP water levels for the three VLM scenarios with those without VLM. VLM Scenario S3 includes the additional reductions ground levels from earthquake-induced settlement. In the downstream reach of the river, where water levels are tidally dominated, VLM and earthquake settlement has little, if any effect, on maximum water levels.

Further upstream, where fluvial events determine the maximum water level, water levels are reduced by VLM and earthquake settlement due to the reduction in ground level. Where the water levels are still tidally influenced the reduction in water level is less than the corresponding general reduction in ground levels. Towards the upstream end of the project area, where river levels become independent of tide level, the reduction in water levels tends to equal the reduction in ground level. This is shown on Figure 36.

The model simulations indicate that within the project area the potential reductions in river water levels due to future VLM is generally less than the corresponding amount of VLM for all three VLM scenarios considered. **Given the uncertainty in future VLM and its effects on river levels, it may therefore be prudent to base the flood defence design crest levels on modelled water levels excluding VLM and to provide allowance for the full potential amount of future VLM as an additional component of flood defence construction crest level.**

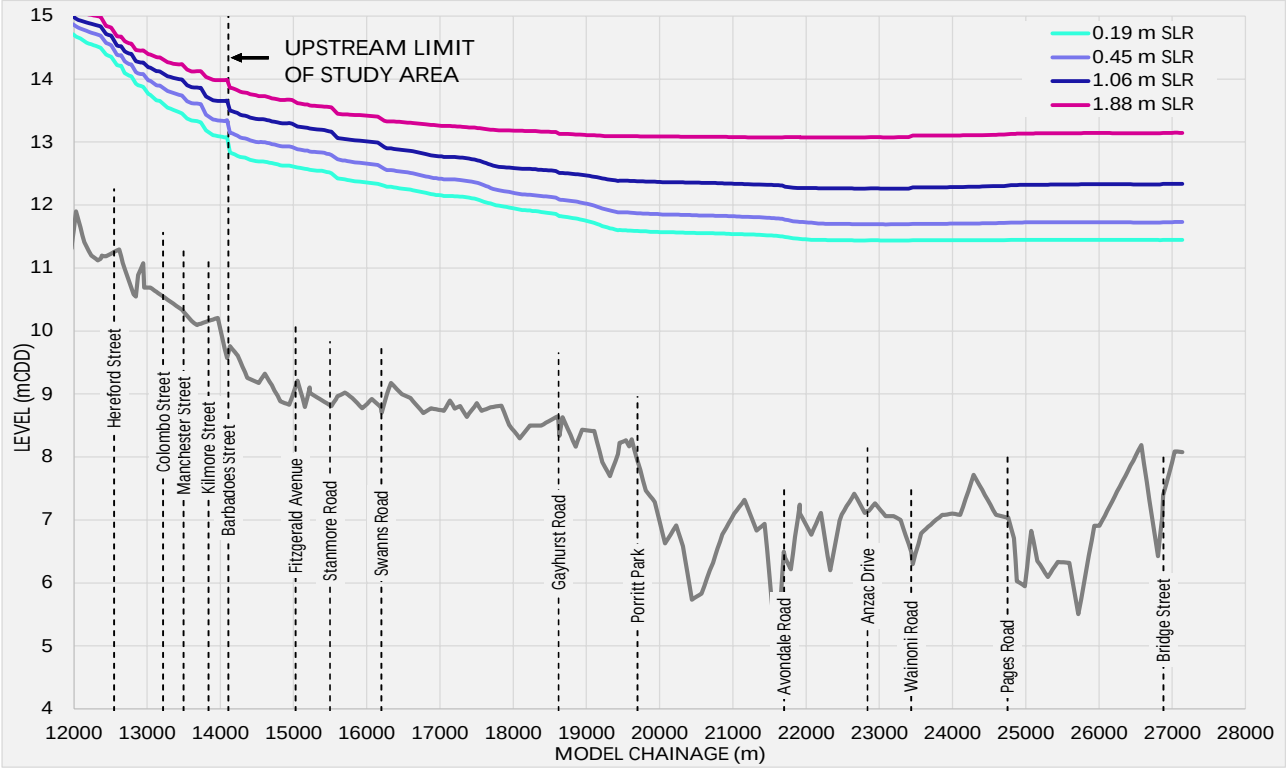


Figure 34. OARC Scheme model results for maximum water levels in the Ōtākaro Avon River for 0.5% AEP with 0.19 m, 0.45 m, 1.06 m and 1.88 m SLR (without VLM).

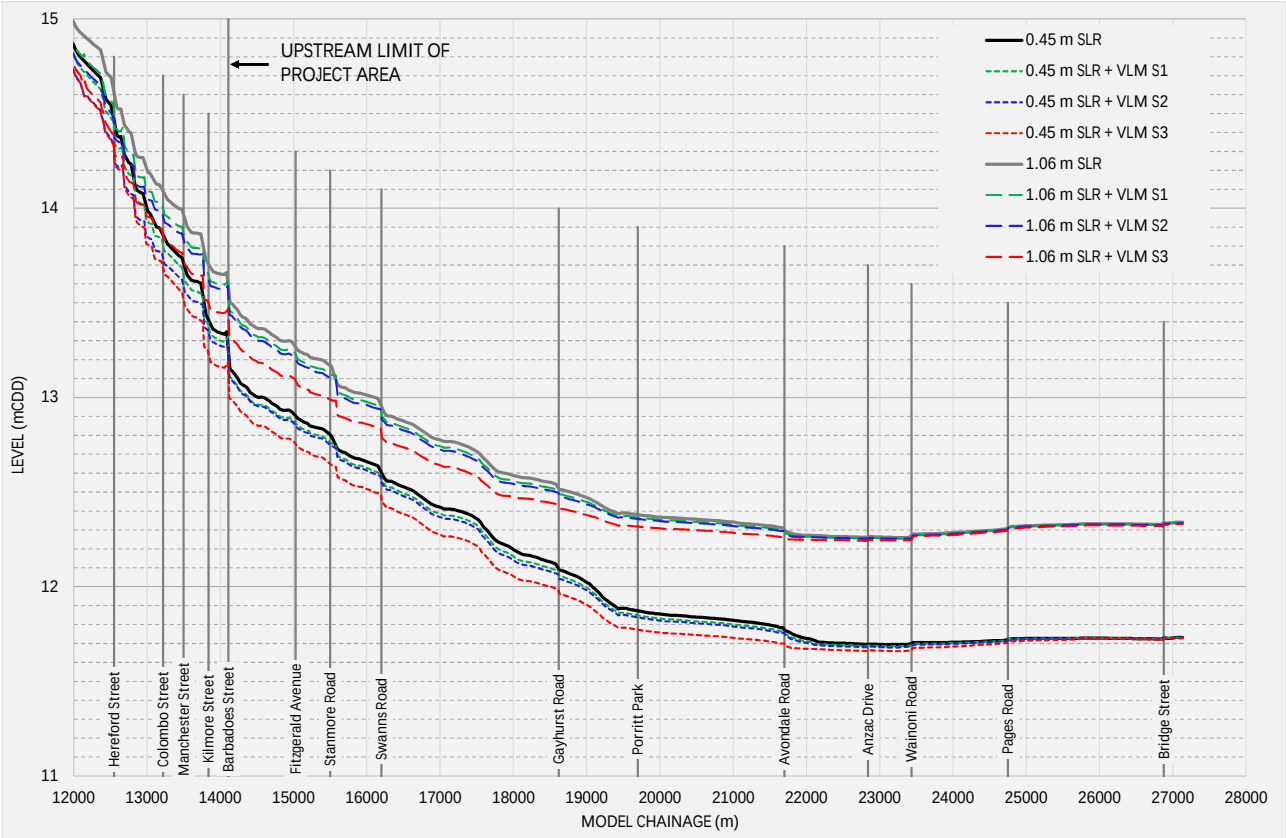


Figure 35. OARC Scheme model results for maximum water levels in the Ōtākaro Avon River for 0.5% AEP with 0.45 m and 1.06 m SLR (with and without VLM).

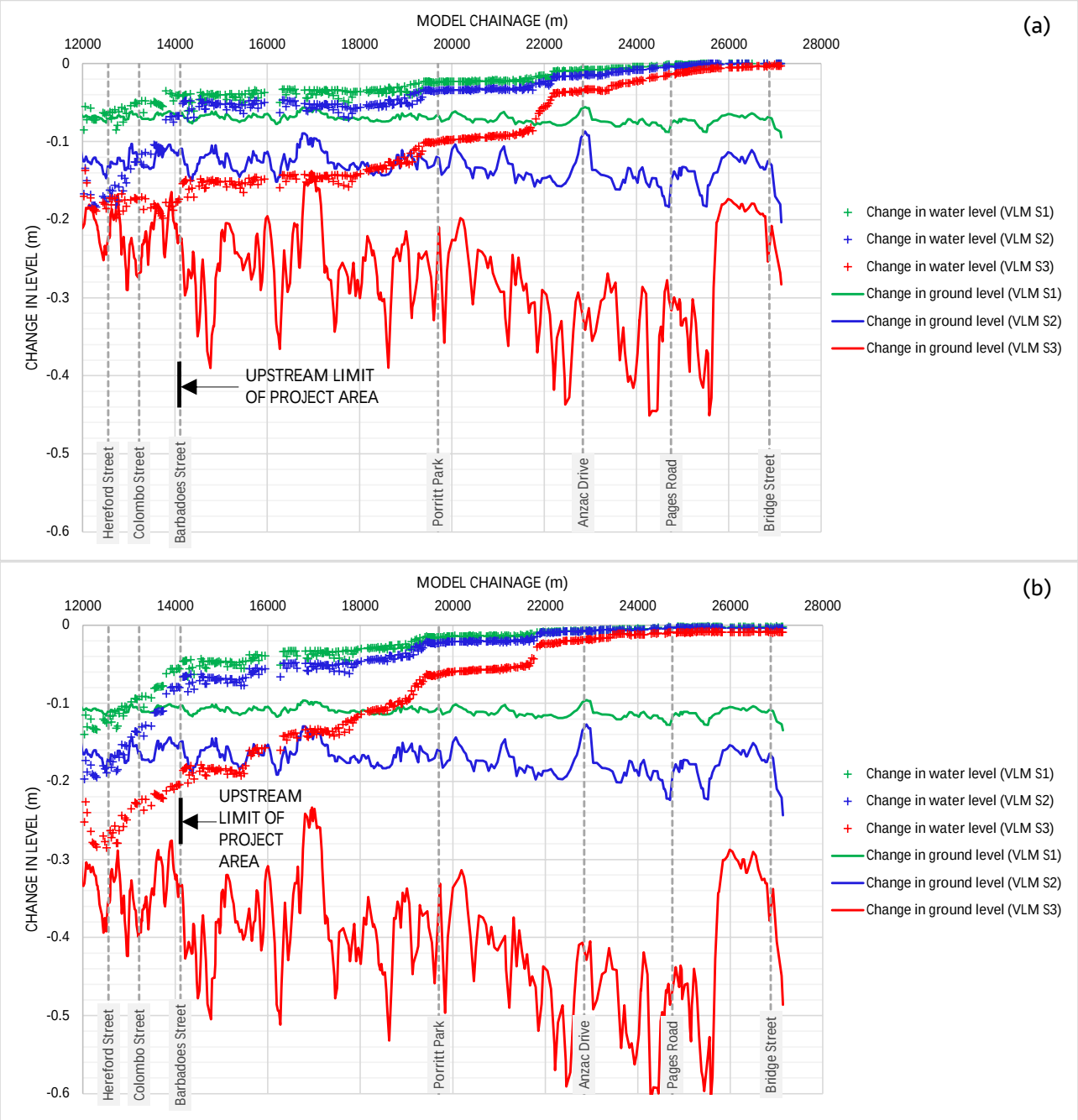


Figure 36. Change in maximum modelled water levels in the Ōtākaro Avon River with OARC Scheme due to VLM (and, in Scenario S3, earthquake settlement) compared to change in ground level along the river (a) for 0.45 m SLR; (b) for 1.06 m SLR.

4.2.4 Properties flooded

Figure 37(a) and Figure 37(b) show, for the 10% AEP and 0.5% AEP respectively, the number of buildings with 'under floor flooding' and 'above floor flooding' with the OARC Scheme, based on the model results for each of the scenarios in Table 14 excluding VLM.

'Under floor flooding' is defined as any building footprint which intersects the modelled flood extent and 'above floor flooding' is defined as any building intersecting the modelled flood extent for which the freeboard from the flood level to the floor level is less than 100 mm. This indicates when houses may be at risk of above floor flooding. This freeboard amount is intended to allow for unmodelled actions or processes that risk water rising above floors such as bow waves from cars and capillary action raising water up structures among others.

Results for flooding without the OARC Scheme (with and without the existing stopbanks) are shown for comparison.

Figure 37(c) and Figure 37(d) show the effect of VLM on the number of buildings flooded for 0.45 m SLR and 1.06 m SLR.

The building counts for all scenarios and AEPs are tabulated in Table 15.

- **For the 10% AEP, the total number of buildings affected by flooding with the OARC Scheme is very similar to that with the existing stopbanks up to a sea level rise of 0.45 m** because the existing stopbanks are equally effective in preventing overtopping for this range of scenarios. However, the increase in affected buildings due to earthquake settlement in the 0.45 m SLR scenario is smaller for the OARC Scheme because the new flood defences include allowance for settlement and overtopping is prevented.
- **For the 0.5% AEP, the total number of buildings affected by flooding with the OARC Scheme is less than with the existing stopbanks even at lower values of sea level rise** because the existing stopbanks start to overtop under the present-day climate state for this magnitude of event. Overtopping of the existing stopbanks increases further with sea level rise resulting in a higher number of affected buildings. With the OARC Scheme the number of buildings affected in the earthquake settlement scenarios is less than in the existing stopbank and no stopbank scenarios without earthquake settlement provided that the flood defences do not structurally fail during the earthquake and any damage is repaired prior to a flood.
- **For both AEPs, the number of buildings affected with the OARC Scheme increases substantially above 1.06 m SLR due to additional inundation from the sea** through low points in the dunes together with greater rainfall intensity.
- **For all VLM scenarios there is only a small increase – less than 5% – in the total number of buildings with under floor flooding** for 0.45 m SLR. For VLM Scenario 3, which also includes earthquake-induced settlement, there is a somewhat larger increase in under floor flooding for 1.06 m SLR (around 10%).
- **The effect of VLM on the number of buildings with above floor flooding is also small in both SLR scenarios, except for VLM Scenario 3,** where the number of buildings at risk increases substantially – by more than 100%. This is comparable to, but a little greater than, the effect of earthquake settlement without VLM (noting the greater uncertainty in results for the earthquake scenarios).

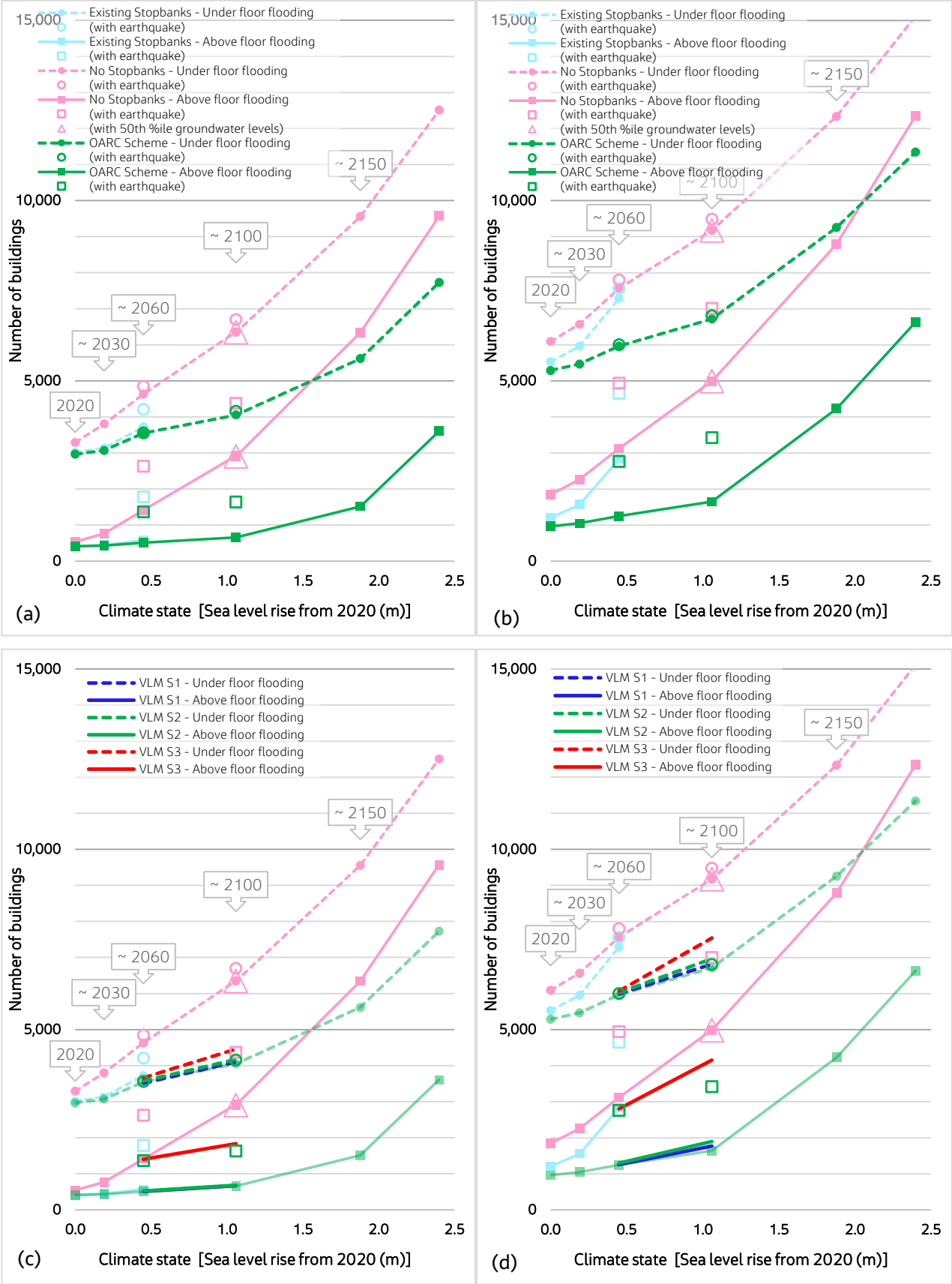


Figure 37. Model results for number of buildings with under floor and above floor flooding with OARC Scheme in: (a) 10% AEP and (b) 0.5% AEP, without VLM; (c) 10% AEP and (d) 0.5% AEP, with VLM.

Table 15. Approximate number of buildings subject to flooding with OARC Scheme.

				Total building footprints intersecting modelled flood extent			Buildings where flood level within 100 mm of floor level			Buildings where flood level above floor level		
SLR and indicative timing	**VLM**	**Land settlement from earthquake**	**Groundwater levels**	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP
0 m SLR (2020)	None	no	85th percentile	2964	4322	5288	412	670	963	114	208	349
0.19 m SLR (2030)	None	no	85th percentile	3069	4419	5467	433	702	1048	116	230	385
0.45 m SLR (2060)	None	no	85th percentile	3549	5008	5964	507	876	1245	154	303	487
		yes	85th percentile	3560	4968	6006	1364	2062	2763	595	973	1435
	S1	no	85th percentile	3509	4925	5991	509	847	1260	154	306	500
	S2	no	85th percentile	3569	4985	6023	523	868	1294	164	316	509
	S3	yes	85th percentile	3662	5062	6074	1405	2114	2798	615	1013	1490
1.06 m SLR (2100)	None	no	85th percentile	4052	5509	6714	661	1066	1646	211	422	756
		yes	85th percentile	4153	5611	6807	1634	2486	3422	762	1262	1982
	S1	no	85th percentile	4106	5565	6816	666	1110	1767	220	445	841
	S2	no	85th percentile	4172	5659	6963	687	1153	1895	226	465	932
	S3	yes	85th percentile	4460	6102	7539	1835	2917	4153	862	1622	2684
1.88 m SLR (2150)	None	no	85th percentile	5613	7789	9255	1513	3057	4227	804	2138	3129
2.4 m SLR (>2150)	None	no	85th percentile	7729	9927	11343	3609	5438	6630	2850	4470	5527

Table 16 shows the number of buildings at risk of above floor flooding within the **area benefiting from the OARC Scheme** in the largest event considered (0.5% AEP), for the 'more likely' scenario of future VLM S2 (without earthquake-induced ground settlement) and for VLM combined with earthquake-induced ground settlement in ~2060 (VLM S3), compared to the rest of the Stage 3 project area.

In both the 2060 and 2100 future scenarios, the OARC Scheme is estimated to reduce the number of buildings with a 0.5% AEP of above floor flooding by around 80% to 90% within the area benefiting from the scheme. In the event of ground settlement following an earthquake and increased VLM following such an event, the modelling indicates that the OARC Scheme would still substantially reduce the number of buildings at risk in the area benefiting from the scheme (by around 65% to 75% for the modelled scenario of ground settlement) provided the flood defences are restored to their previous functional state where needed after such an event. (Note that any reduction in performance of the stormwater drainage network due to earthquake damage is not allowed for in this assessment).

In the wider project area, outside the area benefiting from the OARC Scheme, nearly 900 buildings are estimated to be at risk of above floor flooding in 2060 and 2100. The number of buildings at risk could increase substantially – double, for example – following earthquake-induced ground settlement. Outside the area benefiting the ground levels are higher than in the floodplain and flooding is generally shallower and predominantly due to runoff from pluvial events. Drainage of catchments which outfall to the sea rather than the river can also be influenced by storm tides in Pegasus Bay in some of the future scenarios.

Table 16. Estimated number of buildings with 0.5% AEP of flooding above floor level in the area benefiting from the OARC Scheme

		0.45 m SLR (~2060)		1.06 m SLR (~2100)	
		Without earthquake (VLM S2)	With earthquake (VLM S3)	Without earthquake (VLM S2)	With earthquake (VLM S3)
Outside area benefiting from OARC Scheme		876	1,865	870	1,872
Within area benefiting from OARC Scheme	*Without OARC Scheme*	2,638	3,424	4,765	6,186
	With OARC Scheme	411	913	984	2,178

4.2.5 Flood damages

Annual Average Damage (AAD)

Figure 38 and Table 17 summarise the AAD from flooding over the project area with the OARC Scheme in place, as calculated using FloodFX and the model results for each of the OARC Scheme scenarios listed in Table 14. The corresponding AADs for flooding without the OARC Scheme (with and without the existing stopbanks) are also shown, for comparison.

It should be noted that for the OARC Scheme scenarios, the new flood defences are taken to be constructed, or adapted through further raising, to contain the largest flood event simulated (0.5% AEP) in all of the SLR scenarios considered. The feasibility of providing this scale of structure and standard of protection in the more extreme future scenarios simulated (e.g., 2.4 m SLR) has not be assessed in this project.

In the short term (0.19 m SLR, ~2030) the reduction in flood damages with the OARC Scheme over the existing stopbanks is relatively modest (around 12%). **However, under further climate change, when the existing stopbanks are no longer functional, the benefits of the OARC Scheme are much more substantial** – e.g., a reduction in AAD of 70% in around 2060 (0.45 m SLR) and 85% in around 2100 (1.06 m SLR).

With the OARC Scheme in place, the AAD over the project area does not increase significantly with sea level rise until this exceeds 1.06 m. This is because the new flood defences prevent fluvial and tidal flooding from the river for the range of events modelled and the residual flooding from pluvial ponding does not increase as significantly with climate change as the potential flooding from the river.

Inundation from the sea, through low points on the shoreline of Pegasus Bay, will tend to increase the flood damages in the project area for SLR over 1.06 m based on present day shoreline ground levels. Changes in the elevation of the dunes, and shoreline more generally, through morphological change, coastal erosion, management practices or changes to shoreline infrastructure could mean that the onset of significant coastal inundation occurs at a lower or higher SLR.

With the OARC Scheme, damages from flooding following earthquake-induced land settlement are much lower than they would be without new flood defences. Provided the new flood defences remain functional following a seismic event, or are repaired prior to the next flood event, the OARC Scheme will continue to provide a similar standard of protection from flooding from the river. Without stopbanks, land settlement increases the depth of any flooding from the river since river water levels are not reduced by the same amount as the ground level (and not at all in the tidal reach). The effect of land settlement on pluvial flooding in the model is relatively small. However, the model scenarios do not allow for any damage to the stormwater network, which could be time consuming to remediate following an earthquake event, increasing pluvial flood risk.

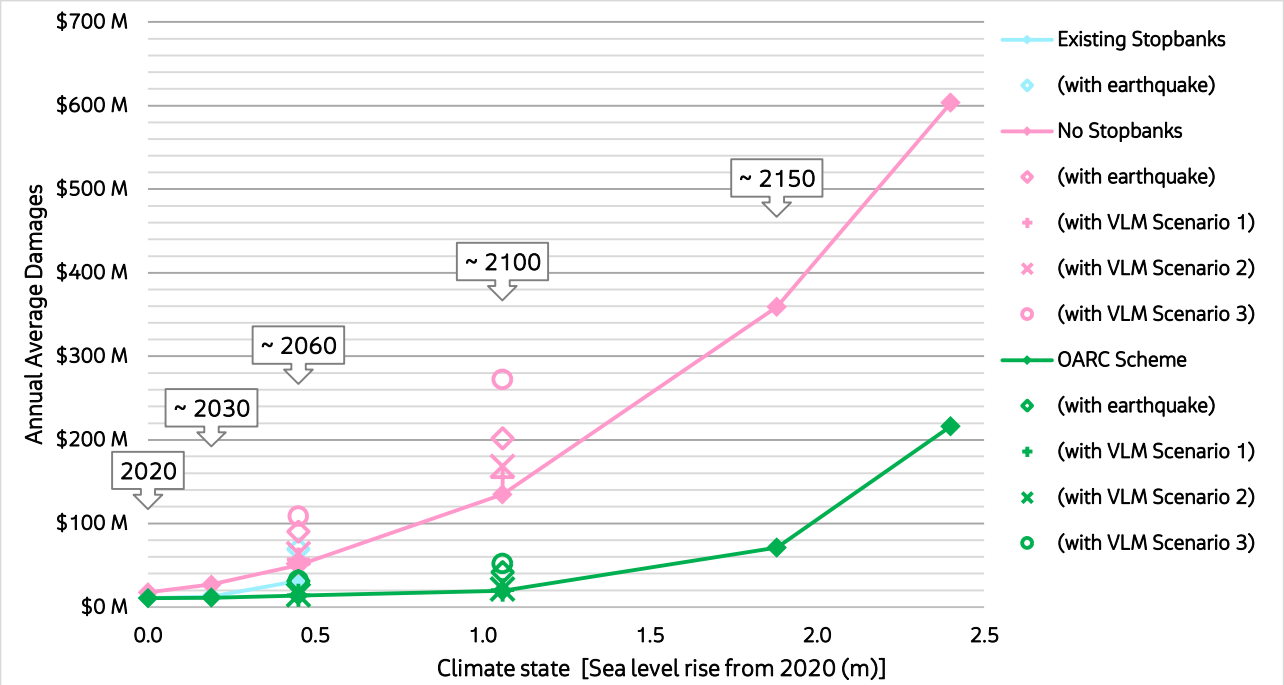


Figure 38. AAD from flooding in the project area with OARC Scheme.

Table 17. Summary of Average Annual Damage from flooding in project area ($M)

Flood management	VLM	Earthquake	Future scenario – SLR (m)					
			0	0.19	0.45	1.06	1.88	2.4
Existing stopbanks	None	No	11	13	31	-	-	-
		Yes	-	-	69	-	-	-
No stopbanks	None	No	18	27	50	135	359	604
		Yes	-	-	90	202	-	-
	S1	**No**	**-**	**-**	**57**	**156**	**-**	**-**
	S2	**No**	**-**	**-**	**64**	**169**	**-**	**-**
	S3	**Yes**	**-**	**-**	**109**	**272**	**-**	**-**
OARC Scheme	None	No	11	11	14	19	71	217
		Yes	-	-	31	41	-	-
	S1	**No**	**-**	**-**	**14**	**20**	**-**	**-**
	S2	**No**	**-**	**-**	**14**	**21**	**-**	**-**
	S3	**Yes**	**-**	**-**	**32**	**52**	**-**	**-**

Table 18 shows the AAD within the area benefiting from the OARC Scheme for the 'more likely' scenario of future VLM S2 (without earthquake-induced ground settlement) and for VLM combined with earthquake-induced ground settlement in ~2060 (VLM S3), compared to the rest of the Stage 3 project area.

The AAD from flooding in this area amounts to 80% to 90% of the total flood damage estimated for the entire Stage 3 project area. The new flood protection measures in the OARC Scheme are estimated to reduce the total flood damage in the area benefiting from the OARC Scheme by 90% to 95% for these future scenarios.

Table 18. Estimated AAD in the area benefiting from the OARC Scheme

		0.45 m SLR (~2060)		1.06 m SLR (~2100)	
		Without earthquake (VLM S2)	With earthquake (VLM S3)	Without earthquake (VLM S2)	With earthquake (VLM S3)
Outside area benefiting from OARC Scheme		$9 M	$22 M	$11 M	$26 M
Within area benefiting from OARC Scheme	*Without OARC Scheme*	$55 M	$87 M	$158 M	$246 M
	With OARC Scheme	$4 M	$8 M	$8 M	$23 M

Present value cumulative damages

Cumulative present value damages have been calculated for the three potential future pathways of climate change and earthquake-induced land settlement in Table 19 for the same two discount rates as the damages for with and without the existing stopbanks. The AAD value for each year in the pathways has been linearly interpolated from the values shown in Figure 38. For the VLM scenarios, AAD in 2020 is the same as without VLM and AAD in 2030 has been interpolated from the 2020 scenario without VLM and the 2060 scenario with VLM. Not all scenarios have been simulated beyond 2100. To illustrate the general future trend, indicative total damages beyond this date have been estimated using the AAD values at 2100.

Table 19. Pathways for assessing cumulative flood damages (with OARC Scheme).

Pathway	2020	2030	2060	2100	2120+
OARC1	OARC Scheme				
OARC2	OARC Scheme			OARC Scheme [*Earthquake settlement*]	
OARC3	OARC Scheme		OARC Scheme [*Earthquake settlement*]		
OARC-VLMS1	OARC Scheme				
OARC-VLMS2					
OARC-VLMS3	OARC Scheme		OARC Scheme [*Earthquake settlement*]		

It should be noted that the purpose of this damage assessment is to enable a comparison of the relative performance – e.g., 'better' or 'worse' – of the OARC Scheme and existing flood protection measures rather than absolute measures of benefits for benefit-cost assessment. For this purpose, present value damages have been calculated for the OARC Scheme in place over the whole of the period considered for the existing stopbanks and no stopbanks scenarios – i.e., from 2020. The OARC Scheme will not be operational until around 2030 and AADs prior to that date should be those for the existing stopbanks. However, as shown in Table 17 AAD for the existing stopbanks and OARC Scheme are similar in the first decade of the assessment and therefore the effect on long term cumulative damages will be small.

Further details of the limitations in the assessment are provided in the memo in Appendix C.

Figure 39 and Figure 40 show how the cumulative present value damages for the OARC Scheme model accrue using the New Zealand Treasury variable discount rate and fixed discount rate sensitivity test respectively. Damages for existing stopbanks and no stopbanks scenarios are shown for comparison. Table 20 summarises the cumulative present value of flood damages to 2060 and 2100 for these scenarios.

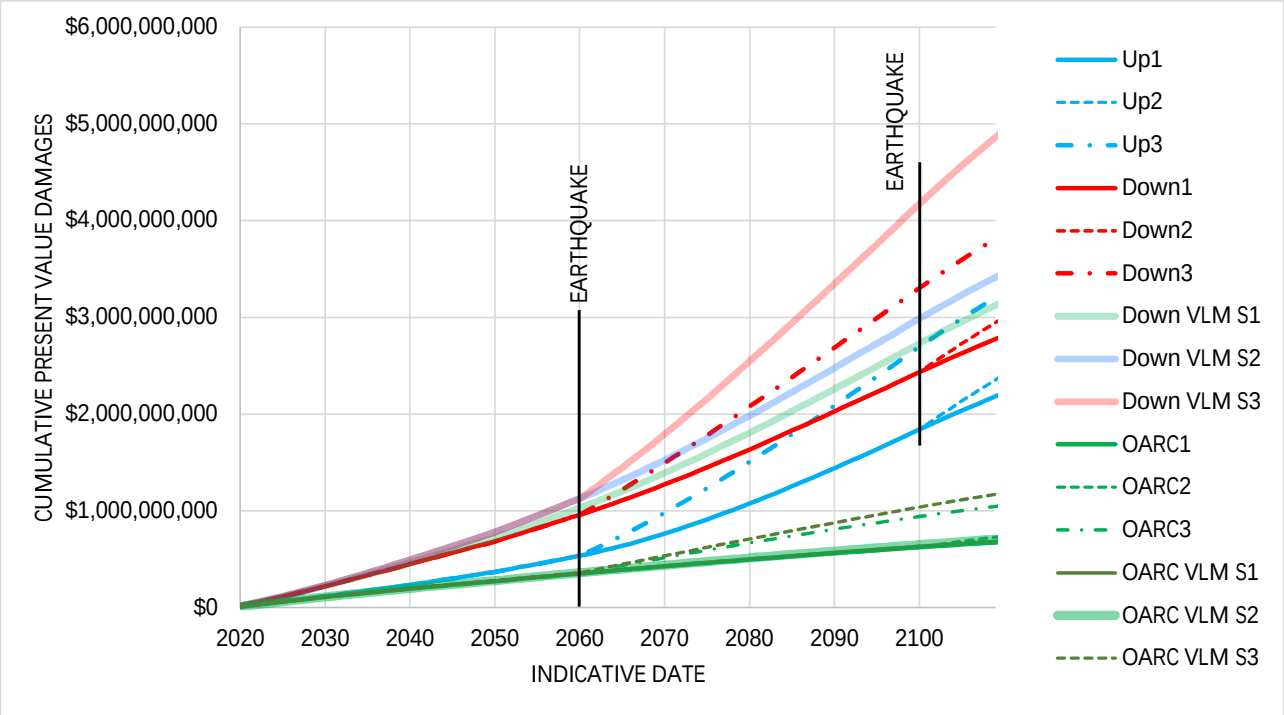


Figure 39. Cumulative present value damages from ~2020 for future pathways with and without the OARC Scheme using New Zealand Treasury variable discount rate (2% for the first 30 years and 1.5% thereafter).

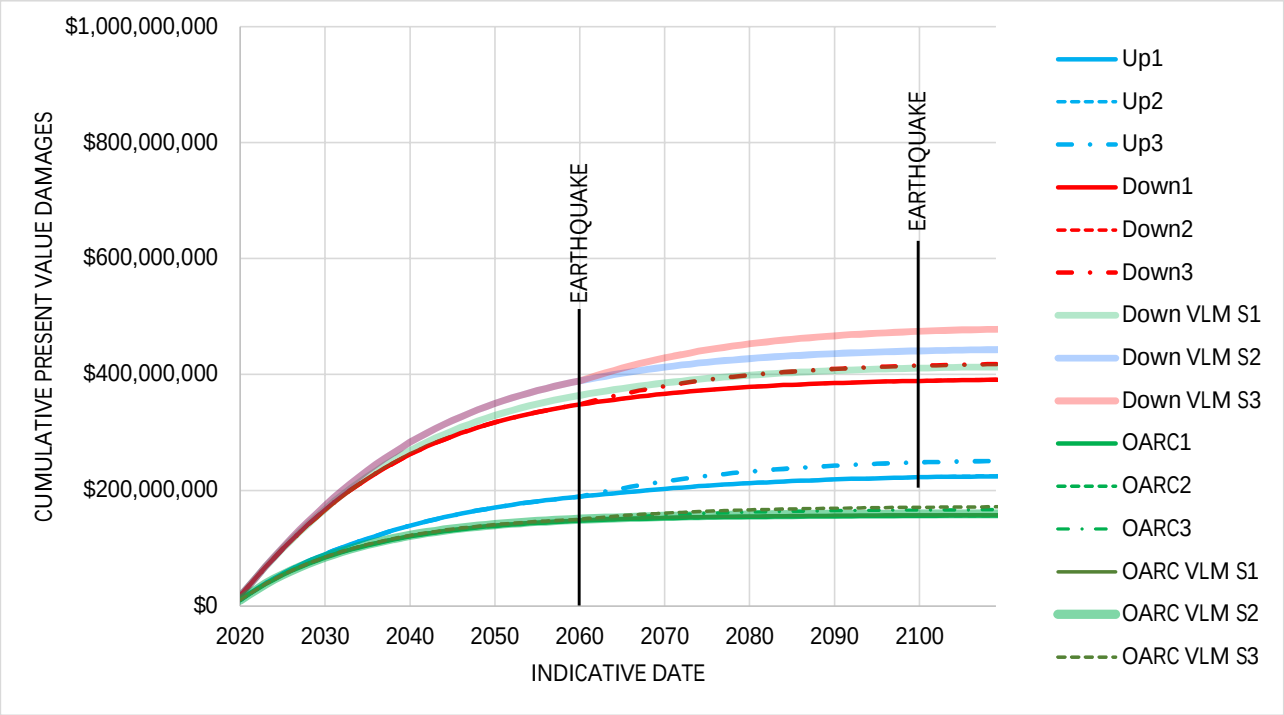


Figure 40. Cumulative present value damages from ~2020 for future pathways with and without the OARC Scheme using a fixed discount rate of 8% (New Zealand Treasury sensitivity test).

Table 20. Comparison of estimated cumulative present value damages with and without OARC Scheme allowing for VLM ($M).

Discount rate	Approximate date	2060			2100			
	VLM Scenario	NONE	S1	S2	NONE	S1	S2	S3
Variable rate (2% for 30 years followed by 1.5%)	No stopbanks	960	1030	1130	2430	2730	2990	4170
	OARC Scheme	350	350	360	620	630	650	1040
	Difference	610	680	770	1810	2090	2330	3130
Fixed rate sensitivity test (8%)	No stopbanks	350	360	390	390	410	440	470
	OARC Scheme	150	150	150	160	160	160	170
	Difference	200	220	240	230	250	280	300

As shown in Table 20, the OARC Scheme is expected to significantly reduce the total cumulative damages from flooding that would be incurred with no new flood management infrastructure. The reductions in present value cumulative damages are relatively insensitive to the rates of VLM considered, except for those to 2100 in Scenario 3, which include the additional settlement from an earthquake (in 2060) and additional post-seismic settlement damages. **Based on the New Zealand Treasury recommended variable discount rate, cumulative present value damages to 2060 are reduced by around $600 Million to $800 Million.**

Damages to 2100 are reduced by around $2 Billion. The additional damage avoided from earthquake-induced land settlement could amount to a further $1 Billion. It should be noted that in the damage calculations, the cumulative average annual damage to a property is not capped – i.e., it is assumed that damage from any flood events is repaired, and properties are liable to repeated damage in any subsequent flood events. In practice, a property may be written off after repeated flood events if the cumulative damage is large relative to the value of the property although additional write off costs could also be incurred. This could reduce the total future damages, particularly for the "no stopbanks" case where there is potential for deeper flooding and higher damages to individual properties.

The reduction in present value damages resulting from the OARC Scheme is highly sensitive to the discount rate adopted. **For a fixed rate of 8% the reduction in damages to 2060 (around $200 Million to $250 Million) are around one-third of those for the variable rate. Reduction in present value damages to 2100 are an order of magnitude lower than for the fixed rate (around $250 Million to $300 Million).**

As noted in Section 4.1.3, the present value flood damages have been calculated using the indicative earliest dates for each state under the RCP8.5 H+ climate change scenario. If emissions were to follow a lesser scenario, these future climate states could occur several decades later than the dates adopted in our assessment. This would result in a reduction in the cumulative present value flood damages to a particular future date.

Cumulative cash costs of the flood defences and pumpstations are understood to be approximately $580 Million to 2060 and $690 Million to 2100 based on programme level estimates (potential uncertainty around +/-50%). The corresponding **present value costs are estimated to be around $380 Million and $420 Million respectively using the New Zealand Treasury variable discount rate** or **around $110 Million up to both 2060 and 2100 for a fixed discount rate of 8%**.

4.3 OARC Scheme design exceedance events

The potential impacts of extreme rainfall and storm tide events, exceeding the design standard of the OARC Scheme in two future climate scenarios (~2060 and ~2100), have been assessed using a modified version of the OARC Scheme model for VLM Scenario 2. In the modified model the flood defence crest levels are set to the anticipated design levels for the 2060 and 2100 climate scenarios in accordance with Christchurch City Council's Ōtākaro Avon River Stopbanks Design Standards.

Two types of design exceedance events were simulated for each future scenario.

- Extreme pluvial flood event

  Rainfall depth double that of the 0.5% AEP 18-hour duration storm adopted in the project, representing an event more extreme than a '1 in 10,000 year' event based on extrapolation of design rainfall data, combined with a 7.7% AEP tidal boundary condition, as adopted for the 0.5% AEP pluvial events in the rest of the model simulations.

- Extreme tidal flood event

  Tide boundary 0.4 m higher than the 0.5% AEP storm tide boundary condition adopted in the project, representing an event more extreme than a '1 in 10,000 year' event based on extrapolation of storm tides at Sumner Head, combined with a 7.7% AEP 18-hour duration rainfall boundary, as adopted for the 0.5% AEP tidal events in the rest of the model simulations.

The magnitudes of these events are very much larger than the design containment level of the OARC Scheme (1% AEP with freeboard). The events have been simulated as "stress tests" to help understand where the scheme might overtop in such extreme flood events, the area's most at risk, and the relative consequences of such events occurring with the OARC Scheme in place rather than to identify improvements to the OARC Scheme.

Figure 41 shows the model flood extents for the 2060 climate scenario for the stress test events and for the largest tidal and pluvial events simulated (0.5% AEP) with the existing stopbanks (if they were still functional at this time) and with the OARC Scheme.

Figure 42 shows the model flood extents for the 2100 climate scenario for the stress test events and for the largest tidal and pluvial events simulated (0.5% AEP) without any stopbanks (the existing stopbanks would no longer be functional at this time) and with the OARC Scheme.

Figure 43 and Figure 44 show the maximum water surface and modelled flood defence crest levels along the Ōtākaro Avon River.

For the extreme tidal events the model results suggest that:

- For the 2060 future scenario, the extent of flooding in an extreme event (i.e., ~0.01% AEP) with the OARC Scheme in place will be less than that in a 0.5% AEP event with the existing stopbanks, provided the stopbanks are not breached in these circumstances. Upstream of the Pages Road bridge, the modelled depth of overtopping of the new OARC flood defences is very small (~ less than 40 mm, or dry) and there is very little flooding from the river. Downstream of Pages Road overtopping depths are around 100 mm and there will be more risk of breaching. The risk of breaching will be far greater for the existing stopbanks given their greater fragility and much greater depth of overtopping.
- Similarly, for the 2100 scenario, the modelled extent of flooding in an extreme tidal event with the OARC Scheme is generally no greater than that in the 0.5% AEP event without any stopbanks and generally far less extensive upstream of the Anzac Drive bridge. The modelled depth of overtopping on the new flood defences is slightly greater than in the 2060 scenario (around 150 mm).

For the extreme pluvial events the model results suggest that:

- Upstream of Porritt Park the potential extent of flooding in an extreme pluvial event in 2060 with the OARC Scheme is much greater than that for a 0.5% AEP event with the existing stopbanks. The depth of overtopping is much greater in the upper reach of the project area – 200 mm to 800 mm – and breaching is far more likely. Flooding in this event is also due to the increased surface water runoff from rainfall over the lower catchment of the river.
- For the 2100 scenario the extent of flooding in the extreme event with the OARC Scheme is also greater than that in the 0.5% AEP event without any stopbanks upstream of Porritt Park and the depth of overtopping is substantial in the upper reach of the project area – 200 mm to 600 mm – meaning breaching is likely.

These results indicate that the OARC Scheme could provide better protection from a future extreme tidal event than the current flood management measures provide for a less extreme (0.5% AEP) event, provided the flood defences are not breached in such an event.

The differences in flooding are because the freeboard provided in the flood defence crest level provides for containment of a relatively extreme tidal event due to the small increases in storm tide levels with reducing likelihood whereas the freeboard is relatively small in relation to the increase in fluvial water levels with reducing likelihood.

Extreme pluvial events are likely to place considerable loading on the flood defence capacity since water levels can significantly exceed flood defence crest levels. In the project area outside the Ōtākaro Avon River Corridor, extreme pluvial events will cause increased local ponding as local drainage systems will be overwhelmed by the rainfall. Elevated water levels in the Avon River also reduce capacity for local drainage, resulting in poorer drainage conditions and increased flood risk in these areas.

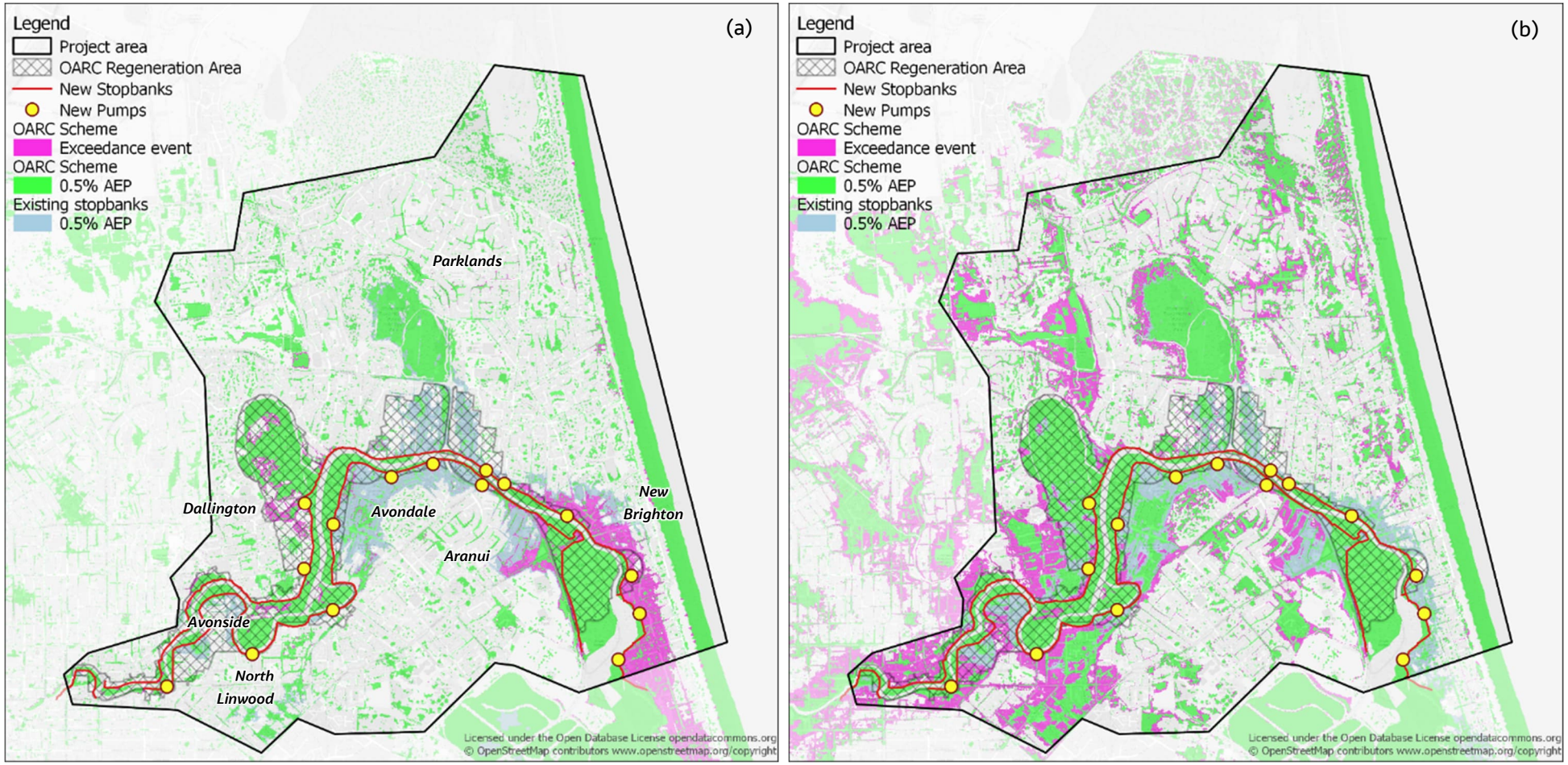


Figure 41. Modelled flood extents for design exceedance event stress tests and 0.5% AEP design event for 0.45 m SLR (~2060): (a) tidal event; (b) pluvial event.

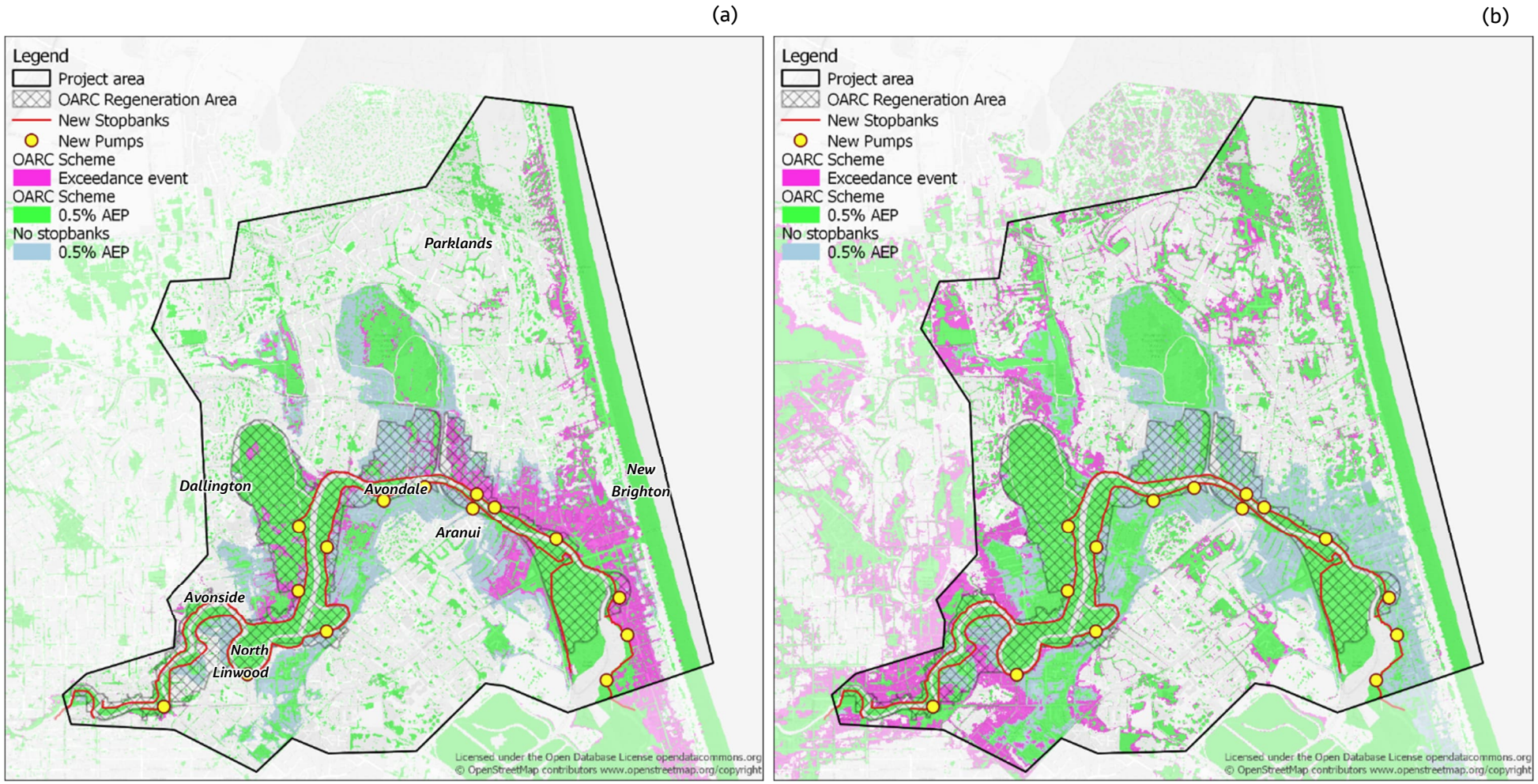


Figure 42. Modelled flood extents for design exceedance event stress tests and 0.5% AEP design event for 1.06 m SLR (~2100): (a) tidal event; (b) fluvial event.

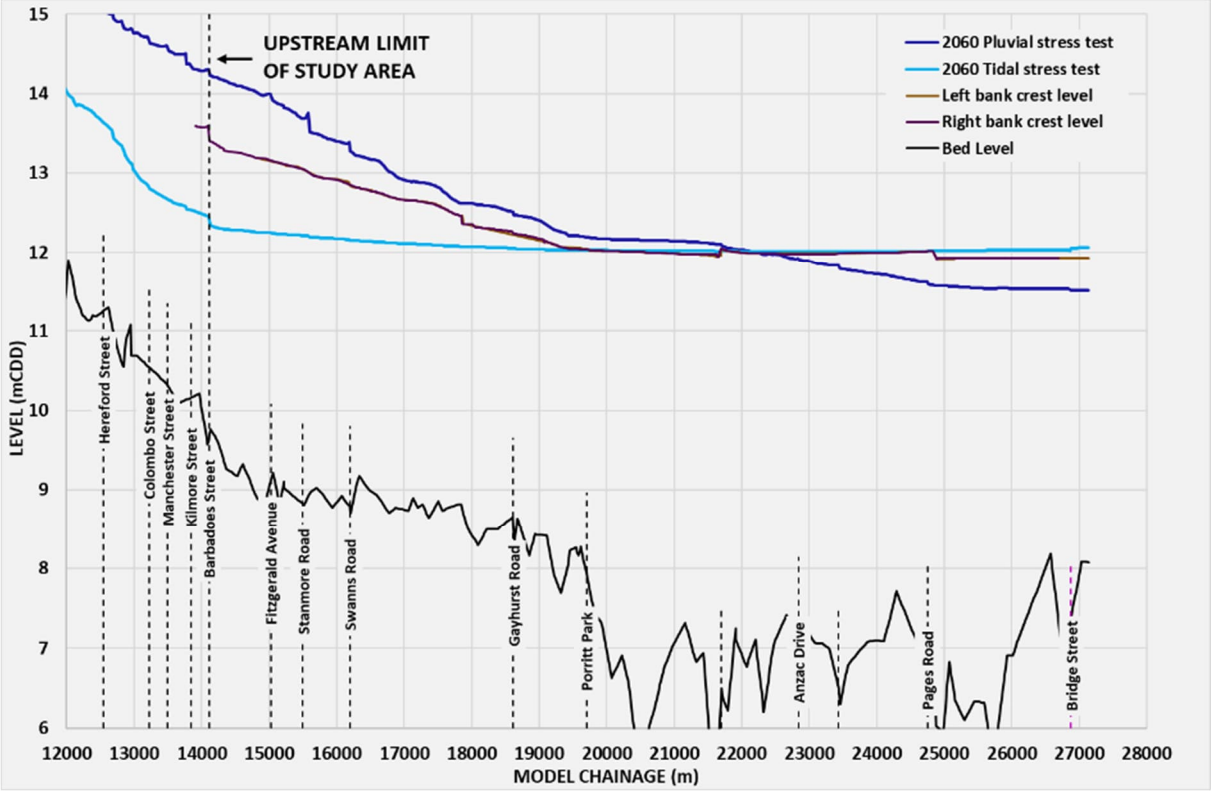


Figure 43. Water level and flood defence crest profiles along the Avon River for the 2060 pluvial and tidal stress test results

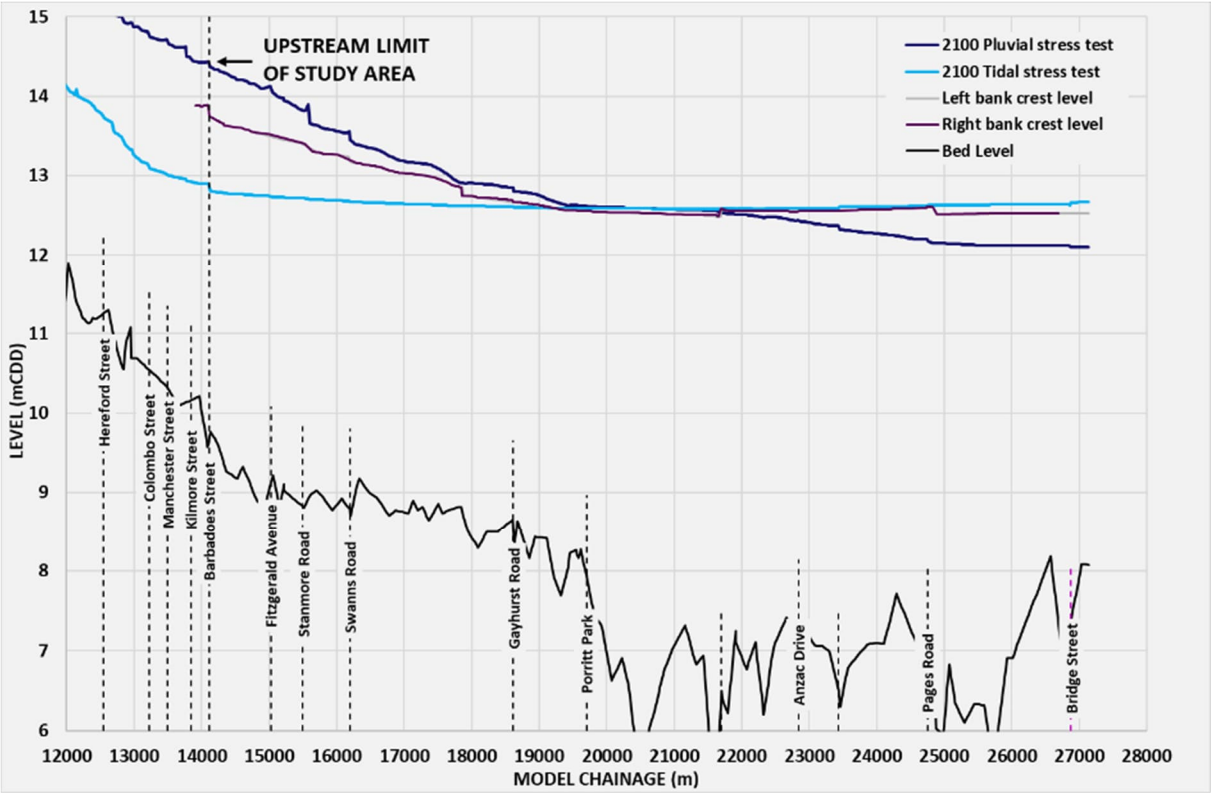


Figure 44. Water level and flood defence crest profiles along the Avon River for the 2100 pluvial and tidal stress test results.

5. Project response indicators

The revised scope for Stage 3 of the multi-hazards project scope limits the development of full Dynamic Adaptive Policy Pathways (DAPP) for the lower Ōtākaro Avon River catchment. The study focuses on the currently preferred initial risk management pathway, the proposed OARC Scheme, with a limited consideration of complementary or alternative options for comparison purposes. The preferred pathway includes new river flood defences and additional stormwater pump stations which have adaptive elements – provision to raise defence crest levels and install additional pump station capacity – which can be implemented on similar principles to a DAPP process in response to rising sea level and increasing rainfall intensity.

These measures will reduce flood risk in the Stage 3 project area by largely preventing flooding from the Ōtākaro Avon River and improving the disposal of runoff from extreme rainfall in the project area. However, residual hazards from surface water flooding and elevated groundwater are highly likely to require additional or alternative management responses. The multi-hazards project aims to provide Council with an understanding of when future upgrades to the OARC Scheme may be required and also identify when, and where, additional or alternative responses to flooding or groundwater hazards may need to be considered.

The need for further responses to hazards is assessed by comparing the model flood hazard data in each of the future scenarios to a set of 'project response indicators' (PRIs). In Task 2 of the project, PRIs were selected for each of the principal land uses or assets in the Stage 3 project area (buildings, people's safety for example). These PRIs were developed solely for use in this stage of the project and are not a reflection of Council policy or of community risk tolerance. We recognise that the PRI's may be used through a future CHAP process, including potentially being adjusted up or down based on community input to better reflect the community and Council's tolerance for impacts.

The PRIs are each a quantitative measurement of flood hazard (such as probability of flooding to a particular depth or annual average damage to an asset) which can be compared to the flood model results. They have been selected through a review of relevant literature and practice and provide an indication of when the magnitude of the hazard may have reached a level to require a response. Such a response could include additional investment in the planned risk management infrastructure (flood defence or pump station upgrades) or a switch to an alternative risk management approach such as a change in land use.

The term 'project response indicator' is used as an alternative to 'adaptation threshold' to reflect the fact that whilst the technical principles are similar, the purpose of application differs and the particular use of the indicators in this project and to the modelled hazard data needs to be distinguished from that of a DAPP process. The methodology by which the PRIs were developed and further discussion on the approach to PRI development is outlined in the memo in Appendix B.

Table 21 presents the PRIs proposed for hazard assessment in the project. While it is noted that the proposed PRIs cannot be representative of all individual elements, the selected PRIs are considered to allow for a broad scale assessment of when a response may be needed to groundwater and flood hazards.

Table 21. Project Response Indicators.

Project Response Indicators for Groundwater Hazards ***Indicators refer to the 85th percentile groundwater level in metres below ground level (mbgl)***	
Element	***Proposed PRI value***
Local ponding/flooding	Emergent groundwater (<0 mbgl)
Buildings	New builds - 0.3 mbgl Older buildings - 0.3 mbgl (sandy soils) and 0.7 mbgl (silty soils)
Contaminated Sites	Surface exposure at site - 0 mbgl Services within 50 m of contaminated site - 0.5 mbgl
Parks and Reserves / Sports Fields	Sandy soils - 0.3 mbgl Silty soils - 0.5 mbgl
Roads	Local roads - 0.1 mbgl Main arterial routes - 0.3 mbgl
Service Stations	0.5 mbgl – buoyancy of underground storage tanks
Stormwater / Wastewater Laterals	Dependent on pipe depth – groundwater at mid-level of pipe
Stormwater / Wastewater Mains	Dependent on pipe depth – groundwater 1 m above top of pipe for buoyancy
Project Response Indicators for Flood Hazards ***Indicators refer to the depth of water in metres (m) above ground level or Damage Ratio[33] (DR) for a specified likelihood of flooding in terms of Annual Exceedance Probability (AEP)***	
Element	***Proposed Indicators***
People's safety (roads and properties)	0.4 m at 0.5% AEP
Buildings	Any of: underfloor damage at 10% AEP, above floor damage at 2% AEP, DR greater than 0.1 at 0.5% AEP
Contaminated Sites	0 m at 0.5% AEP (i.e., no flooding for all AEPs considered)
Roads	Use people's safety threshold (lower than hazard to roads themselves)
Service stations	As for buildings
Stormwater Laterals / Mains	None
Wastewater Laterals / Mains	None
Water Supply Laterals / Mains	None
Stormwater Pump Station	0.3 m at 0.5% AEP
Wastewater Pump Station	0.3 m at 0.5% AEP
Wastewater Monitors	None
Water Supply Station	None
Parks and Reserves / Sports Fields	0.2 m at 10% AEP

We have compared the PRIs for each land use element in Table 21 to the groundwater projections developed in Stage 2 of the project and the flood depths from the OARC Scheme model simulations described in Section 4.2 of this report to identify whether or not the PRI value is exceeded for each element in the project area for all of the future scenarios considered. Land use elements for which the groundwater or flood hazard PRIs are

[33] As defined in Table 3 of RiskScape: Flood fragility methodology, NIWA Client Report: WLG2010-45, August 2010

exceeded are then mapped for each scenario to identify where in the project area the residual hazards may require further responses.

Section 6 of this report presents and discusses the results of applying the PRIs to the land use and hazard data. The PRI mapping is based on current land use data and understanding of existing assets and these have not been modified in future scenarios. For instance, only existing buildings are considered in all future scenarios but some of these buildings might be replaced in the future with new builds constructed to higher floors levels so reducing the number of buildings at risk. Similarly, no allowance is made for future modifications to utility networks or future remediation of contaminated sites.

6. Performance of the OARC scheme

6.1 Approach to assessing performance

The objective of Stage 3 of the Multi-Hazards project is:

> "*to assess the performance, impacts and long term viability of the Ōtākaro Avon River Corridor Regeneration Area (the OARC) set back stopbanks along the Avon River*" with the view to identifying whether there are issues related to managing flooding and other hazards that would make existing land use untenable behind the flood defences, and when these issues may occur.
>
> (Section 2.3.1 of this report)

The results of the flood model simulations summarised in **Section 4** of this report demonstrate the *performance* of the OARC Scheme in terms of its effect on: the overall extent and depth of flooding; the number of buildings affected by under floor and above floor flooding; the estimated annual average flood damages; and, cumulative present value flood damages over the next 100 years, compared to the existing flood management measures over their remaining functional life and without any new measures beyond that.

These results provide a measure the benefits of the OARC Scheme, in terms of the reduction in flood hazard in comparison to the existing measures and identify the remaining residual flood hazard in the project area with the OARC Scheme in place.

In addition to the residual surface flood hazards, **other hazards** – identified and considered in Stage 1 and Stage 2 of the project – could affect the viability of future land use in the area benefitting from the OARC Scheme. The realised benefits of the investment in the OARC Scheme may be reduced if costly additional measures are needed to address these various and potentially compounding hazards and so more fully realise the benefits of the OARC Scheme. Assessment of the cascading consequences of these hazards for flooding in Stage 1 and Stage 2 of the project and updated in Stage 3 of the project (Section 7.2 of this report) identified the following hazards as likely to be the most important.

- Hazards from high groundwater levels: investigations of shallow groundwater levels completed in Stage 2 of the project (Aqualinc, 2020)[34] identified the potential for the depth to groundwater to become shallow enough through sea level rise to adversely affect infrastructure and other elements of the project area in the future climate states developed for the project.
- Earthquakes: the effect of potential settlement of ground levels through liquefaction in an earthquake event on flooding has been assessed in the future scenarios simulated in the flood model. However, seismic events will also potentially affect the structural integrity of the new flood defences and their performance in providing flood protection.
- Vertical Land Movement (VLM): new data for ongoing VLM in Christchurch indicate that current, 'post-seismic', rates of VLM are up to an order of magnitude higher than previous estimates of 'inter-seismic' rates of VLM. Whilst the rate of VLM is expected to decline to the inter-seismic rate within a few decades, future earthquake events are thought likely to result in a return to higher post-seismic rates of VLM. The change in ground levels over the project area through VLM may affect the residual flood hazards in the project area in the future scenarios considered.
- Tsunami: modelling of tsunami events with a likelihood approaching that of the flooding considered by the project (0.2% AEP and 0.04% AEP) was undertaken in Stage 2 of the project[35] to identify the

[34] LDRP45: Impacts of earthquakes and sea level rise on shallow groundwater levels, Project number: C17054 (Aqualinc, 14 August 2020)

[35] Land Drainage Recovery Programme: Tsunami Study (NIWA, February 2018)

extent and depth of flooding from such events with the existing stopbanks. The models indicated the potential for these events to impact areas benefitting from the OARC Scheme.

- Coastal inundation and erosion: flood modelling for Stage 3 of the project indicates direct inundation of the project area from storm tides along the open coast is likely to occur under higher sea level rise scenarios based on present day ground levels along the coastline. The Coastal Hazard Assessment for Christchurch District (Tonkin + Taylor, September 2021[36]) shows that the dune ridge along this coastline is likely to erode landward in the future due to the impacts of rising sea level, as well as short-term storms, potentially resulting in reductions in the width and crest level of the dunes. This could result in increased inundation of the area benefiting from the OARC Scheme. Erosion and wave runup in storm events could result in overtopping at lower values of sea level rise but such inundation may be more localised.

Other hazards may also affect flooding or the viability of future lands use in the project area – such as, changes in rainfall patterns, breaching of flood defences, fluvial erosion and blockages of structures or drainage pipes and channels – but assessment of such hazards are beyond the scope of the project.

In this section of the report we consider

- the residual flood hazards in the project area with the OARC Scheme in place arising from pluvial, fluvial and coastal storm events using the flood model results.
- the potential hazards arising from high groundwater levels in the project area, which are not addressed by the OARC Scheme and not simulated directly in the flood model, using the future groundwater surfaces developed in Stage 2 of the project.

We have used the **Project Response Indicators (PRIs)** developed in Stage 3 of the project (**Section 5** of this report) to identify *where* and approximately *when* the consequences of these two hazards may require an additional mitigating response, based on the timing of the future climate states estimated in Stage 2 of the project (ref Section 3.1 of this report).

In Section 7 of this report we assess how the other potential multi-hazards interact with the OARC Scheme and impact on the benefits of the scheme in reducing flood risk.

6.2 Assessment against project response indicators

The basis of the design for the OARC Scheme is to prevent flooding from the Ōtākaro Avon River for coincident coastal and fluvial events of a combined likelihood of 1% AEP through new raised flood defences. Flood defence crest levels will be constructed, or progressively raised in the future, to allow for the effects of climate change on water levels in the river and settlement of the flood defence to maintain required freeboard. The new flood defences will also reduce the risk of overtopping in more extreme events (e.g., 0.5% AEP) with a reduced freeboard. Figure 32(a) shows, for example, the extent of the project area over which the flood model simulations indicate that the 0.5% AEP flood depths will be reduced by the OARC Scheme in the 0.45 m SLR scenario.

Residual hazards from surface water flooding and high groundwater levels, which are not directly addressed by the scheme, are likely to affect land use over the project area, including within the area benefiting from a reduction in river flooding by the OARC Scheme. The PRIs developed in Stage 3 (Section 5 of this report) are intended to provide an *indication* of where the effects of surface flooding and high groundwater levels on these elements may be severe enough to signal that additional measures, and investment, may be required to manage these risks. The aim is to provide Council with an indication of the scale of additional issues that may need to be resolved, their location and when they may occur or evolve over time. It should be noted that

[36] Tonkin + Taylor (2021). Coastal Hazard Assessment for Christchurch District Summary Report. Prepared for Christchurch City Council. September 2021.

these PRIs have been developed primarily to inform the multi-hazards project and indicate where issues may occur. They do not imply an obligation on Council to take action where PRIs are exceeded.

PRI Mapping

The PRIs were applied to the flood model outputs of Stage 3 of the project and future groundwater surfaces developed by Aqualinc in Stage 2. Publicly available and Council GIS datasets for each element type were used to map individual elements for which the relevant PRI is exceeded for each of the future OARC Scheme scenarios in Table 6. Appendix J provides details of the data sources and how the PRIs as defined have been applied to the data, including any necessary simplifications which have been made in the analysis.

Section 6.3 summarises the outcomes of the PRI mapping for groundwater and flood hazards. The maps provide a cumulative picture of the exceedance of PRIs for all elements in each scenario. In considering the overall impact of hazards on land use, it is useful to understand where PRIs are exceeded for multiple elements. The number of elements impacted, the severity of the impact, the frequency of impacts and their extent are all factors that could trigger a need for additional mitigating measures.

Review of PRIs

The PRIs were developed from a review of scientific knowledge of the flood hazards and groundwater hazards. Applying these PRIs to the specific data available for hazards and land use in the project area provides some insights to the relevance and benefits of each type. In Section 6.4 we reconsider these PRIs and discuss whether there would be benefits in modifying any of them for use in other work.

Monitoring of evolving hazards

Adaptive planning aims to enable preparation for future events whilst considering the uncertainties. DAPP identifies a set of actions or management approaches to address hazards once they exceed a limiting severity. Adaptation Thresholds (ATs) are set to describe the situation where the current management approach is no longer delivering the desired outcome. The adaptation thresholds need to relate to community values, risk exposure or agreed levels of service. Triggers and Signals are set that precede ATs. Triggers are the point at which action needs to be taken to progress a change in the management approach to avoid reaching the AT. They should be chosen to allow sufficient lead time for the new approach to be implemented prior to the AT being met. Signals provide early warning that a trigger is approaching and indicate that early engagement on the change should commence. To understand how the impact of a hazard is developing in relation to the Signal, Trigger and AT, the evolving hazard or impact of the evolving hazard needs to be monitored.

Within the multi-hazards project, we have developed PRIs rather than ATs and are not seeking to develop triggers or signals. The PRIs however can be used by Council in future adaptation planning with the community to help inform the selection of ATs and hence Triggers and Signals. In Section 6.6 we discuss a range of possible approaches to monitoring that could help inform how hazards are changing in the future.

Example approach to managing groundwater hazard

Identification of specific intervention actions and pathways are generally excluded from Stage 3 of the project. However, the project scope does include a task to consider options for applying an engineering solution to manage high groundwater and their indicative costs. In Section 6.7 we use the results of the PRI mapping to outline, at a high level, where an engineering pathway for managing groundwater may be needed in areas which benefit from the OARC Scheme in terms of flood hazard but are exposed to groundwater hazards. We have used the engineering approach previously developed for Council by Beca in 2018[37], which uses pumping to reduce groundwater levels, to indicate the scale of works needed and a high-level cost

[37] Beca (2018) Earthquake Effects on Groundwater Levels - Case Study Options Report – Draft B Unpublished Client report for Christchurch City Council Dated 7th August 2018.

estimate. This provides Council with an indication of the effort that may be required to manage groundwater rise, if needed.

6.3 PRI mapping

Maps showing where the flood and groundwater hazard for each land use element exceeds the corresponding PRI have been developed for each scenario of future climate state and combinations of future climate and earthquake induced land settlement. Table 22 provides a summary interpretation of the mapping for both types of hazard and the maps for the two hazards in each future scenario are compared in Figure 45 to Figure 57.

The maps show the cumulative exceedances of the PRIs for all the land use elements in the form of a combined 'heat map'. The intention is to indicate areas more susceptible to PRI exceedance for multiple elements since this further intervention is more likely to be justified in such areas. A more detailed commentary on the PRI exceedances is provided together with the maps in Appendix K, for groundwater hazards, and Appendix L, for flood hazards.

Table 22. Summary of assessment of exceedance of groundwater and flood hazards PRIs for land use elements in the project area for future climate scenarios.

	Groundwater hazard	Flood hazard
Overview	Rising shallow groundwater is a long-term, or chronic hazard rather than an acute hazard. While groundwater levels will vary over seasons and from year to year, the anticipated long-term trend in the project area is for groundwater to rise, primarily due to rise in mean sea level. This will result in longer periods over which groundwater levels are above specific levels such that the water table will be at, or less than, specific depths below ground level for longer. Settlement of ground levels from earthquake events and long-term vertical land movement will further reduce the depth to the water table. Effects from this slow, creeping groundwater rise will therefore be seen over time by the community. When considering the function of land use as a whole, exposure to multiple impacts from groundwater rise are perhaps more likely to trigger community concerns that seek a management response. The change in impacts over time is likely to be a slow increase in the frequency of issues, their duration and the severity of impact. Community tolerance to these types of impacts may therefore be very different to the impacts of flooding where damage occurs in discrete events that may impact a larger proportion of the community. In assessing PRIs for groundwater hazards, the 85th percentile groundwater level is referenced – this relates to a groundwater level which is exceeded 85% of the time, reflecting the hazard posed by a chronic state of groundwater.	Flooding is an acute hazard, experienced as discrete events that impacting a range of lands uses and people within a community. Climate change will result in a long-term, chronic increase in both storm tide levels (through rise in mean sea level) and the magnitude of high intensity rainfall events which will increase the likelihood and impacts of flooding. The community however may not be aware of the change in hazard over time since exposure is only in discrete shock events and it may take a long time for the change in frequency or magnitude of events to become evident. In this way the evolution of flood hazard differs to rising groundwater hazard. The OARC Scheme flood defences provide a high standard of protection from flooding from the Ōtākaro Avon River. There are however areas benefiting from this protection where flooding will still occur from rainfall in the catchment in areas where runoff ponds or where the capacity of the existing stormwater network is exceeded. The depth and extent of this pluvial flooding is expected to increase over time due to increased intensity of rainfall with climate change. Pockets of flooding are observed over the whole catchment, and these tend to increase in number, area and depth with climate change. The numbers of buildings at risk from this residual flooding and the potential flood damages also increase over time. Pockets of flooding in the north and north-east of the project area do not benefit from the OARC Scheme as they are disconnected from the river, drain directly to the sea, and would not be flooded from the river even in higher sea level rise or VLM scenarios. Other pockets of flooding are in areas that do benefit directly from the OARC Scheme flood defences and pumpstations. These areas are of more relevance when considering PRI exceedances since this residual flooding may impact land use despite the investment in the OARC Scheme and additional investment may be required to manage flooding in these areas. It is also noted that Council would also need additional investment to manage flooding in many flood pockets across the city not associated with this scheme.

	Groundwater hazard	Flood hazard
		Not all flood pockets are of depths that may impact land use, for instance shallow flooding may be tolerated in areas if it does not enter buildings or damage assets.
0.19 m SLR to 0.45 m SLR (approximately 2030 to 2060) Figure 45 - Figure 50	For lower levels of SLR (0.19 m and 0.45m), the groundwater hazard, as indicated by exceedance of groundwater PRIs is generally most prevalent within the OARC Regeneration Plan area and areas of parks such as Travis Wetland and Clare Park. The current residential land use areas are less impacted. Sections of the wastewater and stormwater pipe networks are shown as exceeding PRIs across much of the project area from 0.19 m SLR (2030). These perhaps reflect the depth of some of these piped assets. These exceedances develop over time most notably in Avonside with additional clusters emerging in the coastal suburbs, Aranui, Dallington, Burwood, Parklands and Wainoni. Vertical land movement increases the size of these emerging clusters. VLM most notably changes building PRI exceedances rather than other assets. Numbers of properties at risk increase and the extent of impact in each suburb grows but no new areas of potential impact are predicted.	For the 0.19 m and 0.45 m SLR scenarios, smaller amounts of exceedances of most PRIs are evident and these are distributed across the whole lower Avon area with little clustering of multiple PRI exceedances in specific suburbs. This indicates multiple pockets of potential smaller scale and lower impact effects could occur. Building PRI exceedances especially show this trend for the 0.19 m and 0.45 m SLR scenarios with a scattering of buildings across the whole area and few clusters. Property PRI, referring to peoples' safety, is generally not exceeded across much of the project area in the 0.19 m and 0.45 m SLR increments. In these lower SLR scenarios (0.19 m and 0.45 m) there are a few small pockets of road PRI exceedances within local roads in Avondale, Dallington, Aranui, North Linwood and Wainoni. The S1 and S2 scenarios of Vertical land movement has little impact on flood PRI exceedance in 2060 with just a few buildings extra being at risk in areas already exhibiting PRI exceedances. The future earthquake S3 scenario does not change numbers of overall buildings at risk notably but there is a redistribution of the actual buildings at risk with some added and some removed compared to the S2 scenario across the project areas. This is likely due to differential changes in settlement across the project area redistributing the ponding of water. The changes are spread over the whole area rather than specific pockets of flooding getting removed and new ones being added.
1.06 m SLR (approximately 2100) Figure 51 - Figure 55	Under 1.06 m SLR (~2100) there is widespread groundwater PRI exceedance across multiple suburbs in all VLM scenarios. Under Scenario 2 VLM, widespread PRI exceedance impacts all residential Avonside and the western margin of coastal suburbs in 2100. Clusters of PRI exceedance grow in size and impact a wider variety of land use assets in Linwood, Aranui, New Brighton, Burwood, Dallington and Parklands. The S3 future earthquake scenario indicates a significant increase in the extent and number of exceedances of building PRI's over the S1 and S2 scenarios. This indicates that the reduction in depth to groundwater could potentially impact a sizeable area.	By ~2100 (1.06 m SLR) there is some clustering of PRI exceedances relating to the viability of residential land use in suburbs closer to the Ōtākaro Avon River – Aranui, North Linwood, Wainoni and Dallington. These PRIs relate to roads, buildings and property (public safety) that could cumulatively impact a residential area. There is also some clustering of PRIs in the northern suburbs of North New Brighton, Waimairi Beach and Parklands. Increased vertical land movement has little impact on the distribution of PRI exceedance across the project area in 2100. As for 2060 the S3 with earthquake scenario exhibits the most predicted redistribution of impacts between individual buildings but overall limited change to the wider spatial pattern of impacted suburbs.

	Groundwater hazard	Flood hazard
1.88 m SLR (approximately 2150) Figure 56	Under 1.88 m SLR (~2150) significant sea level rise influence on coastal groundwater occurs throughout the suburbs of Waimairi Beach, Parklands, North New Brighton, and New Brighton as well as Dallington and Bexley. Further exceedances in areas around the Ihutai/Avon River are also observed with more asset types exceeding PRIs across wider areas in Aranui, Avondale, Wainoni, and Dallington. Thes are all areas which benefit most directly from inundation protection from the OARC Scheme. VLM has not been modelled for this scenario.	Under 1.88 m SLR (~2150) there is a large increase in exceedance of PRIs. A notable increase in the clustering of exceedances for roads, buildings and property (peoples' safety) is evident in the South New Brighton and New Brighton suburbs next to the OARC Regeneration Plan area and the proposed OARC flood defences. The spatial extent and clustering of exceedances of PRIs expands in Aranui, Wainoni, North Linwood, Burwood and especially Dallington around the Ōtākaro Avon River. With 1.88m SLR areas further away from the Avon River in North New Brighton and Waimairi Beach are also exhibiting multiple PRI exceedances. VLM has not been modelled for this scenario.
Emergent groundwater	Emergent groundwater is largely confined to parks & wetlands until 1.0 m SLR (~2100) with parts of New Brighton and Avondale becoming increasingly affected. Under 1.88 m and 2.44 m SLR much of Parklands, Waimairi, Brighton, Aranui, Avondale, Dallington are affected by emergent groundwater. Gradual vertical land movement results in a small increase in emergent groundwater extent. Earthquake induced land settlement increases the size of the areas affected by emergent groundwater. Earthquake-induced land settlement experienced at 2100 is approximately equivalent to the impact of a further 0.8 m SLR in as much as the distribution of exceedances in the 2100 S3 VLM scenario look broadly similar to the 1.88m 2150 no VLM scenario.	n/a
Contaminated sites	Contaminated sites include all present and historic HAIL sites within the project area including chemical manufacture and storage, vehicle fuelling, electrical works, cemeteries, and waste treatment. The underlying data set is conservative, coarse and lacks allowance for severity or level of contamination, depth of contamination or risk of mobilisation of contamination. In addition, contamination can occur on sites that are not classed as HAIL sites. In early scenarios a number of sites exceed the PRI threshold within the OARC Regeneration area and in parks (Bottle Lake, Waimairi golf course). Earthquake settlement results in an increase of contaminated land areas exceeding PRIs, in particular triggering the area immediately south of Horseshoe Lake which does not exceed PRI in the highest SLR scenario.	Contaminated land exceeding PRI is relatively evenly distributed across the project area in early SLR scenarios. These then expand spatially in higher SLR scenarios. As with the groundwater contaminated land PRI, the underlying data is conservative and coarse and lacks allowance for severity, level or nature of contamination. Contaminated land is not itself a land use and as such flooding does not impact its use. It does however present a risk of mobilisation of contaminants that can affect land near to contaminated sites and limit the ability to use the land for other activities, including naturalisation of that land. In part the limitation is due to the challenges involved in consenting land disturbance activities where the contaminated material may interact with flood or groundwater. This PRI and data may therefore be most useful when considering the future flood risk and future

	Groundwater hazard	Flood hazard
	This area is contaminated under HAIL category A10 – persistent pesticide bulk storage or use and was red-zoned following the Christchurch earthquakes. Of note, is the high correlation between contaminated sites and parks. Given the historic nature of contamination risk for most sites the exceedance of PRIs themselves are less likely to make the current land use unable to function or impact surrounding residential land uses. However, this pattern of exceedance of PRIs could be used to inform future management of these potentially contaminated sites as it provides data for site specific assessments to consider whether groundwater rise can risk mobilisation of contaminants. Vertical land movement has little impact on contaminated land groundwater PRI exceedance.	management of contaminated sites. Vertical land movement has little impact on contaminated land surface water PRI exceedance.
Parks and Reserves	Areas where parks exceed PRI are prevalent closer to the Ōtākaro Avon River and wetland areas such as Horseshoe Lake and Travis Wetland. The extent of park areas exceeding PRI extend further from the river with SLR. From 1.06 m SLR (~2100) and onward, these areas also extend from the coast further inland. Parks particularly affected include Broadhaven reserve, Chisnallwood intermediate school grounds, Waimairi Beach Golf Club, Avondale Park and Avondale playground. Increased vertical land movement increases the size of the areas exceeding PRI, however, generally does not result in new park or reserved exceeding PRI exceedance. With the exception being Wainoni Park under Scenario 3 VLM in 2100.	For Parks land uses, outside of existing wetland and OARC Regeneration areas (dual function); Aranui primary school, Wainoni park, Bexley Park and Titirangi reserve exceed PRIs in earlier SLR scenarios. From 1.06 m SLR (~2100 and beyond), areas of Rāwhiti School, Rāwhiti Golf Club, Waimairi Beach Golf Club, Bottle Lake Forest, Christchurch golf club and Avondale golf club exceed PRI. Vertical land movement has little impact on parks and reserves surface water PRI exceedance.
Roads	For groundwater depths exceeding the PRIs for roads is, exceedance along SH74 as early as 0.19 m SLR (~2030) is significant. SH74 through Aranui is one of the major roads that exceeds PRIs over the various scenarios. This stretch of road is also vulnerable to vertical land movement and earthquake induced land settlement. Local roads exceeding PRI follows a similar trend to parks and emergent groundwater: increasing around the river corridor in earlier scenarios and then from the coast inland.	Roading sections exceeding PRI are located in clusters of a few streets in individual suburbs across the project area. These expand significantly for 1.06 m SLR (~2100) and higher SLR scenarios. An approximately 400m long stretch of SH74 in Bexley (opposite Cockayne Reserve) exceeds PRI in 2060. This stretch increases and extends through Bexley in increasing SLR scenarios and indicates the area of State Highway most likely to exceed the flooding PRIs. Vertical land movement has little impact on road surface water PRI exceedance.
Service stations	We identified 8 current service stations within the project area. Previous vehicle refuelling, service and repair site are captured in the contaminated land PRI as HAIL category F. No service stations exceed the groundwater level PRI under 0.19	Of the 8 service stations identified, BP Gloucester St and Challenge South Brighton are identified as exceeding PRI in the 0.19 m SLR scenario (and all others). No

	Groundwater hazard	Flood hazard
	m or 0.45 m SLR (~2030 to 2060). Allied Fuel Wainoni and Challenge South Brighton exceed the PRI at 1.06 m SLR indicating potential impacts on these assets may occur sometime between 2060 and 2100. Additionally, BP New Brighton exceeds the PRI at 1.88 m SLR and Mobil Aranui at 2.44 m SLR. Earthquake induced land settlement results in the groundwater levels below Challenge New Brighton to exceed PRI. VLM does not change the pattern of PRI exceedances.	further service stations are identified as exceeding PRI in any of the modelled scenarios (including VLM).
Water network	PRI is exceeded for clusters of stormwater mains located in Marshlands and Waimairi-Parklands in early epochs. These clusters increase in time with sea level rise. PRI is exceeded for smaller clusters in Aranui and Wainoni (coinciding with exceedance of PRIs for other elements). Stormwater mains close to the river are increasingly affected in early scenarios and by land subsidence. Gradual vertical land movement has little impact on PRI exceedance in 2060 and a modest impact in 2100. Earthquake events increase identified clusters across the project area. Coastal stormwater mains are more affected than inland mains in later scenarios. For wastewater mains, PRIs are exceeded more extensively than for stormwater mains – in Parklands, Waimairi and New Brighton, Marshlands, North Linwood and Aranui. The areas of exceedance increase gradually in future epochs. Vertical land movement and earthquake settlement have a relatively small effect on the extent of PRI exceedances.	Stormwater and especially wastewater pumps within and in proximity to the OARC Scheme area exceed their respective PRI sooner than pumps servicing areas further from the Avon. Exceedances start from the lowest 0.19 m SLR around the Avon, and it is not till between 0.45 m and1.06 m SLR that they are observed further north.
Co-location of exceedances of groundwater hazard and flood PRIs across suburbs and over time	The co-location of multiple hazards may be more likely to result in community concerns about the impacts on specific areas and land uses. This could result in Council and community needing to invest more money to develop solutions to address the observed effects. The distribution of groundwater and flood hazards PRI exceedances differ over time in different suburbs. Where PRIs for both these types of hazards are exceeded, there may be even greater impact on land use. The mapped PRIs in Figure 45 to Figure 57 show that in both 0.19 m and 0.45 m SLR scenario, flood hazard PRIs are more widely and frequently exceeded than groundwater PRIs. In Avondale, groundwater hazard and flood hazard PRIs are both exceeded in these future scenarios. By the time SLR reaches 1.06 m SLR (~2100), multiple groundwater hazard PRIs are exceeded in South New Brighton close to the OARC Scheme flood defences as well as in Avondale, whereas flood hazard PRI exceedances are more focused in Dallington, North Linwood, Wainoni and Avondale. ▪ With 1.88 m SLR (~2150) there are many groundwater PRI exceedances and emergent groundwater across much of the area between the OARC flood defences and the coast in New Brighton and South New Brighton as well as Avondale, Aranui and Dallington. The spatial extent of groundwater PRI exceedances in Avondale and New Brighton areas is much greater than thar for flooding PRI exceedances. North New Brighton and Waimairi beach have multiple PRI exceedances for both groundwater and flood hazard PRIs. Parklands is an area that has a much greater extent of exceedance of groundwater hazard PRIs than for flood hazard PRIs.	

	Groundwater hazard	Flood hazard
	▪ With 2.4 m SLR the exceedances are spread over large areas. In the coastal suburbs, multiple groundwater and flood hazard PRIs are exceeded over much of the same area. Avondale and Aranui have much greater spatial extents of groundwater PRI exceedances than flooding in the 2.4 m SLR scenario. Dallington exceeds PRIs for both groundwater and flood hazards. Burwood and North Linwood have more flood related PRI exceedances and fewer groundwater ones. Parklands area has some flood hazard PRI exceedance but much more spatial extent of exceedances of the groundwater PRIs. Overall, there are several areas where the PRI exceedances indicate that both groundwater and flood hazards would present a risk to land use elements. Timings of exceedances vary somewhat, with flood hazard PRIs tending to be more widely exceeded in earlier scenarios than groundwater hazard PRIs. Between the 1.06 m and 1.88 m SLR scenarios (~2100 to 2150) PRI exceedances become very much more widespread for both groundwater and flood hazards with some clustering for different elements in the same locations in suburbs, particularly along the coastline were coastal inundation starts to contribute to flood hazard and groundwater levels become very close to the ground surface due to the proximity of the elevated sea level.	

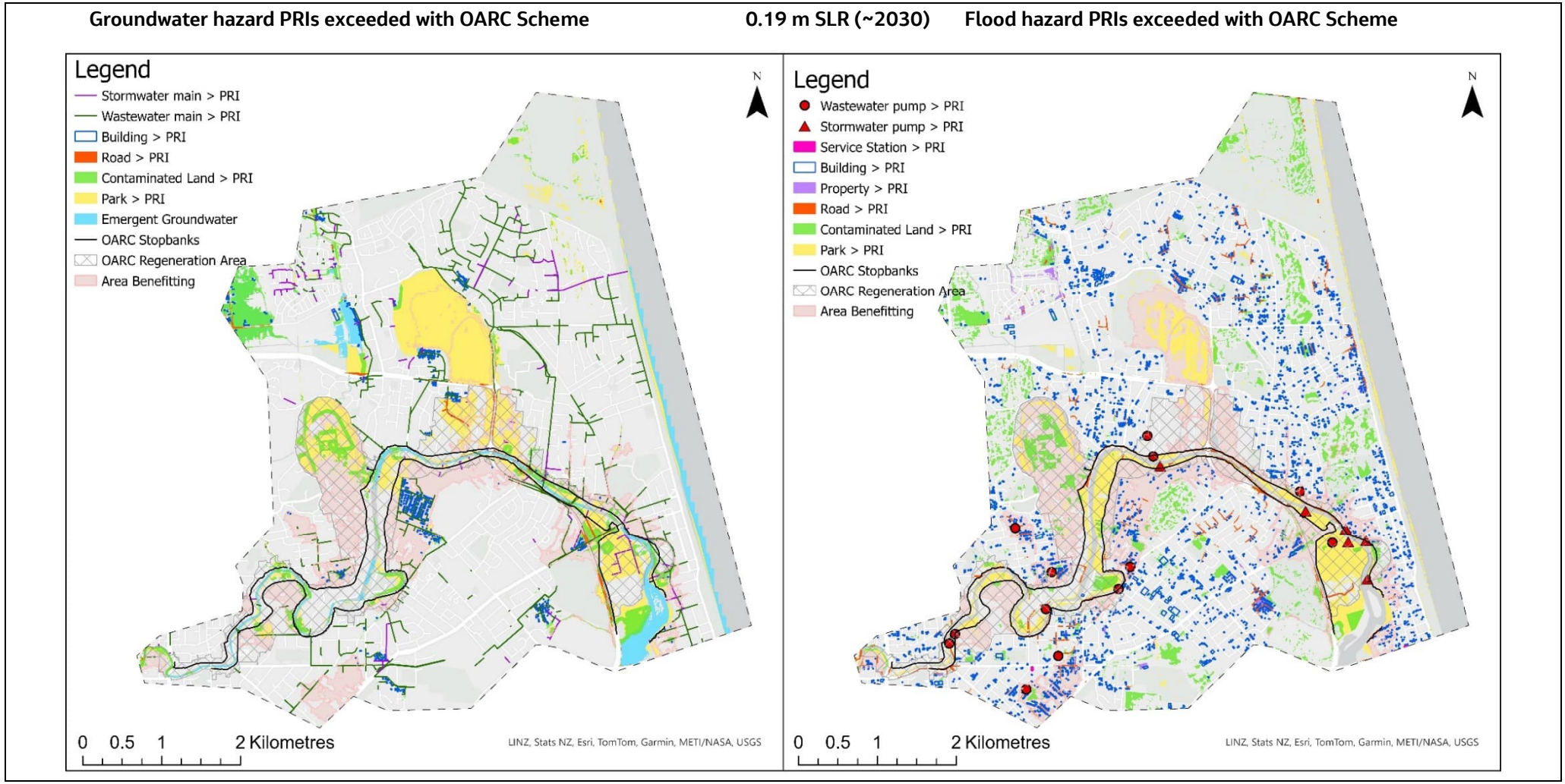


Figure 45. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 0.19 m SLR scenario (approximately 2030).

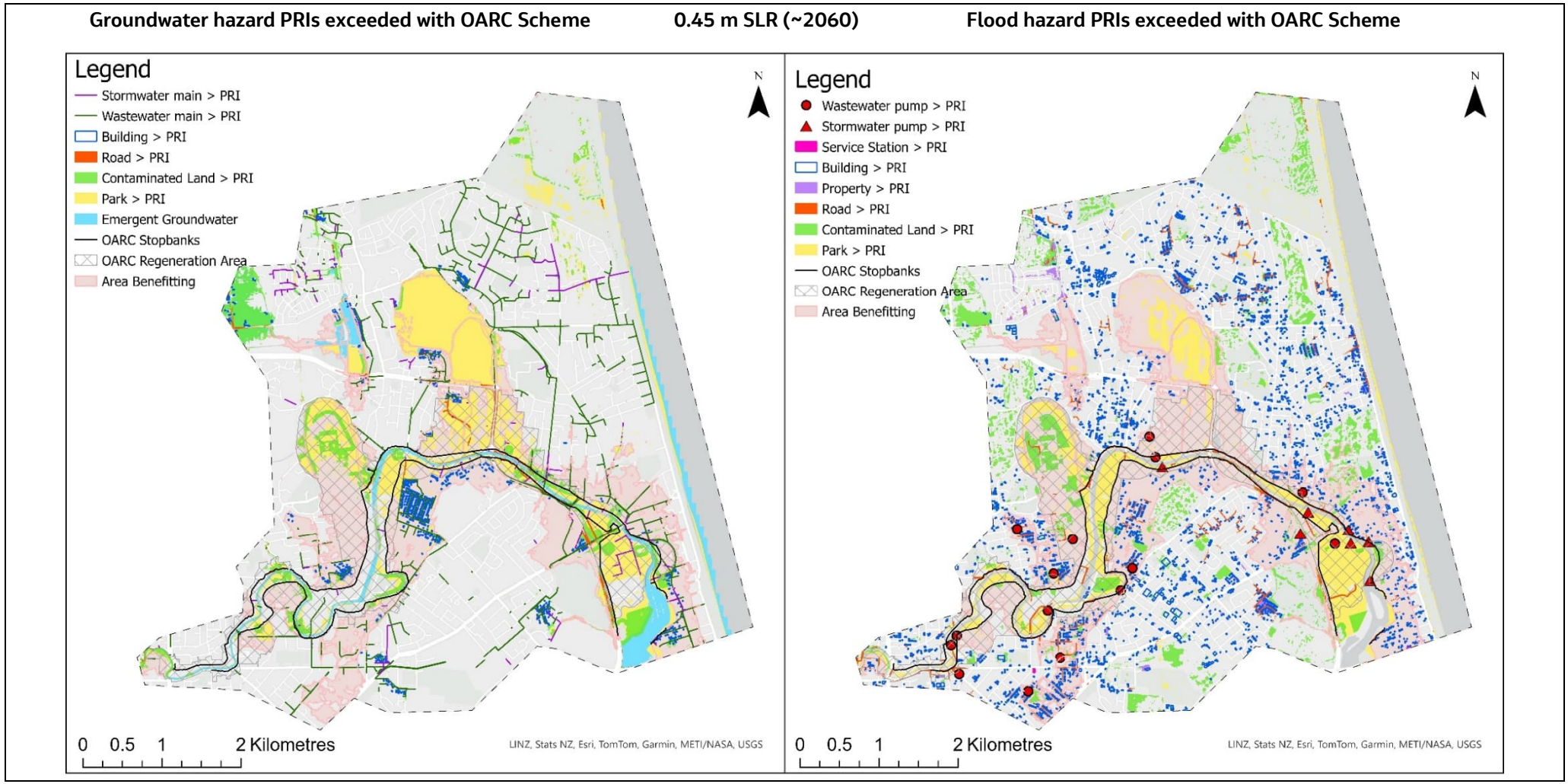


Figure 46. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 0.45 m SLR scenario (approximately 2060).

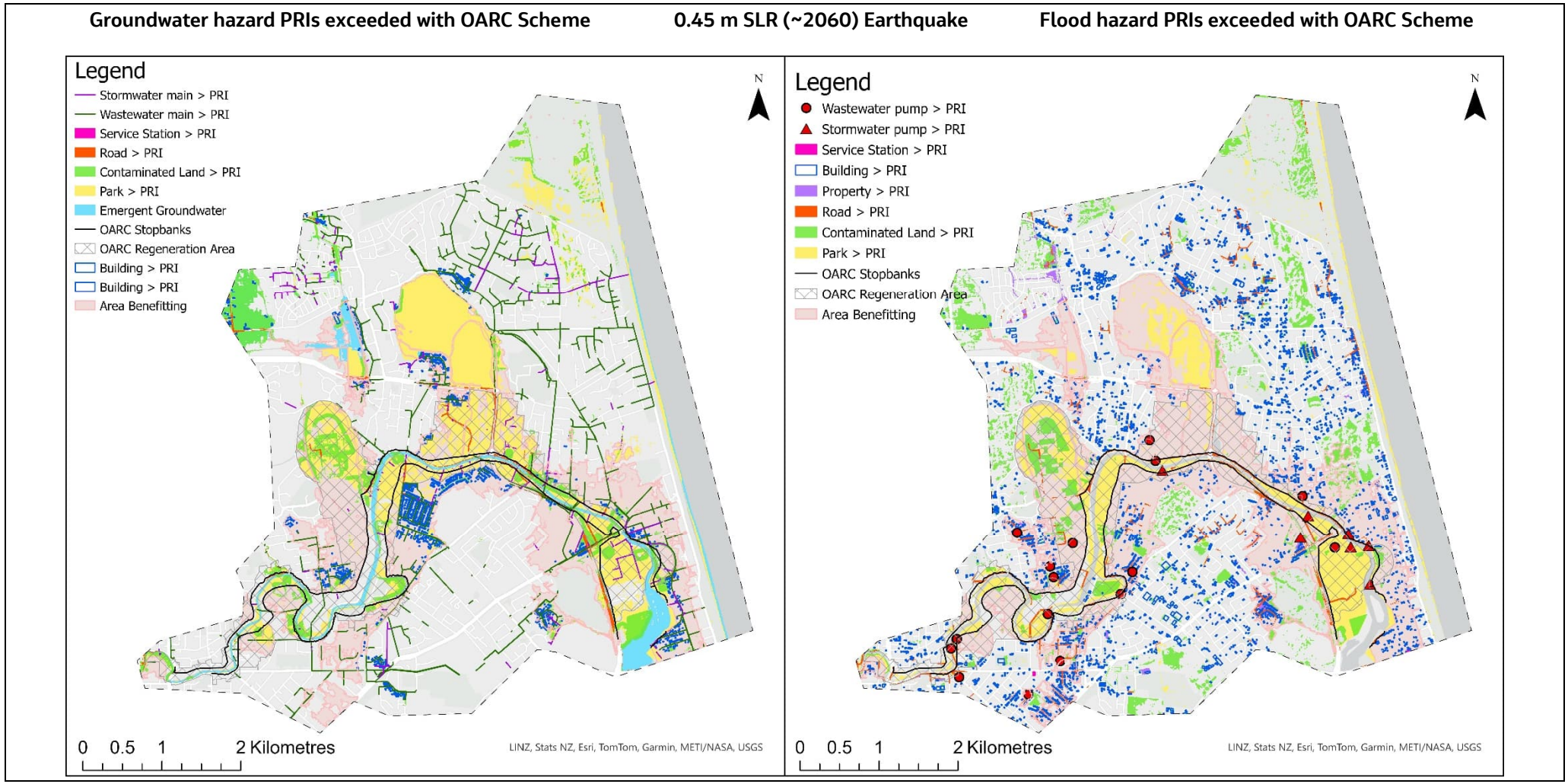
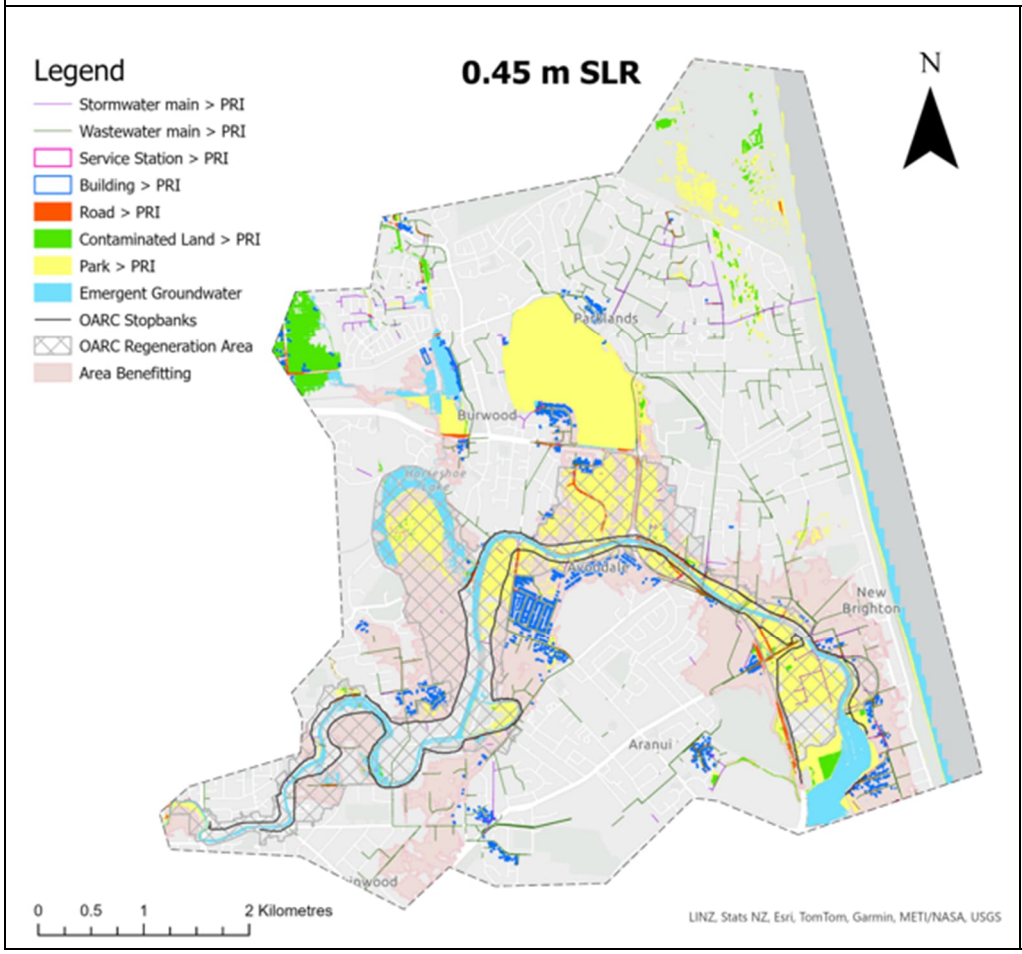


Figure 47. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 0.45 m SLR scenario (approximately 2060) with earthquake settlement.

Groundwater hazard PRIs exceeded with OARC Scheme	0.45 m SLR (~2060) S1 VLM	Flood hazard PRIs exceeded with OARC Scheme



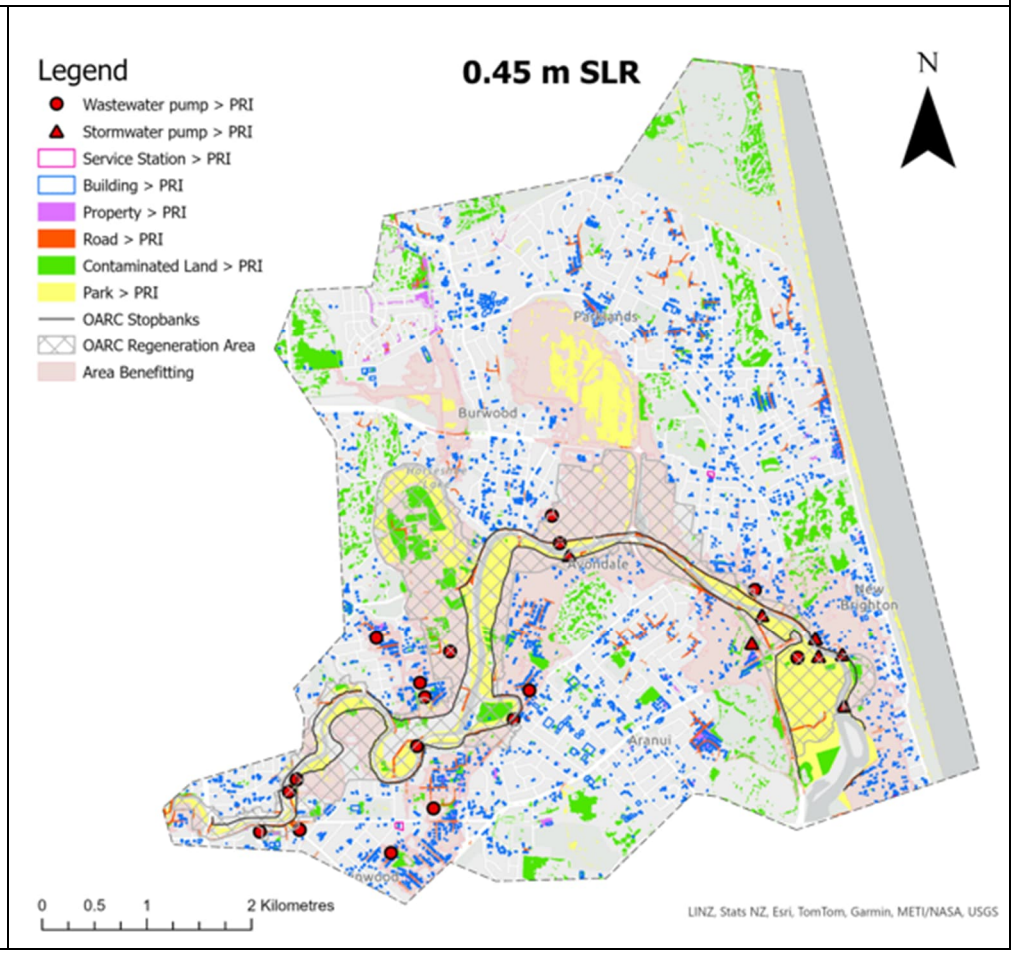


Figure 48. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 0.45 m SLR scenario (approximately 2060) with Scenario 1 Vertical Land Movement.

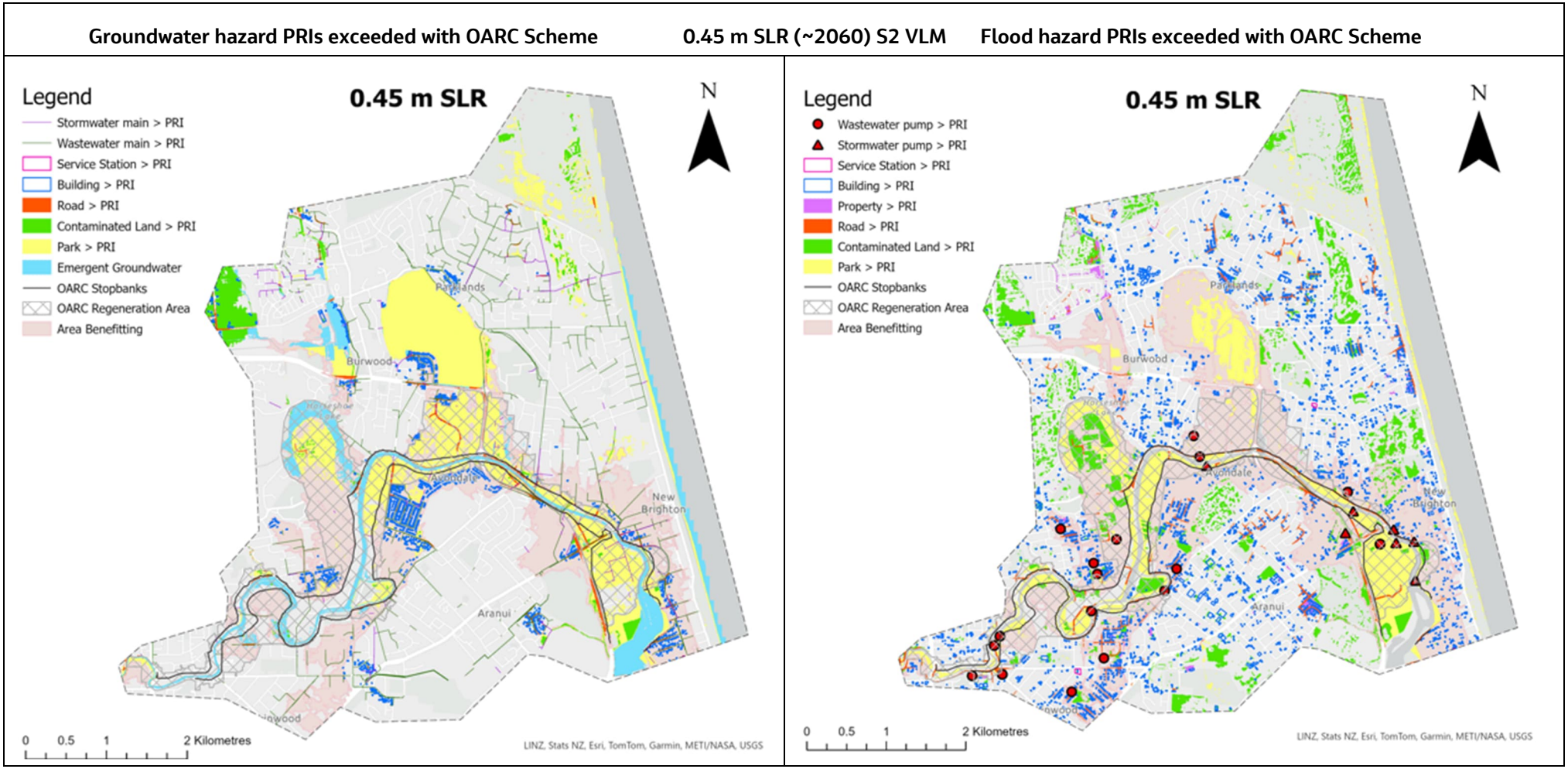


Figure 49. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 0.45 m SLR scenario (approximately 2060) with Scenario 2 Vertical Land Movement.

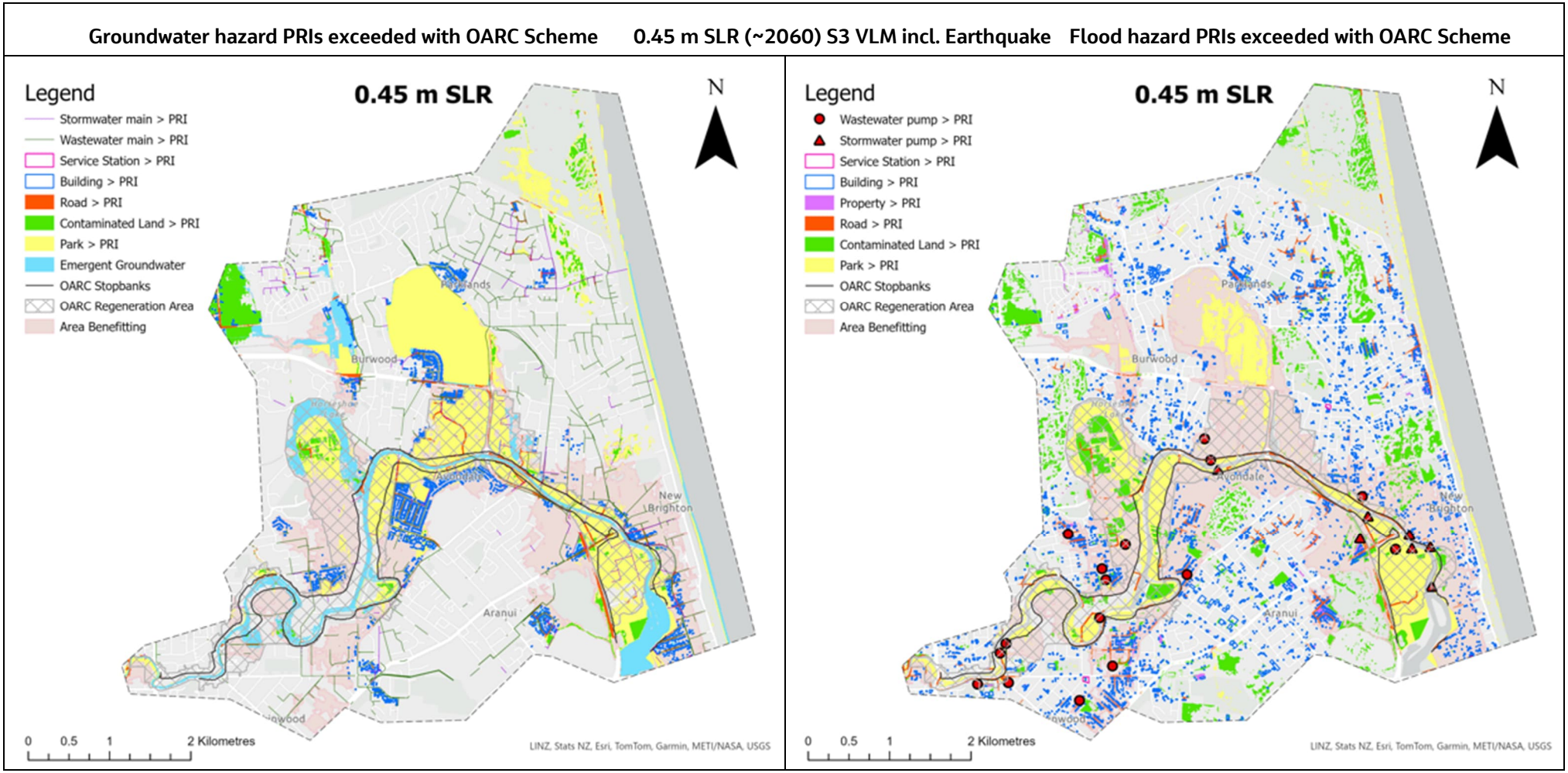


Figure 50. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 0.45 m SLR scenario (approximately 2060) with Scenario 3 Vertical Land Movement including earthquake.

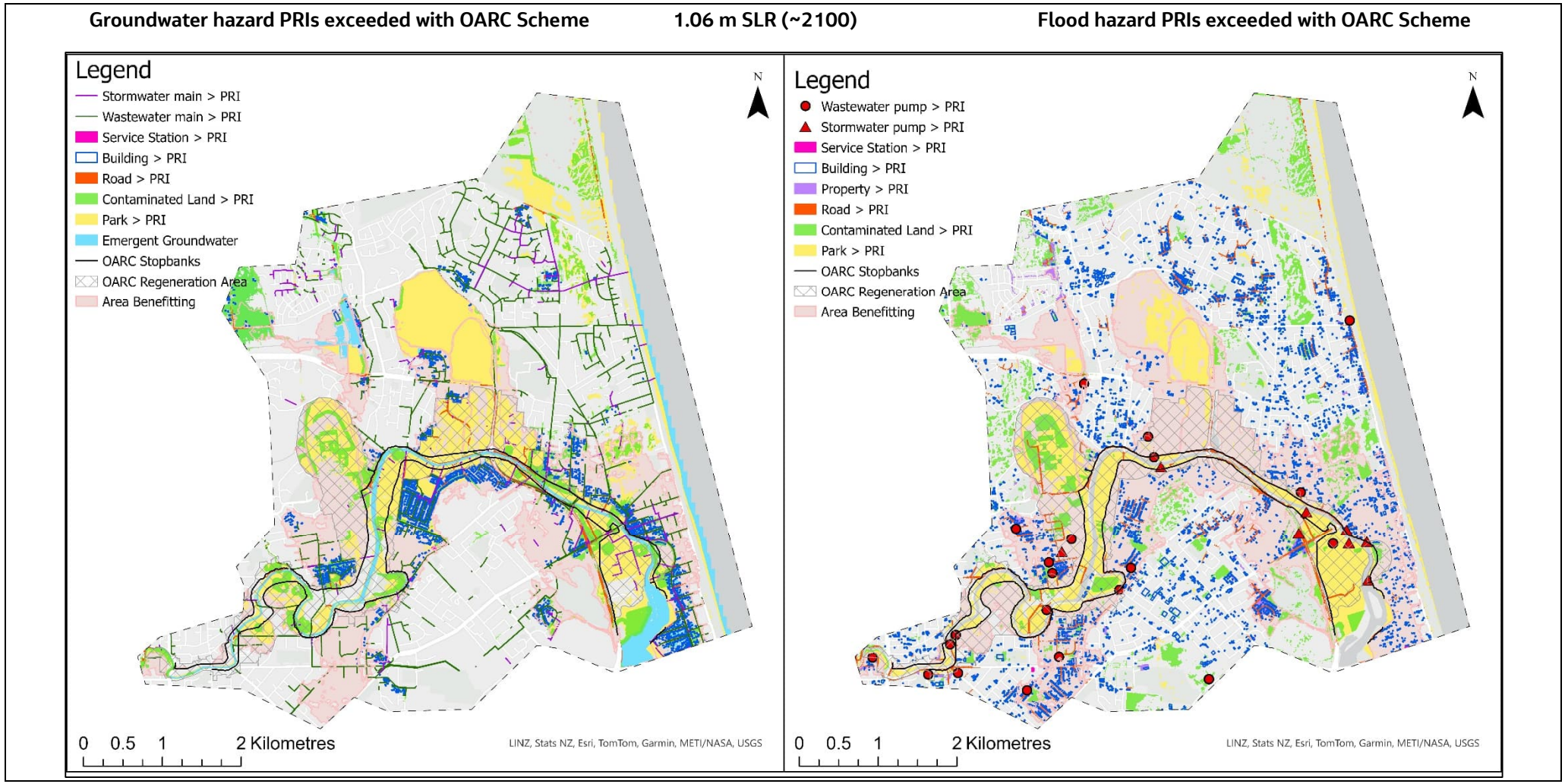


Figure 51. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 1.06 m SLR scenario (approximately 2100).

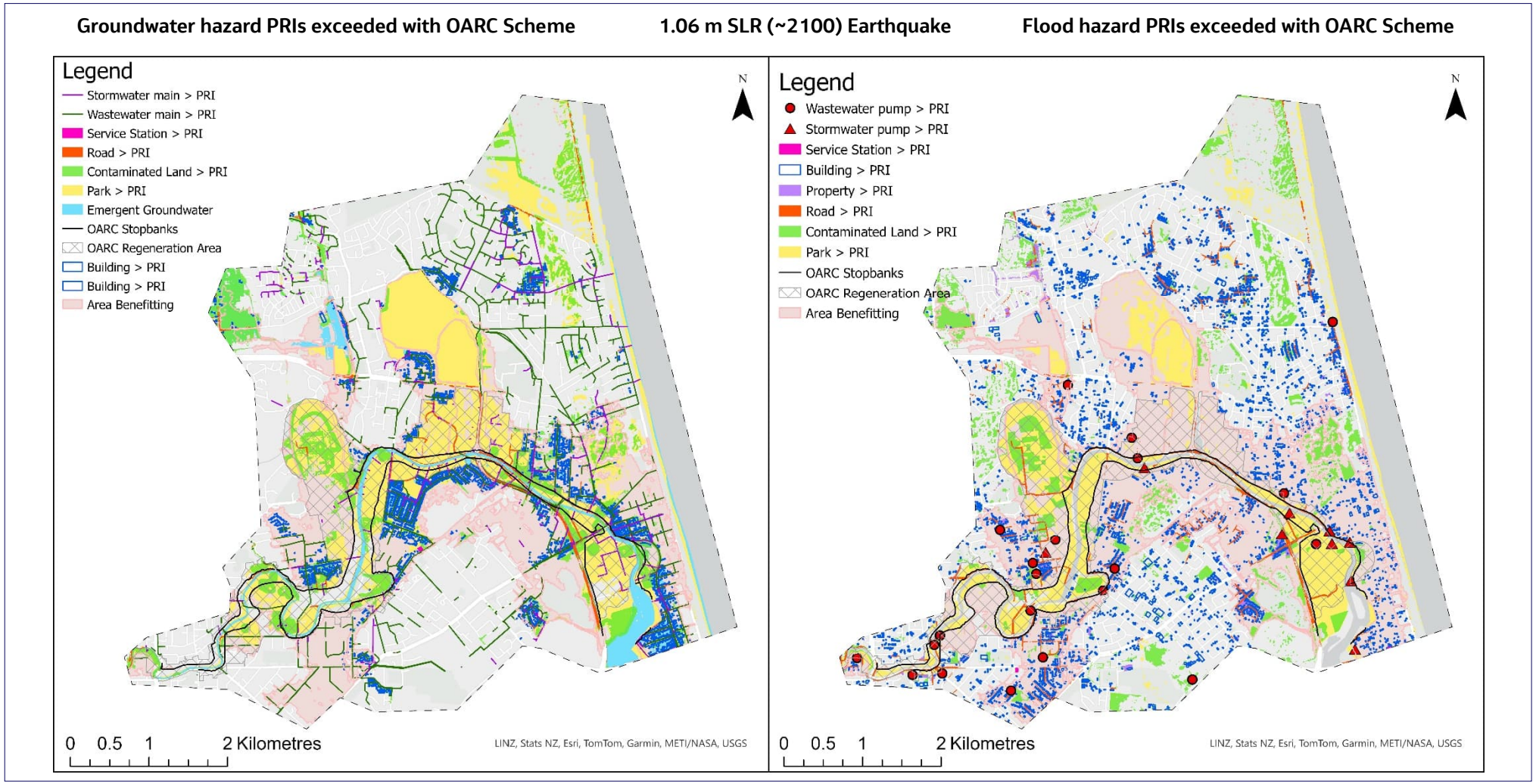


Figure 52. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 1.06 m SLR scenario (approximately 2100) with earthquake settlement.

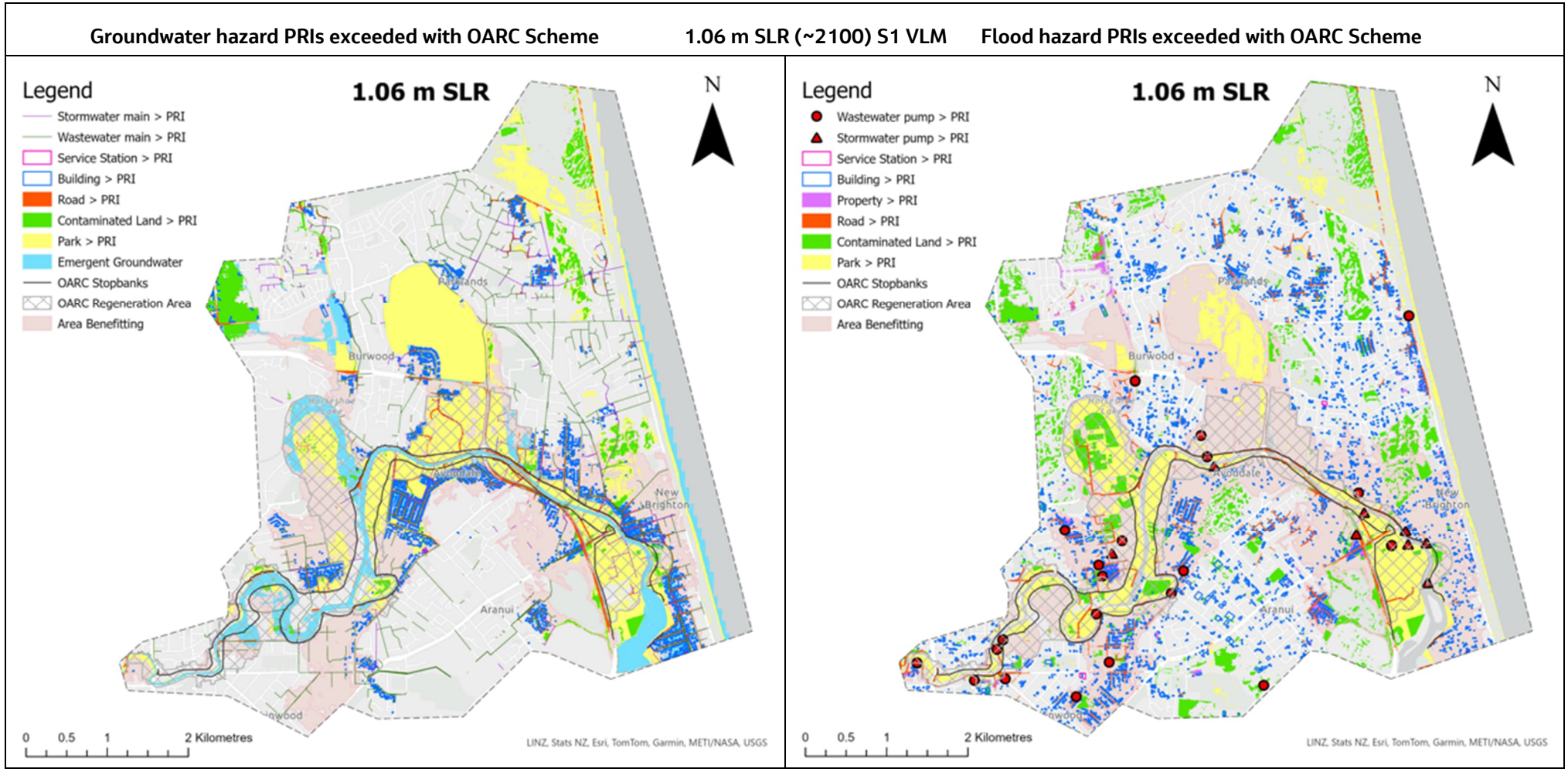


Figure 53. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 1.06 m SLR scenario (approximately 2100) with Scenario 1 Vertical Land Movement.

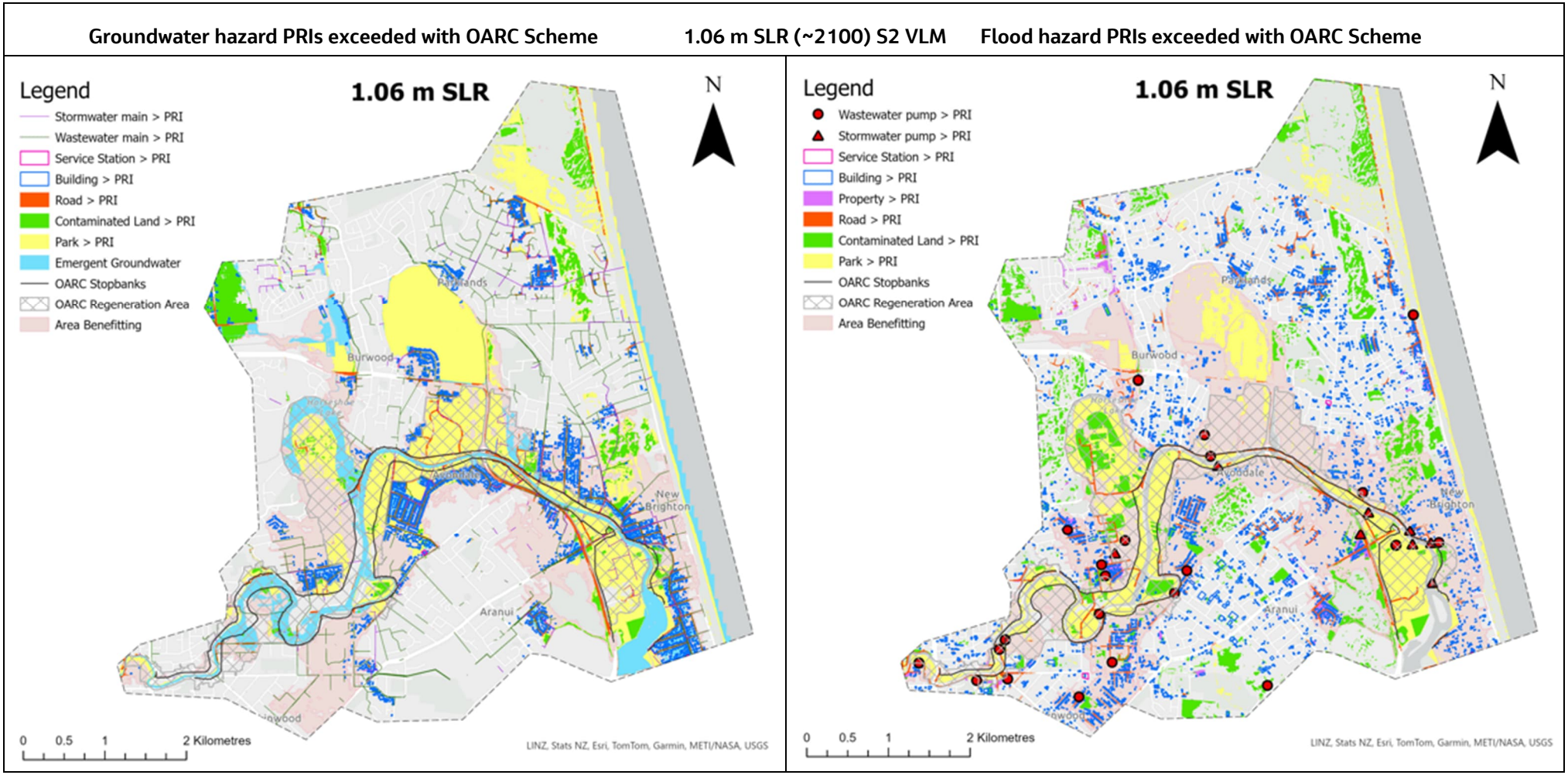


Figure 54. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 1.06 m SLR scenario (approximately 2100) with Scenario 2 Vertical Land Movement.

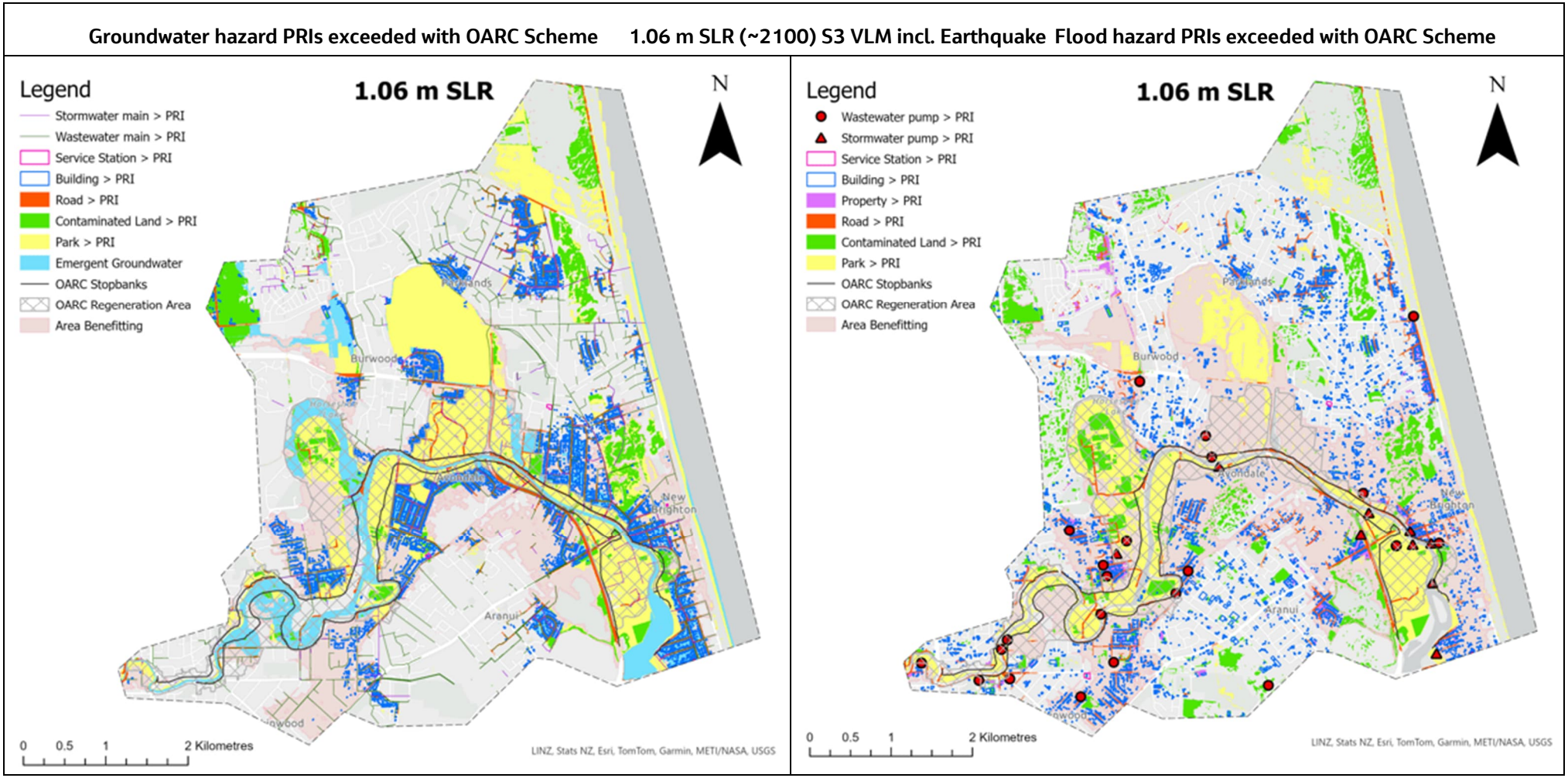


Figure 55. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 1.06 m SLR scenario (approximately 2100) with Scenario 3 Vertical Land Movement including earthquake.

Groundwater hazard PRIs exceeded with OARC Scheme **1.88 m SLR (~2150)** **Flood hazard PRIs exceeded with OARC Scheme**

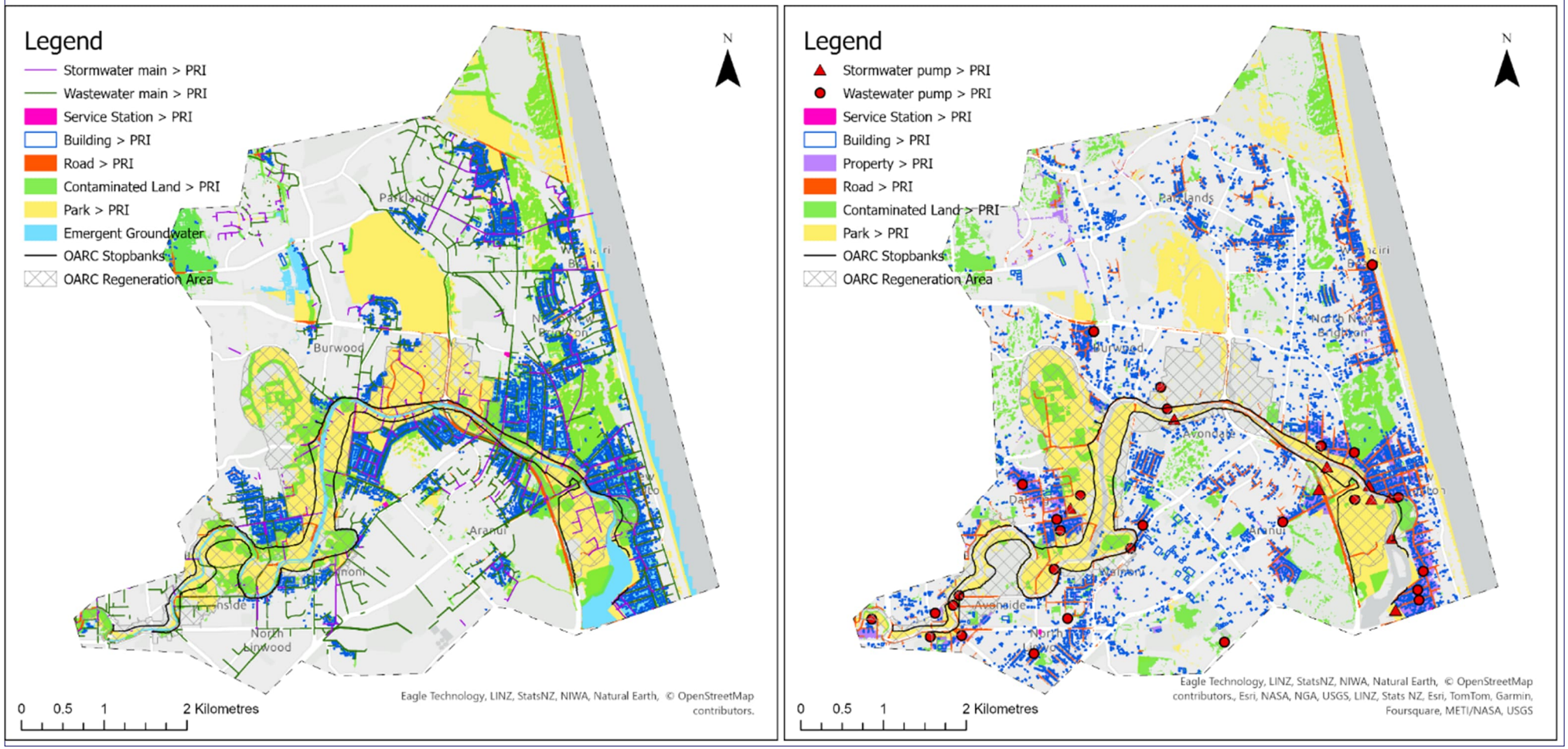


Figure 56. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 1.88 m SLR scenario (approximately 2150).

Groundwater hazard PRIs exceeded with OARC Scheme **2.4 m SLR (>2150)** **Flood hazard PRIs exceeded with OARC Scheme**

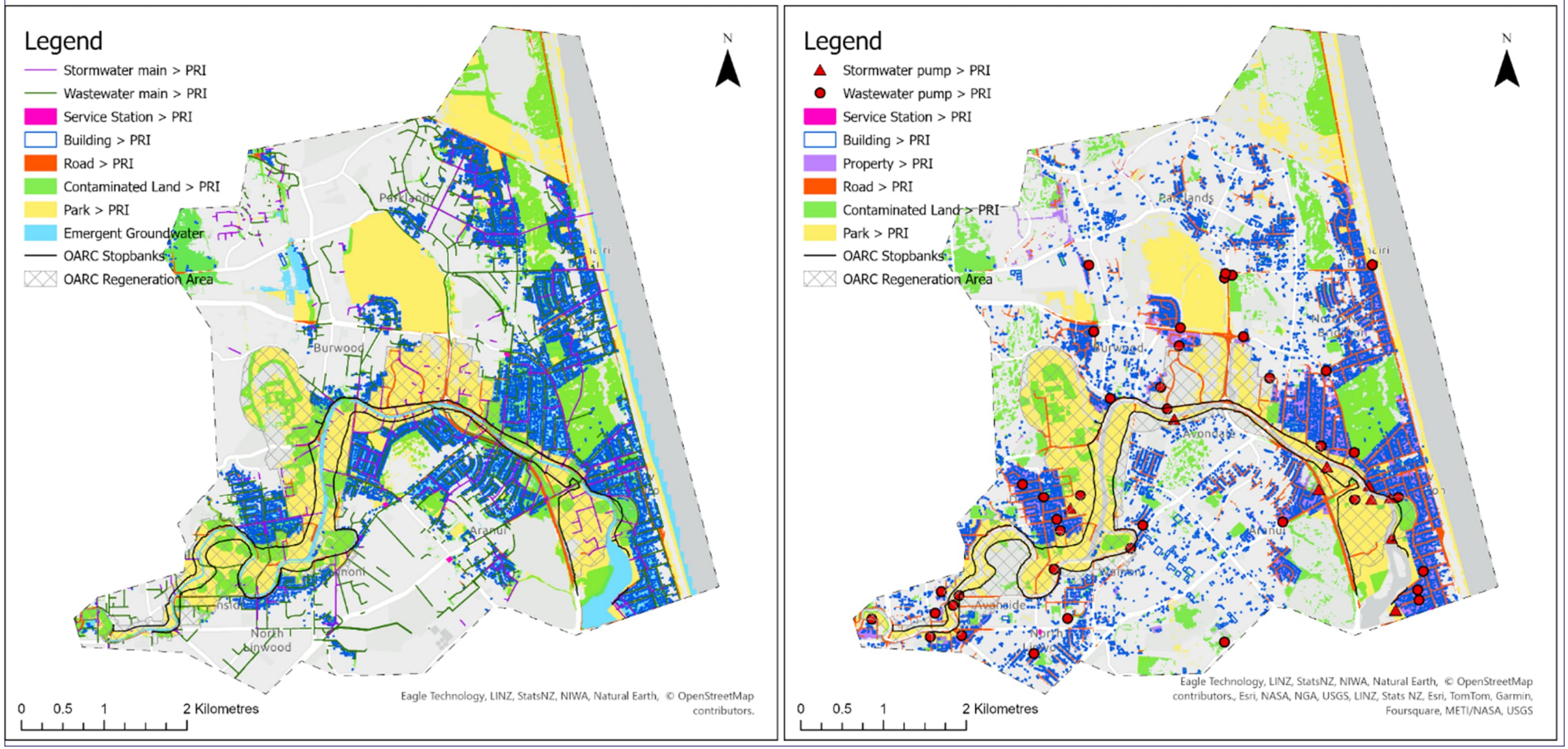


Figure 57. Location of land use elements where groundwater hazard and flood hazard exceed Project Response Indicators for 2.4 m SLR scenario (beyond 2150).

6.4 Residual risk to buildings from groundwater and flood hazard

A key objective for Stage 3 of the project is to identify the extent to which other hazards may impact land use in the area benefiting from the OARC Scheme, defined as the part of the project area over which the flood modelling indicates that the OARC Scheme has potential to provide benefit by reducing flood depths for a and so has the potential to reduce flood damages.

The PRIs for buildings identify where groundwater or residual flood hazard may impact buildings. We have analysed these spatially to identify the number of buildings that potentially benefit from the OARC Scheme for which groundwater or flood hazard PRIs are exceeded. The results are presented in Table 23 for the 2060 and 2100 scenarios with VLM and future earthquake scenarios and graphically in Figure 58 and Figure 59.

- By 2060, groundwater PRIs for 20-25% of buildings that benefit from the OARC Scheme are estimated to be exceeded, allowing for VLM but not allowing for any future earthquake-induced land settlement.
- By 2100 this rises to around 40% of buildings within the area benefiting from the OARC Scheme.
- With a future earthquake (VLM Scenario 3) absolute numbers of properties benefiting from the OARC Scheme but for which groundwater PRIs are exceeded increase to around half of all buildings in 2100.
- PRIs for flood hazards are exceeded for approximately 30% of buildings in the area benefiting from the OARC Scheme, in all VLM scenarios including Scenario S3 which allows for future earthquake-induced land settlement.
- PRIs for both groundwater and flood hazards are exceeded for between 10% and 15% of buildings in the area benefiting from the OARC Scheme in 2060 and 2100, increasing to up to 23% in 2100 with earthquake-induced land settlement.
- Over all the scenarios and epochs considered, PRIs for either groundwater hazard or flood hazard (or both) are exceeded for around 40% to 60% of all buildings in the area benefiting from the OARC Scheme.

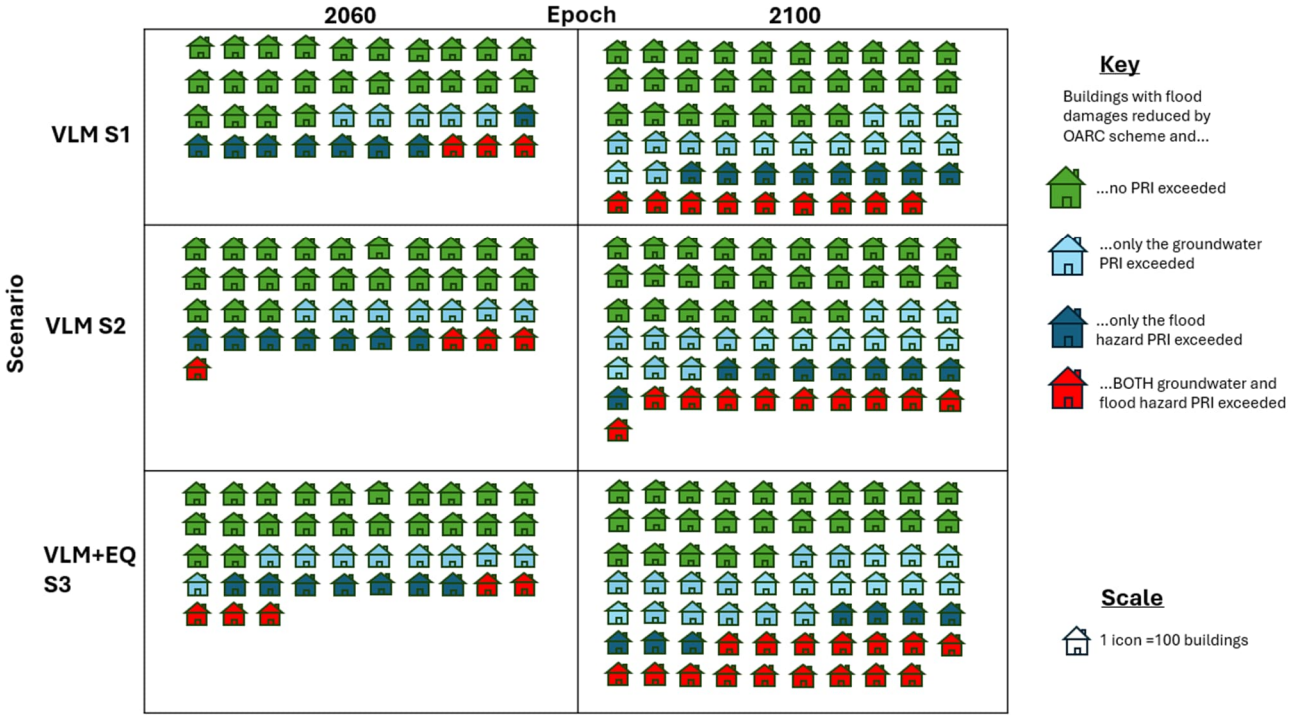


Figure 58. Buildings protected from flooding by the scheme that are at risk of groundwater and flood hazard PRI exceedance impacts

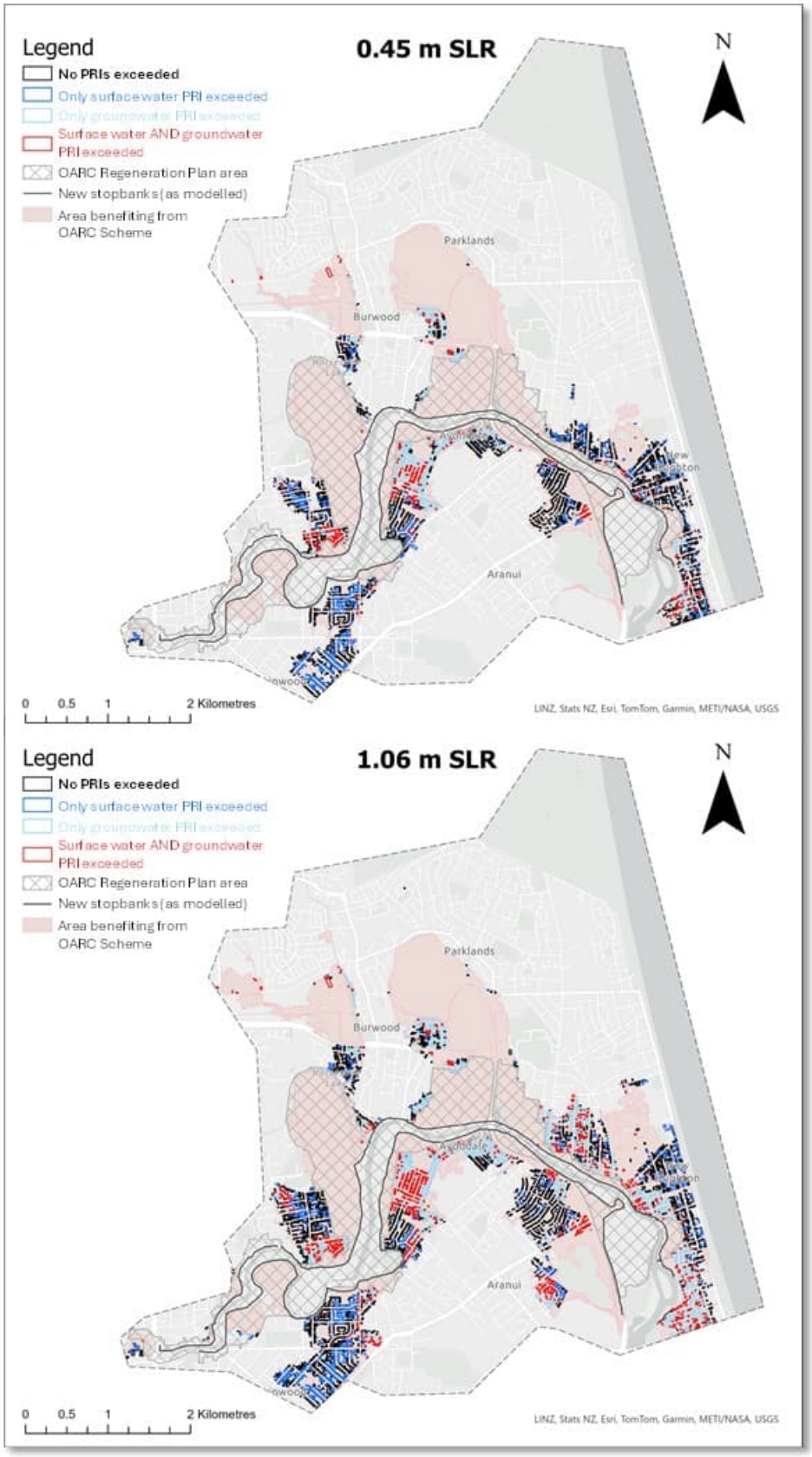


Figure 59. Locations of buildings in the area benefiting from the OARC Scheme for which no PRIs are exceeded (black), only surface water PRIs are exceeded (dark blue), only groundwater PRIs are exceeded (light blue) or both PRIs are exceeded (red) in future scenarios of 0.45 m SLR and 1.06 m SLR.

Table 23. Number and percentage of buildings protected from flooding by the scheme that are at risk of groundwater and flood hazard PRI exceedance impacts

Scenario	Number of buildings where flood depths are reduced by the OARC Scheme	Buildings where flood depths are reduced by the OARC scheme and…							
		… the groundwater PRI is exceeded		… the flood hazard PRI is exceeded		… BOTH groundwater and flood hazard PRI are exceeded		…no building PRI is exceeded	
	Count	Count	%	Count	%	Count	%	Count	%
S1 2060	3959	773	19.5	1095	27.7	317	8	2408	60.8
S1 2100	5900	2425	41.1	1767	29.9	931	15.8	2639	44.7
S2 2060	4107	1036	25.2	1156	28.1	408	9.9	2323	56.6
S2 2100	6140	2578	42	1869	30.4	1004	16.4	2697	43.9
S3 2060	4346	1459	33.6	1290	29.7	548	12.6	2145	49.4
S3 2100	6925	3723	53.8	2338	33.8	1589	22.9	2453	35.4

Notes:

- Flood damage may be reduced for buildings in the area benefiting from the OARC Scheme, but flooding is not necessarily prevented by the OARC Scheme.
- Counts for groundwater and flood hazard PRI exceedance are the totals exceeding the PRI so include within their counts the buildings where both PRIs are exceeded. To add the percentages up to 100% the 'both' percentage needs to be subtracted off the sum of the individual hazard exceedances before adding the 'no PRI' percentage.
- PRI values for buildings are:

  For groundwater, when depths are within 0.3m of ground level for new builds and older buildings with sandy soils and 0.7m for older buildings with silty soils for at least 15% of the time.

  For flood hazard when any of the following occur: underfloor damage at 10% AEP, above floor damage at 2% AEP, DR greater than 0.1 at 0.5% AEP

6.5 Review of PRIs

The PRIs for groundwater and flood hazards were developed through research and consideration of available knowledge on the effects of shallow groundwater and flooding. We found that there are few existing standard thresholds for many potential impacts either in New Zealand or globally and that there is less guidance available for groundwater thresholds than flood thresholds. The PRIs were therefore developed from a range of national and international research, and we consider them to be appropriate for this type of assessment.

Having applied the PRIs to the available hazard and land use data we have reviewed our approach and the results to identify limitations or whether any modifications to them may be justified for use in other work.

The values chosen would not change. For the purposes of this assessment, we do not consider that any changes are needed in the values adopted for the PRIs. We have not sought to confirm whether actual effects are being found at these threshold values and as such that they are the point at which a system stops functioning and a change is needed. In general, we consider that a definitive numerical threshold for many assets may be challenging to identify due to the range in tolerance to effects on individual elements. For

example, flooding may damage a particular asset but whether it is repaired and kept functioning may vary depending on the value of that asset in that location.

Cumulative mapping of combined PRI exceedances to identify impacts on a land use is effective. This approach is more useful as a means of understanding whether an overall system of land use may be impacted by the hazard than considering elements individually. Buildings and roads are key elements within residential areas – where PRI exceedances for these elements coincide there is a higher risk of impacting residential land use overall. The stormwater and wastewater network PRIs can also be used in this way as they also affect the functionality of a residential suburb if impacted. However, it was noted that much of the wastewater main network exceeds PRIs in early scenarios of climate change due to the depth of the elements. Further investigation of how the groundwater levels impact the functionality of the wastewater system – e.g., due to water ingress and shortened asset lifespan – would help to understand how far this hazard contributes to the overall impact on land use.

Flood hazard PRIs for people's safety (the property PRI), buildings and roads are the most useful for understanding the potential impacts of flooding on residential areas. These three PRIs all relate to primary aspects of residential land use and where clusters of overlapping PRI exceedances occur these provide higher confidence of impacts in those areas.

Emergent groundwater was a useful PRI to indicate local ponding and flooding. Emergent groundwater is a concept that is easy to communicate as the community can picture what ponding and flooding from groundwater looks like and what it may impact. This PRI is therefore easy to interpret as exceedances become more prevalent with increasing climate change. It should be noted however that the underlying groundwater rise modelling and data used in this analysis has a number of uncertainties that may influence the mapped outcome.

Buildings PRIs clearly illustrate the changing risk in suburbs. The changing distribution of building PRI exceedances with climate change provides a useful indication of where houses may be at risk, in which suburbs and in which scenario they would get worse.

PRIs for contaminated sites can be interpreted differently to the other PRIs. Contaminated land differs from pipes, roads and buildings which are elements that support the community land use. The PRIs for contaminated land site refer to the risk of rising groundwater or surface flooding mobilising contaminants from the sites and polluting surrounding areas. Contaminated land is often a historic or legacy activity or land use rather than a present-day active use which a community would wish to maintain. In addition, the underlying HAIL dataset identifies activities that are at risk of creating contamination and not all sites are verified as contaminated. Contamination can occur on sites that are not listed as HAIL sites. PRI exceedances are therefore useful for risk screening these sites but is harder to interpret them in combination with the other PRIs. The exceedance of contaminated land PRIs on parkland sites in residential areas does not necessarily have an impact on the viability of those residential land uses.

The contaminated land data used in the assessment is taken from the Hazardous Activities and Industries List (HAIL) database which indicates where potentially contaminating activities have occurred. Some of those sites may then have been investigated and may be known to be contaminated. The data is relatively coarse in that it identifies land parcels but not what contaminants may exist or the location on site or depth. As such the PRI assessment is necessarily a high-level risk screening assessment and does not indicate the actual risk of contaminant mobilisation or not from specific sites with rising groundwater or flooding.

Parks and reserves and sports fields perhaps need screening to exclude wetland sites. The parks and reserves data covered many types of land use. Some of these, such as Clare Park and Travis Wetland, are wetland environments and are more compatible with high groundwater and flooding or have flood management functions built into them. While there is value in understanding how high groundwater and flooding expands out from these areas into surrounding land uses over time, it may be sensible to screen out certain parks from the data where those parks are considered to be compatible with flooding or high groundwater in future analysis. This could then allow assessments to focus on park land uses where high

groundwater and flooding could more obviously impact the use of that park such as sports fields, school playing fields and other recreational facilities such as cycle tracks and walking tracks.

Availability of appropriate data is key to assessing PRI exceedances. Within this work we did not manage to obtain or generate a suitable dataset for wastewater laterals that would provide both spatial location and depth and so we could not assess that PRI. The outcomes of this type of assessment depend on the quality of the spatial data used and the availability of such data should be considered when developing any PRIs. Some datasets are more robust and have more relevant details, such as elevations, to inform the analysis. Datasets often require some form of processing or analysis to be used in this type of assessment.

6.6 Monitoring of evolving hazards

6.6.1 Monitoring for groundwater hazards

The main elements for which groundwater hazard PRI are exceeded in the project area over time are buildings, roads, wastewater mains, stormwater mains, contaminated land and parks.

Direct long-term monitoring of groundwater levels within areas where PRIs are predicted to be exceeded over time would be valuable to understand the trends in changing groundwater levels over time. This can inform the community on how the hazard itself is changing over time and when PRIs may be approached. This monitoring however does not provide information on whether the impacts of the changing hazard are occurring. Future ATs may be more likely to be based on changing impacts rather than just the changing hazard. For example: functionality of the stormwater system or cost to maintain that functionality rather than just its exposure to groundwater. Therefore, monitoring of impacts on assets should also be considered and could include:

Wastewater mains – monitoring of indicators of the functionality of the system or cost to maintain it such as:

- Changing amounts of water ingress (Increased wastewater flows over time not from increased housing or population)
- Increasing pump station run times, maintenance and repair costs for networks increasing compared to other similar assets in the city

Stormwater mains - monitoring of indicators of the functionality of the system or cost to maintain it such as:

- Increase reported nuisance flooding caused by lack of capacity in the stormwater network due to groundwater ingress
- Increasing pump station run times, maintenance and repair costs for networks increasing compared to other similar assets in the city

Buildings – monitoring of groundwater impacts on the sanitary state of houses:

- Collection of data on location and prevalence of damp and mouldy houses – for instance data from Council community housing could be gathered and compared to monitored groundwater levels

Roads – monitoring of increased damage and repair costs:

- Collection of data on the damage to roads in high groundwater areas and repair costs when compared to other similar assets in the city that are not in shallow groundwater areas.

Contaminated Land – monitoring of groundwater levels and environmental risk:

- Impacts of high groundwater on contaminated land is very site specific as it depends on the type and depth of contaminants and their potential mobility as well as the likely receiving environments (surface water or groundwater). While it could be possible to develop site specific monitoring for

each identified HAIL site, this would be costly since there are many sites within the project area. Decisions on whether to monitor would be better made using some form of risk screening of sites that present a greater risk to the environment. Monitoring of long-term changes in groundwater levels would help inform this risk screening.

Parks – monitoring of useability of parks:

- Park areas that are managed for ecological values may be more adaptable to rising groundwater and may need no monitoring as natural ecological change processes can be allowed to progress.
- Where parks are used for more formal recreational activities – such as sports fields – then their functionality can be impacted. Monitoring of the number of days they are too wet to be useable, or costs to drain or remediate sports surfaces could be undertaken. This data can be compared to other facilities in the city to identify when impacts are occurring.

6.6.2 Monitoring for flood hazards

The main elements for which PRIs are exceeded over time are buildings, properties, roads, contaminated land, parks, stormwater pump stations and wastewater pump stations.

Changing flood hazard over time has been modelled but the actual flood hazard is not something that can be easily monitored over time. It may not be sensible to wait until a large flood occurs, and so can be monitored, before choosing to act, as unacceptable damages or dangers may occur. Drivers of flood hazard that do change with time, such as rising mean sea level or temperature could be monitored instead. Monitoring of changing impacts on assets could include the following:

Stormwater and wastewater pump stations –

- Monitoring of maintenance and repair costs and flood incidents that impact the assets.

Buildings and properties –

- Frequency, depth and duration of nuisance flooding problems in smaller events.

Roads –

- Monitoring of duration and frequency of lack of access.
- Collection of data on the damage to roads from flooding and repair costs when compared to other similar assets in the city.

Contaminated land –

- Impacts of flooding on contaminated land are very site specific and relate to depth and type of contaminants, their potential mobility, erodibility of the site materials and location and type of receiving environments. As such monitoring would be very site specific. A risk screening may be of value to identify sites that could be at risk of impacting receiving environments in a flood.

Parks –

- Park areas that are managed for ecological values may be more adaptable to flooding and may need no monitoring as natural ecological change processes can be allowed to progress.
- Where parks are used for more formal recreational activities – such as sports fields, paths – then their functionality can be impacted. Monitoring of the number of days they are flooded and cannot be accessed or used, or costs to drain or remediate sports surfaces could be undertaken. This data can be compared to other facilities in the city to identify when impacts are occurring.

6.7 Initial assessment of the effects of groundwater hazards relative to the benefits of the OARC Scheme.

Financial damages from chronic groundwater hazards, which will occur with or without the OARC Scheme, have not been evaluated and further assessment is needed to understand these effects together with the feasibility, costs and benefits of managing groundwater hazards alongside flood hazards.

As an initial assessment of the effect of groundwater hazards relative to the benefits of the OARC Scheme, Table 24 compares the damages avoided with the OARC Scheme to the corresponding values if any benefits to buildings where the groundwater PRIs are exceeded are excluded. The present value of damages to 2060 and 2100 have been calculated based on the existing stopbanks remaining functional until approximately 2030 after which damages without the OARC Scheme are those without any stopbanks and damages with the OARC Scheme are those with the new stopbanks.

The results show that the total present value damages avoided with to the OARC Scheme is reduced by around 40% in 2060 and by around 60% in 2100. This reflects the fact that the buildings exposed to the largest flood depths, and which therefore benefit most from the OARC Scheme, tend to be in areas susceptible to the shallowest groundwater and so contribute disproportionately to the benefits of the scheme. In 2060 the reduced benefit of the scheme is however comparable to the cost of the new flood defences and in 2100 the reduced benefit is approximately double the costs. This suggests that the OARC Scheme is still likely to be beneficial overall even if properties affected by residual groundwater hazards are excluded, particularly in the longer term when flood damages without the scheme become substantial.

The PRI exceedance maps show that PRIs for other elements of land use which are needed to access or provide essential services to buildings, such as roads, are often exceeded in the same areas as buildings. However, some of these elements may also be affected by groundwater in areas where building PRIs are not exceeded, so indirectly impacting on their use and reducing the value of the OARC Scheme in reducing flood damages to the buildings.

Table 24. Effect of excluding buildings where groundwater PRIs are exceeded on flood damages avoided through the OARC Scheme (variable discount rate applied to calculate present values).

			2060	2100
Annual average damages ($ Million)	All buildings	without OARC Scheme	64	169
		with OARC Scheme	14	21
	Excluding buildings in area benefitting where groundwater PRIs exceeded	without OARC Scheme	34	51
		with OARC Scheme	11	15
Cumulative present values from 2020[38] ($ Million)	All buildings	without OARC Scheme	990	2850
		with OARC Scheme	360	660
		Damages avoided	630	2190
	Excluding buildings in area benefitting where groundwater PRIs exceeded	without OARC Scheme	710	1410
		with OARC Scheme	340	560
		Damages avoided	370	850
	Costs of flood defences and pumpstations (~+/-50%)		380	420

[38] Present values are calculated on the basis that the OARC Scheme becomes operational in around 2030 at approximately the same time as the existing stopbanks reach the end of their functional life.

6.8 Example approach to managing groundwater hazard

The intent of identifying where groundwater PRIs may be exceeded is to identify where and when additional management responses may be needed to adapt to the impacts of high groundwater levels. It is anticipated that adaptation to the groundwater rise impacts may be required where PRIs for more than one element of land use are exceeded over an area rather than simply where the PRI for an individual element of land use exceeded. This is because the cumulative impacts of PRI exceedances for multiple elements would be more certain to influence the overall functioning of residential land use, for example.

Adaptation responses to high groundwater levels could range from tolerating the risk through to alterations to buildings or utilities to accommodate the hazard, retreating assets or proactively managing groundwater. Each of these responses may provide mitigation to different elements of land use and with different effectiveness. For instance, a policy specifying new build foundation design may keep new houses from being impacted by damp but not address impacts on pipe networks. The different adaptation responses will have different costs and benefits.

Within this project we are not developing options to manage the identified PRI exceedances for either groundwater hazards or flood hazards in each future scenario. However, the project scope includes for a high-level *indication* of the potential capital cost associated with managing groundwater levels through pumping, as a potential adaptation response. It should be noted that no assessment has been made of whether groundwater pumping is a suitable or preferred solution for groundwater management in these areas. The intent is purely to provide Council with an *indication* of the order of magnitude capital costs associated with one potential approach to adapting to this evolving hazard.

6.8.1 Groundwater management areas

Groundwater management areas have been identified primarily as areas where the groundwater hazard PRI for buildings is exceeded, with secondary consideration of exceedance of PRIs for roads, stormwater pipes and wastewater pipes. It is noted that areas where the building PRI is exceeded typically coincide with those where stormwater and wastewater PRIs are exceeded.

To rationalise the delineation of areas for groundwater management, isolated single dwellings, or small clusters of dwellings (less than 5 buildings) that are separate from larger concentrations of buildings which require management have been excluded, as have buildings within the OARC Regeneration area. Buildings on larger sections in predominantly rural areas, such as Marshlands, have also been excluded as these would invoke a significantly greater cost per building compared to more densely occupied residential suburbs. In some cases, where isolated clusters of dwellings were within approximately 100 m of larger clusters and linked by other elements exceeding PRI (such as roads, stormwater pipes or wastewater pipes), the areas were retained for assessment. A degree of judgement has been used to define and map these management areas, i.e., in including certain areas with multiple PRI exceedances and excluding certain areas of small numbers of exceedances. They are not an indication of all areas where groundwater rise could impact individual elements but more an indication of where multiple PRI exceedances indicate that future intervention may be required and justified.

The groundwater management areas are then subdivided into areas of predominantly silty and predominantly sandy soils since the soil type influences the management measures required and the costs. The defined groundwater management areas are summarised in Table 25, Table 26 and Table 27 and mapped in Figure 60 to Figure 68.

Table 25. Summary of Groundwater Management Areas (without VLM).

Scenario	Total area exceeding PRIs (ha)	Predominantly silt area (ha)	Predominantly sand area (ha)
0.19 m SLR (~2030)	59.9	55.2	4.7
0.45 m SLR (~2060)	124.9	101.9	23.0
0.45 m SLR (~2060)[EQ]	155.2	120.6	34.5
1.06 m SLR (~2100)	246.4	141.0	105.4
1.06 m SLR (~2100)[EQ]	319.0	174.0	145.0
1.88 m SLR (~2150)	577.2	229.0	348.3
2.4 m SLR (>2150)	785.2	259.8	525.4

Table 26. Proportion of Groundwater Management Area within area benefiting from the OARC Scheme (without VLM).

Scenario	Total area exceeding PRIs (ha)	Area > PRI and benefiting from OARC Scheme (ha)	Area > PRI and not benefiting from OARC Scheme (ha)
0.19 m SLR (~2030)	59.9	36.1	23.7
0.45 m SLR (~2060)	124.9	90.3	34.6
1.06 m SLR (~2100)	246.4	209.7	36.1

Table 27. Proportion of Groundwater Management Area within area benefiting from the OARC Scheme (with VLM).

Scenario	Total area exceeding PRIs (ha)	Area > PRI and benefiting from OARC Scheme (ha)	Area > PRI and not benefiting from OARC Scheme (ha)
S1 2060	125.5	90.7	34.8
S2 2060	157.2	118.6	38.6
S3 2060	210.5	153.9	56.6
S1 2100	308.9	243.6	65.3
S2 2100	328.6	256.2	72.4
S3 2100	494.6	354.3	140.3

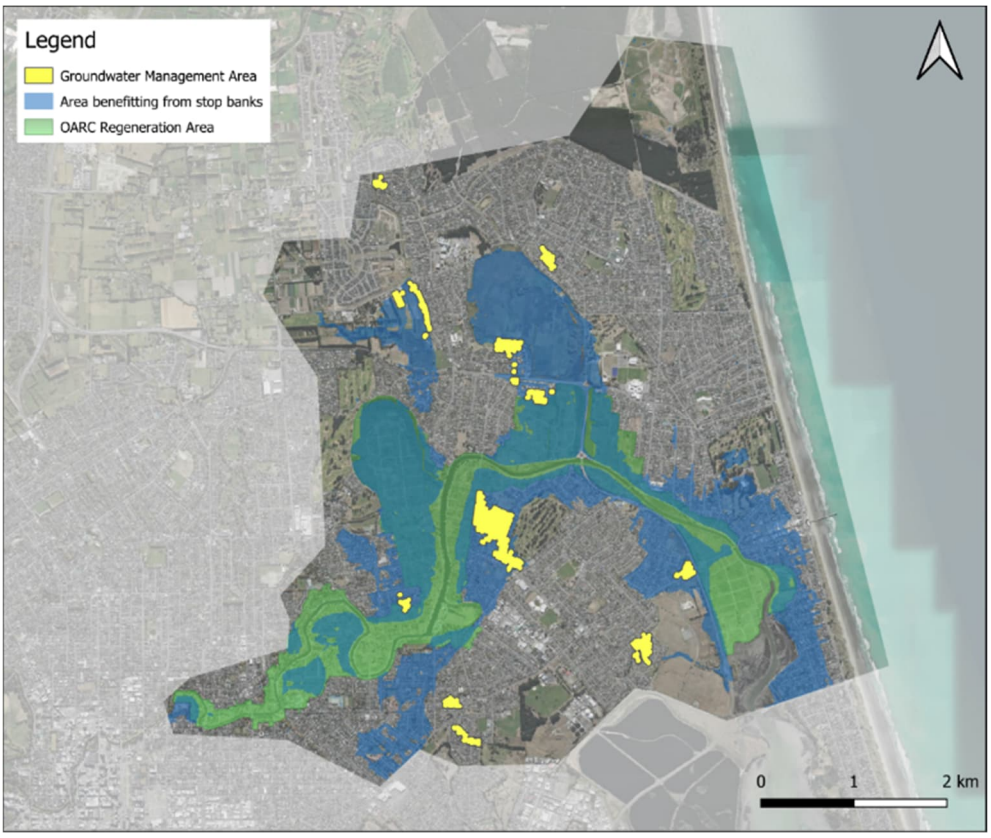


Figure 60. Groundwater Management Areas under 0.19 m SLR (~2030).

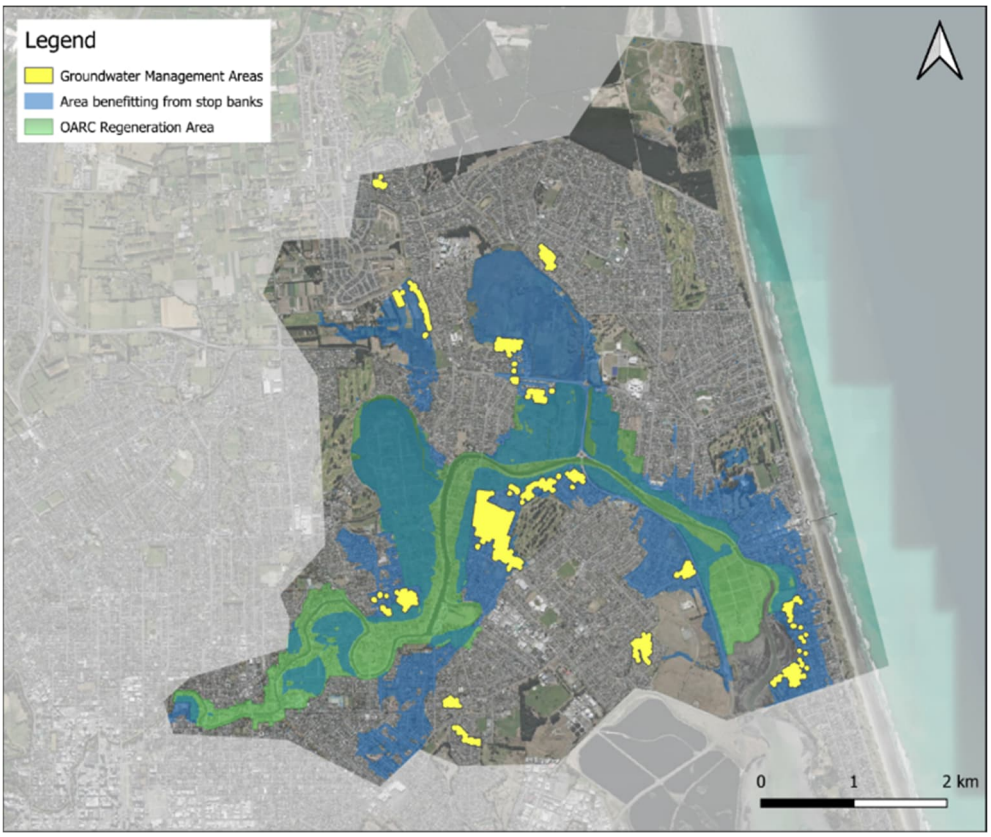


Figure 61. Groundwater Management Areas under 0.45 m SLR (~2060).

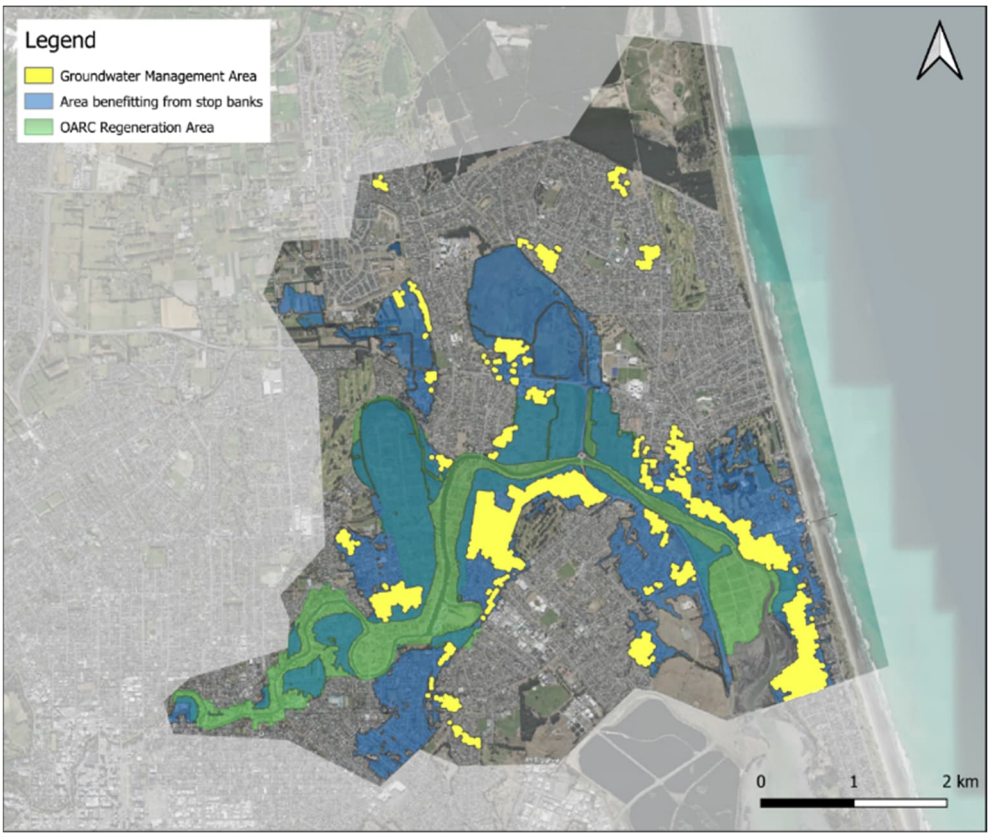


Figure 62. Groundwater Management Areas under 1.06 m SLR (~2100).

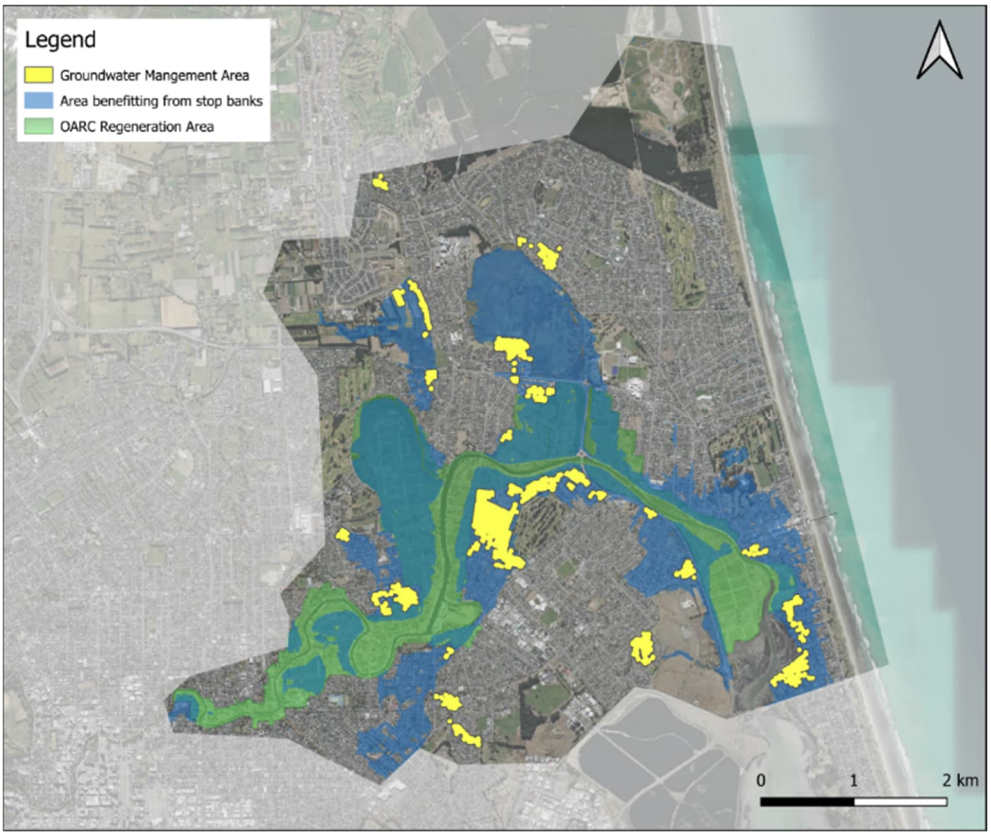


Figure 63. Groundwater Management Areas under S1 2060.

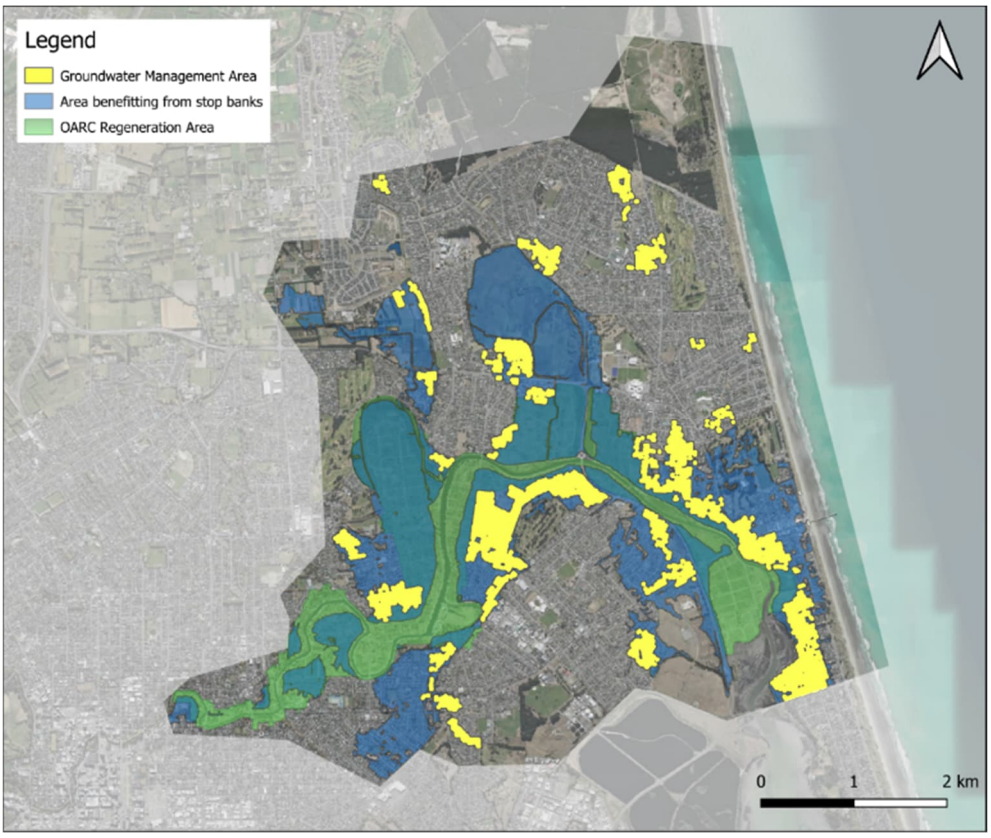


Figure 64. Groundwater Management Areas under S1 2100.

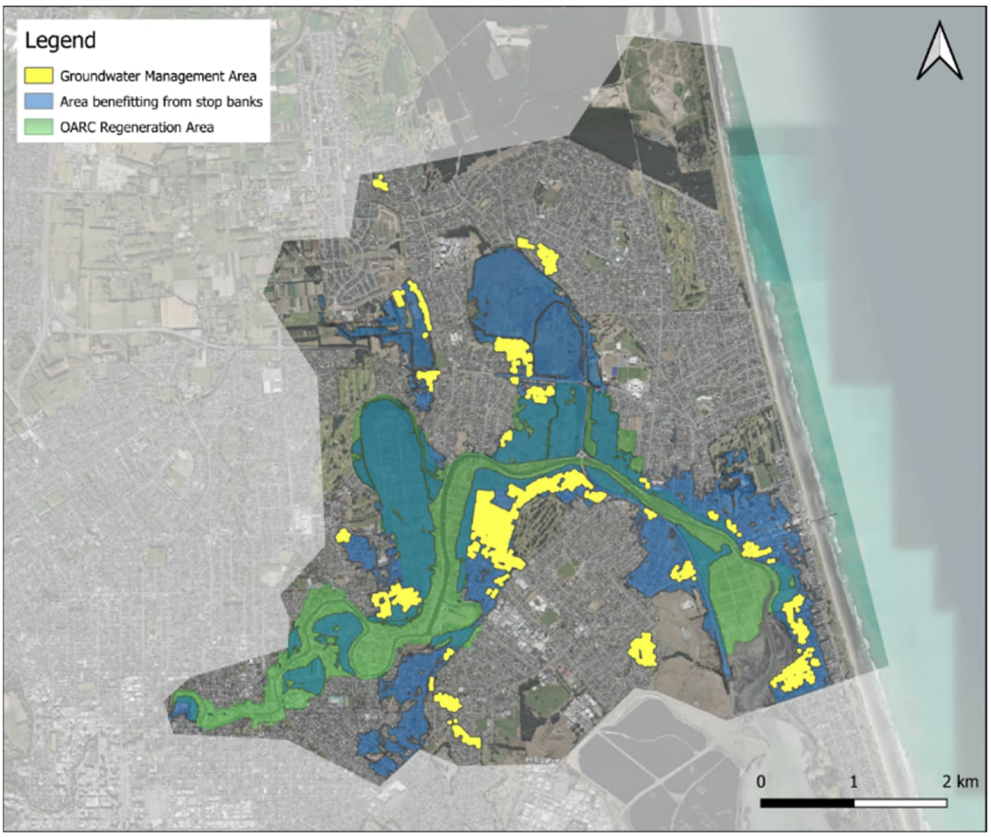


Figure 65. Groundwater Management Areas under S2 2060.

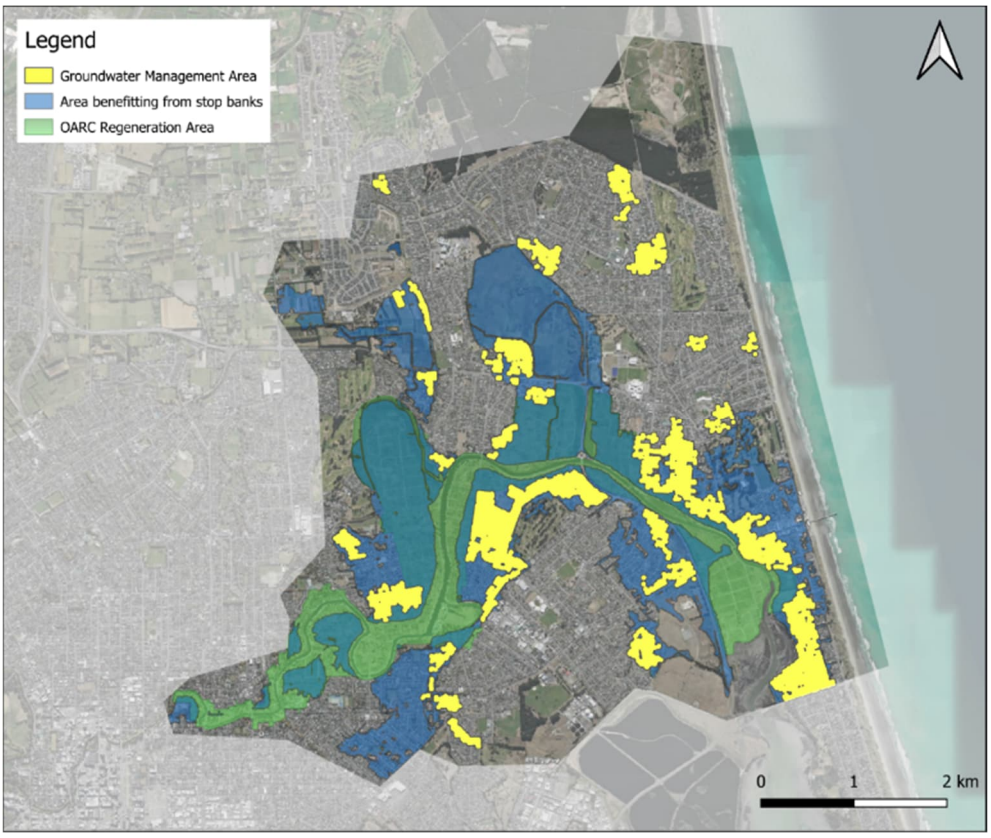


Figure 66. Groundwater Management Areas under S2 2100.

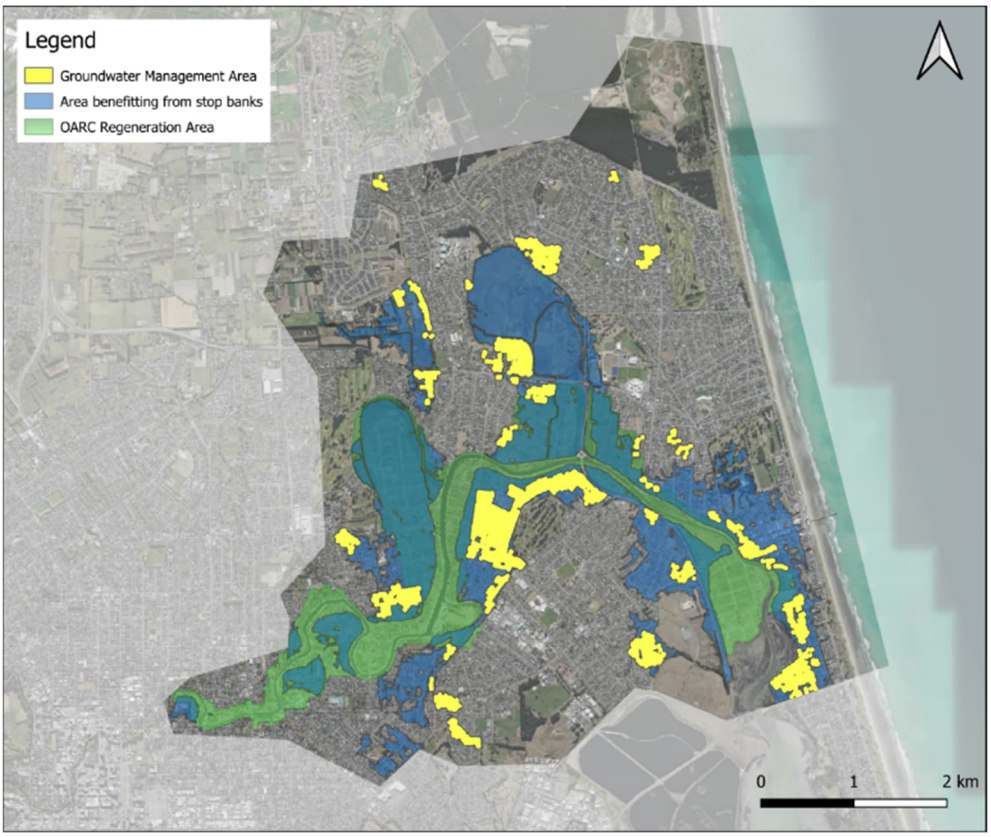


Figure 67. Groundwater Management Areas under S3 2060.

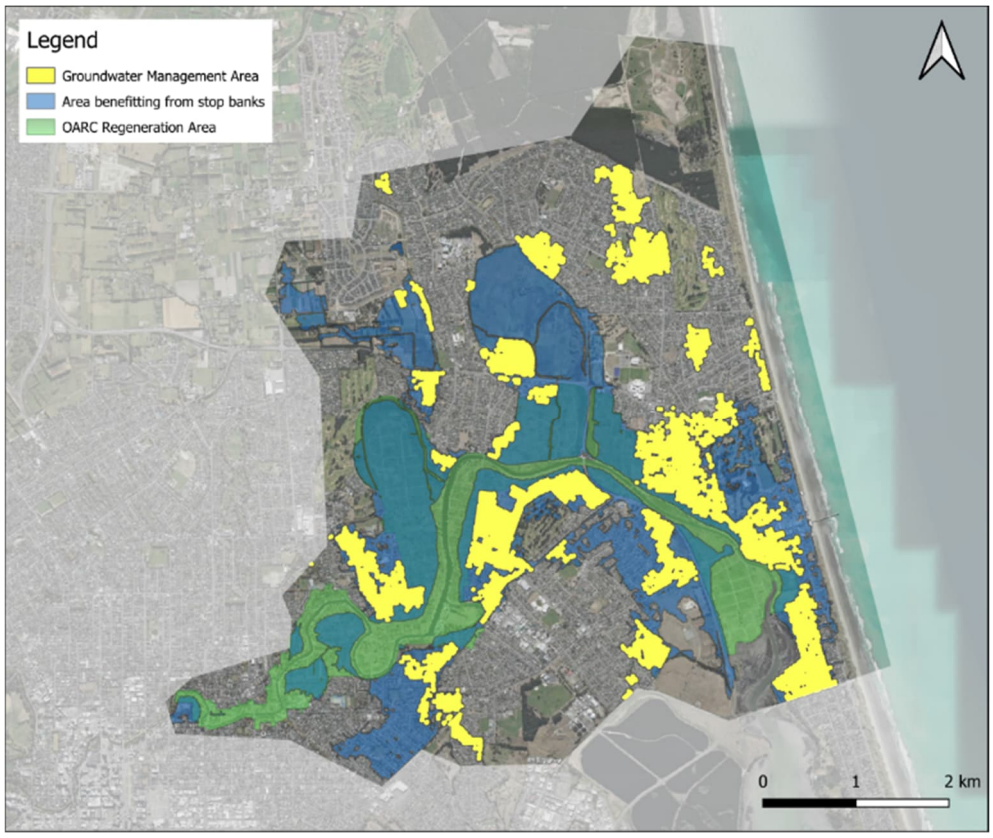


Figure 68. Groundwater Management Areas under S3 2100.

6.8.2 Groundwater management measures and cost functions

Groundwater management measures and associated cost functions are based on the those presented in the Beca (2018) report, 'Earthquake Effects on Groundwater Levels - Case Study Options Report'. The report considered groundwater effects on properties with a threshold groundwater level of 0.35 m below ground level.

The Beca report initially considered a variety of groundwater management options, including:

- Subsoil drainage
- Open drains
- Shallow wells
- Deep wells
- Cut-off walls.

This long list of management options was then refined to two alternative options comprising subsoil drains and shallow wells. Both subsoil drains and shallow wells were considered in predominantly silty areas, whereas in predominantly sandy areas only subsoil drains were considered. All options were assumed to be connected via a reticulation network and connected to a series of pump stations. It is noted that shallow wells in predominantly sandy soils were excluded due to potentially high pumping rates required, and possible consolidation settlement effects. Groundwater disposal was assumed to be direct to the local stormwater network, without treatment or stormwater network upgrades.

It should be noted that the feasibility of obtaining planning consent for such a method of drainage or well pumping to manage groundwater would need to be investigated since it may not be provided for under current planning policies and this could be a key constraint in implementing any solution.

There are limitations with the cost estimates and they are unlikely to capture the full cost and complexity of implementing the management options and the full feasibility and constraints of the options have not been assessed in detail.

The report cites a long list of uncertainties and technical risks associated with the high-level nature of this study, repeated as follows:

- *Engineering assessment and cost estimation outcomes are reliant on the quality of the assessment inputs which include; groundwater modelling (Aqualinc), sea level rise horizons, pre- and post-earthquake ground surface, assumed trigger level for requiring mitigation.*
- *Case study areas have been used to develop potential solutions and costs. Conceptual designs are high level in nature and costs are based on assumed cost unit rates. The city-wide assessment assumes that both the technical solutions, design strategies, area unit costs are a representative average across the city. This may not be the case.*
- *Simplified 2D groundwater modelling bas been used to inform case study concept designs.*
- *Assumptions around asset lives and operation and maintenance requirements, O&M costs and discount rate used in NPV analysis.*
- *Variability in soils (both in plan and with depth)*
- *Variability in ground levels and depth to groundwater*
- *Effects of intercepting groundwater on springs and base flow in waterways*
- *Consolidation settlement (due to consolidation and/or loss of fines)*
- *Mobilising ground contamination through dewatering*
- *Drawing wastewater from leaking wastewater pipes through dewatering*
- *Saline intrusion from dewatering*
- *Mobilisation of fines leading to silting up of subsoils or wells*
- *Flow rates being higher than expected leading to issues with pumps and downstream system capacity*
- *Flow rates or drawdown being lower than expected leading to ineffective performance*
- *Changes in system performance over time*
- *Frequency of Operation & Maintenance work required*

The report also made the following recommendations:

- *This study is used to inform discussion, and consultation about current and future groundwater levels (with sea level rise), and options for responding in terms of groundwater mitigation and land use.*
- *This study is not used to identify specific projects or areas requiring groundwater mitigation, or to set budgets for groundwater mitigation projects or programmes.*
- *Trigger levels for groundwater mitigation are further considered.*
- *Where groundwater mitigation is required, site specific investigations (desktop and field), options assessment and design are undertaken.*
- *To better understand the likely performance of potential groundwater mitigation measures, pilot studies are considered. This is particularly relevant for shallow wells, which have not been widely used for permanent groundwater mitigation in Christchurch.*

The initial list of options was also not exhaustive. Of the options considered, only the cut-off walls are considered to be a proactive option for managing groundwater response to SLR, preventing the propagation

of SLR effects. The other options are reactive and aimed at lowering groundwater levels in already affected areas. Another proactive option not considered is the use of barrier drains to control the effects of SLR before the groundwater management areas become affected. Costs associated with managed retreat were also not considered. Further, any required water treatment or capacity upgrades could significantly increase the costs of these options.

Beca estimated costs for city-wide groundwater management on a per square metre basis, with costs scaled based on the density or proportion of houses per suburb requiring groundwater management. That is, the study identified that there would be economies of scale for larger areas requiring management, as indicated in Figure 69 below.

For this assessment, to provide a range of indicative capital costs, we have considered two potential methods for deriving for cost rates using the Beca rates for those suburbs which are included within the project area for each equivalent sea level rise scenario:

- Cost Basis 1: the average of the costs per square metre estimated by Beca.
- Cost Basis 2: the highest of the costs per square metre estimated by Beca.

It is noted that the Beca study only extended to 100 years into the future with a corresponding 1 m SLR. However as indicated in Figure 69, once the proportion of properties affected exceeds approximately 30% of properties in the management area, there is little further reduction in unit costs. Therefore, the costs for 1 m SLR have been retained for the larger sea level rise scenarios.

A comparison of sea level rise scenarios between Beca (2018) and this study is provided in Table 28. Adopted costs, on a per square metre basis, are provided in Table 29.

These indicative costings have been estimated for comparative purposes. It is important to note that operational costs are not included in these costs, and present value has not been assessed.

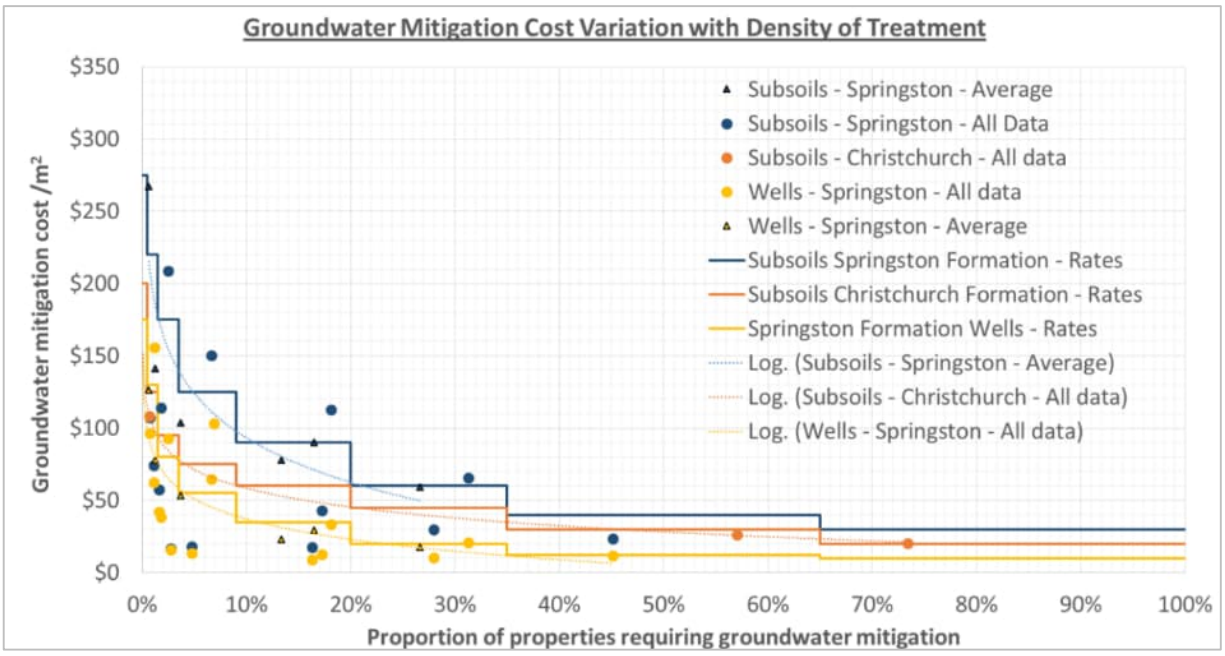


Figure 69. Variation of unit groundwater mitigation costs with density of treatment (Beca 2018).

Table 28. Comparison of Beca (2018) future climate scenarios and multi-hazards Stage 3 scenarios.

Beca (2018) Scenario		Multi-hazards Stage 3 scenarios	
Timing	***Sea Level Rise (m)***	***Approximate timing***	***Sea Level Rise (m)***
Existing	0	-	-
25 years	0.19	2030	0.19
50 years	0.4	2060	0.45
100 years	1.0	2100	1.06
-	-	2150	1.88
-	-	>2150	2.4

Table 29. Adopted Capital cost rates for Groundwater Management ($/m^2) after Beca (2018), excluding operational costs.

Scenario	***Sea Level Rise***	Cost Basis 1 (per m^2)			Cost Basis 2 (per m^2)		
		Subsoil - silt	Subsoil - sand	Wells - silt	Subsoil - silt	Subsoil - sand	Wells - silt
~2030	0.19 m	$235	$150	$141	$275	$200	$175
~2060	0.45 m	$212	$130	$121	$275	$200	$175
~2060 [EQ]	0.45 m + ground settlement	$200	$110	$114	$275	$200	$175
~2100	1.06 m	$189	$91	$107	$275	$200	$175
~2100 [EQ]	1.06 m + ground settlement	$189	$91	$107	$275	$200	$175
~2150	1.88 m	$189	$91	$107	$275	$200	$175
>2150	2.4 m	$189	$91	$107	$275	$200	$175

6.8.3 Groundwater management costs

For the adopted cost functions, wells in predominantly silty soils are considerably more cost effective than subsoil drains. Subsoil drains in predominantly sandy soils are more cost effective than subsoil drains in predominantly silty soils due to the elevated permeability, larger radius on influence and therefore considerably broader spacing to achieve effective dewatering. A range of total costs have been developed by using the two cost basis rates in two management approaches:

- subsoil drains approach for silt combined with subsoil drains for sand, which provides an example of a higher cost option.
- wells in silt areas combined with subsoil drains in sand areas which provides a potentially lower cost option.

The resulting estimated ranges of groundwater management costs for each of the future climate scenarios are provided in Table 30. The costs are for capital costs associated with groundwater management, exclude operational costs, and do not include for any treatment of groundwater or reticulation upgrades required to dispose of pumped groundwater. The costs are based on the Beca 2018 rates and are not modified to present value. It is noted that costs are presented for the total groundwater management area for each SLR scenario, not for the incremental increase in affected area from the previous scenario.

Table 30. Estimated total capital costs of groundwater management, excluding operational costs (2018 rates and not modified to present value).

Scenario	Subsoil – silt	Wells - silt	Subsoil - Sand	Total Cost
Cost Basis 1				
0.19 m SLR (~2030)	$130 M	$78 M	$7 M	$85 M to $137 M
0.45 m SLR (~2060)	$216 M	$123 M	$30 M	$153 M to $246 M
0.45 m SLR (~2060)[EQ]	$242 M	$137 M	$38 M	$176 M to $280 M
1.06 m SLR (~2100)	$267 M	$151 M	$95 M	$247 M to $362 M
1.06 m SLR (~2100)[EQ]	$329 M	$187 M	$131 M	$318 M to $460 M
1.88 m SLR (~2150)	$433 M	$246 M	$316 M	$561 M to $749 M
2.4 m SLR (>2150)	$491 M	$279 M	$476 M	$755 M to $967 M
Cost Basis 2				
0.19 m SLR (~2030)	$152M	$97M	$9M	$106 M to $161 M
0.45 m SLR (~2060)	$280M	$178M	$46M	$224 M to $326 M
0.45 m SLR (~2060)[EQ]	$332M	$211M	$69M	$280 M to $401 M
1.06 m SLR (~2100)	$388M	$247M	$211M	$457 M to $598 M
1.06 m SLR (~2100)[EQ]	$478M	$304M	$290M	$594 M to $768 M
1.88 m SLR (~2150)	$630M	$401M	$697M	$1,097 M to $1,326 M
2.4 m SLR (>2150)	$715M	$455M	$1,051M	$1,506 M to $1,765 M

Table 31. Estimated total capital costs of groundwater management inside and outside area benefiting from OARC Scheme, excluding operational costs (2018 rates and not modified to present value).

Scenario	Total Cost	Cost for areas benefiting from OARC Scheme	Cost for areas not benefiting from OARC Scheme
0.19 m SLR (~2030)	$85 M to $161 M	$51 M to $99 M	$34 M to $62 M
0.45 m SLR (~2060)	$153 M to $326 M	$111 M to $236 M	$42 M to $90 M
1.06 m SLR (~2100)	$246 M to $597 M	$211 M to $512 M	$35 M to $85 M

Table 32. Estimated total capital costs of groundwater management costs under VLM scenarios inside and outside area benefiting from OARC Scheme, excluding operational costs (2018 rates and not modified to present value).

Scenario	Total Cost	Cost for areas benefitting from defences	Cost for areas outside of from defences
S1 2060	$154 M to $326 M	$111 M to $235 M	$43 M to $91 M
S2 2060	$178 M to $404 M	$134 M to $304 M	$44 M to $101 M
S3 2060	$226 M to $532 M	$165 M to $392 M	$60 M to $140 M
S1 2100	$308 M to $744 M	$245 M to $595 M	$63 M to $148 M
S2 2100	$326 M to $785 M	$257 M to $622 M	$70 M to $163 M
S3 2100	$488 M to $1,167 M	$354 M to $859 M	$134 M to $308 M

7. Interaction of OARC scheme with other hazards

7.1 Overview

The extent to which the OARC Scheme may manage the effects of other natural hazards than flood risk or be impacted itself by those hazards has been considered through reference to the hazard cascade assessment prepared in Stage 1 of the multi-hazards project. Hazard cascades which are considered to have a high consequence in exacerbating fluvial and pluvial flooding have been investigated further to provide a better understanding of the implications for the OARC Scheme and to identify potential mitigation measures where appropriate.

7.2 Updated hazard cascade assessment

In Stage 1 of the Multi-Hazards project (Jacobs 2017)[39], the anticipated likelihood and consequence of the cascade of non-flood hazards to fluvial and pluvial flooding (FPF) within the project area was assessed. In Stage 3 of the project the hazard cascade has been reviewed and updated to:

- include any new or additional information on the initial non-flood hazard of the cascade.
- consider the consequences of cascading hazards specifically within the Stage 3 project area (the lower Avon River).

Cascading hazards are defined as: "*The occurrence of one hazard event, followed some time later by a second type of hazard event, whereby the first hazard occurrence has altered some geomorphologic or other condition to such a degree that the second hazard event is either exacerbated or even triggered. In the context of this study, we are interested in when non-flood hazards affect the likelihood or nature of future flooding hazard events*".

Table 33 presents the cascading hazards identified in Stage 1 of the multi-hazards project. The likelihood of cascading hazards is linked to the probability of both hazards occurring within some time period between the two hazards, the length of which will vary for different hazard cascades. The linkage between likelihood and consequence is the degree of permanence to the geomorphic change from the non-flood hazard. So, for example if the initial hazard such as an earthquake permanently lowered ground levels, there may be an increased likelihood and consequence of cascading hazard, although there may be a number of years between the occurrence of the earthquake and a subsequent flood event. A cascading approach also accounts for hazards with temporal "creep" of likelihood and consequence, such as coastal erosion and inundation with rising sea levels.

In the Stage 1 assessment, the rankings of High, Medium and Low used in the table were qualitatively assigned to be representative of the relative differences in likelihood and consequence of the cascade. No attempt was made to quantify the probabilities of occurrence or magnitude of consequence.

The key cascades identified in Stage 1 with high consequence for FPF events within the multi-hazards project area were:

- Future coastal erosion (due to sea level rise)
- Future coastal inundation (due to sea level rise)
- Distant source tsunami
- Local Christchurch earthquakes

[39] Jacobs (2017) LDRP97 Multi-Hazard Analysis: Gap Analysis Report.

- Future high groundwater levels (due to sea level rise)

Applying a similar qualitative approach as applied in the Stage 1 assessment, the updates to the table of cascading hazards are:

- Combination of the earthquake hazards into one category regardless of earthquake location. This reflects the information presented below in Section 7.5 that the likely impacts and consequences of this hazard on the OARC flood defences will be high for local, regional, and distant Alpine Fault earthquakes.
- Inclusion of Vertical Land Movement (VLM) as an additional hazard which has potential cascade effects on the extent and magnitude of FPF events. VLM is the on-going change in ground levels due to both past seismic effects – e.g. the 2010-2011 Canterbury Earthquake Sequence (CES) – and longer term inter-seismic ground level changes. Since Stage 1 of the project, the understanding of ongoing VLM rates and projections of future VLM rates has progressed considerably, particularly in relation to the effects it will have on rates of future Relative Sea Level Rise (RSLR) – e.g. NZ SeaRise Programme; https://searise.takiwa.co/. As set out in Appendix D, the current projections are that recent post-seismic VLM rates from the CES, which range from -20.9 mm/yr to -0.5 mm/yr (median value of -3.9 mm/yr) within the Stage 3 project area, will continue for around a further 30 years (i.e., to 2050), and then return to inter-seismic rates of -1.0 mm/yr to -0.3 mm/yr (median value of -0.8 mm/yr), the negative values indicating settlement rather than uplift. Total ground subsidence under these projections is in the order of 125 mm by 2060, 157 mm by 2100 and 197 mm by 2150. This is discussed further in Section 7.7.
- Address an abnormality in the consequence for the Stage 3 project area of a Waimakariri flood contained within the Waimakariri River stopbanks. The consequence of this hazard for exacerbating flood hazard in the lower Avon catchment is now considered to be 'Low' as it would be contained within the Brooklands area.
- Change the consequence for the cascade hazard of hillslope instabilities from 'Low' to 'Nil' since the Stage 3 project area is not exposed to these hazards.

It is considered that there are no changes to the risk of cascade from other non-flood hazards. Table 33 presents the resulting updated hazard cascade assessment. Section 7.3 describes how each of the hazards which are assessed as having a moderate or high cascade consequence has been assessed within the project and which have been explicitly modelled.

Table 33. Updated anticipated likelihood and consequence of cascade of hazard types to FPF events in the Stage 3 project area.

Hazard	Cascade Likelihood	Cascade Geomorphic Permanence	Cascade Consequence for Exacerbating Flooding in the Stage 3 project area (lower Avon)
Coastal Storm	High	Moderate (estuary/river mouth migration)	Moderate (estuary/river mouth migration)
Snow and Hail Event	Low	Nil	Low (only if very short-term cascade of events)
Extreme Wind Event	Moderate	Nil	Nil
Future Coastal Erosion	High	High	High
Future Coastal Inundation	High	High	High
Distant Source Tsunami	Low	High (estuary/river mouth, estuary infrastructure)	High (estuary/river mouth, estuary infrastructure)
Regional Source Tsunami	Low	Moderate (less likelihood of permanent impacts)	Moderate
Local Source Tsunami	Low	Uncertain	Uncertain
Earthquake (Local, Regional, Distant Alpine Fault)	High	High (liquefaction, vertical displacement)	High
Future High Groundwater Levels	High	High permanent high water table	High
Hill slope instabilities	Moderate	High	Nil
Waimakariri Flood-stopbank contained	Moderate	Moderate (Waimakariri mouth migration)	Low (Contained to Brooklands area)
Waimakariri Flood – stopbank breached	Low	Moderate	Moderate
Vertical Land Movement (VLM)	High	High	High

7.3 Approach to addressing key hazard cascades

The only material change to the hazard cascades identified in Stage 1 of the project is the inclusion of VLM as a 'new' hazard. The key hazards and their interaction with the OARC Scheme are addressed in Stage 3 of the project as follows:

- Distant source tsunami – Section 7.4 of this report discusses how the OARC Scheme may interact with tsunami hazards.
- Local Christchurch earthquakes – the change in flood risk arising from land subsidence from a future earthquake has been explicitly simulated in the existing stopbanks, no stopbanks and OARC Scheme models. The results are discussed in Section 4 of this report. The risk that future earthquakes may pose to the current engineering design of the flood defences is considered in Section 7.5.
- Future coastal erosion – coastal erosion under a range of future sea levels has been considered in Section 7.6 of this report to assesses the potential for new flood pathways from the coastline of the project area. Inundation directly from the coast, now or in the future, could impact the area benefiting from the OARC Scheme. The potential change in risk of inundation from this route over time is discussed in Section 7.6.1.2.
- Future coastal inundation – this is explicitly simulated in the flood models for a range of future sea levels, as discussed in Section 4 of this report. The residual flooding with the flood defences in place is then assessed in Section 5 by identifying areas where flood hazards exceed the Project Response Indicators (PRIs), and further flood risk management measures may be needed.
- Future high groundwater levels – this has been explicitly considered within the project, both within the flood model simulations (which allow for the effect of groundwater on infiltration) and by comparing modelled groundwater levels for a range of future sea levels to the PRIs developed for this project. This is presented in Section 5 of this report and indicates where and when high groundwater may require a further management response. Section 7.8 considers the potential impacts of future sea levels on tidal groundwater fluctuation and seepage through or under the OARC Scheme flood defences.
- Vertical Land Movement – the effects of three potential pathways of VLM on flooding have been explicitly simulated in the flood model for the 0.45 m and 1.06 m SLR future climate scenarios with no stopbanks and with the OARC Scheme. The model ground surface has been modified according to the total amount of VLM from the present day to these future times based on predicted annual rates of VLM. Within the project area no uplift of land is predicted and the VLM is entirely subsidence. Results of the impact of VLM on the depth and extent of flooding, properties at risk of flooding, flood damages and the damages avoided with the OARC Scheme are reported and the effects of VLM on predicted PRI exceedances are explicitly mapped. VLM is also considered in the coastal erosion and inundation assessment.

Section 7.9 of this report concludes by discussing, at a high level, the performance of the OARC Scheme after a major shock hazard and how decision making at that time about surrounding land uses may impact the future of the OARC Scheme.

7.4 Tsunami hazards

The proposed OARC Scheme flood risk management infrastructure is within an area that can be impacted by tsunami. Hydrodynamic modelling of tsunami was undertaken by NIWA during Stage 2 of the multi-hazards project. The results of the modelling have been reviewed to assess the potential for changes in tsunami inundation extent and depths due to the presence of the OARC Scheme flood defences. The likely performance of the flood defences and pumpstations in the event of a tsunami has also been considered.

7.4.1 NIWA tsunami modelling

The NIWA "*Land Drainage Recovery Programme: Tsunami Study*" report (February 2018)[40] presents the results of hydrodynamic modelling of tsunami waves and their impacts on the estuary and adjacent land and rivers, for 0.2% AEP and 0.04% AEP tsunami events under present day sea level and increments of sea level rise up to a 1.06 m. Model results for maximum water depth, velocity and bed shear stress are reported.

Extracts of the mapped flood extents and depths for 0.2% AEP and 0.04% AEP tsunami events with present day sea level and 1.06 m sea level rise are provided in Figure 70 and Figure 71 below and the NIWA report is attached in Appendix E.

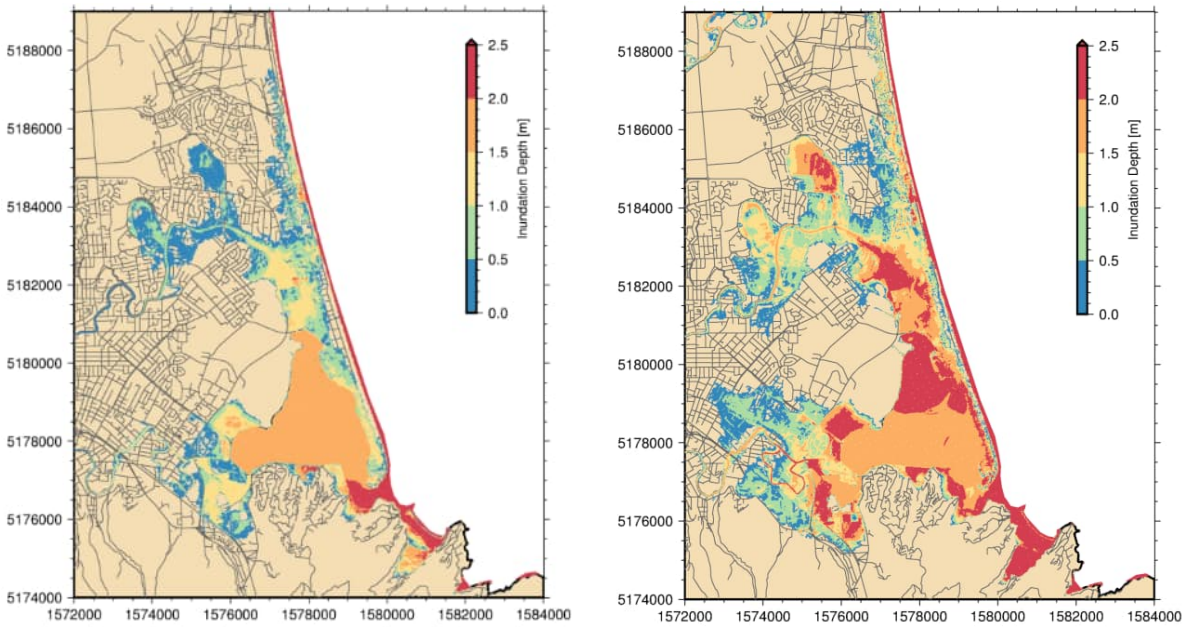


Figure 70. 0.2% AEP tsunami inundation with present day sea level (left) and 1.06 m sea level rise (right).

[40] Land Drainage Recovery Programme: Tsunami Study. NIWA February 2018. NIWA Client Report No 2018039CH

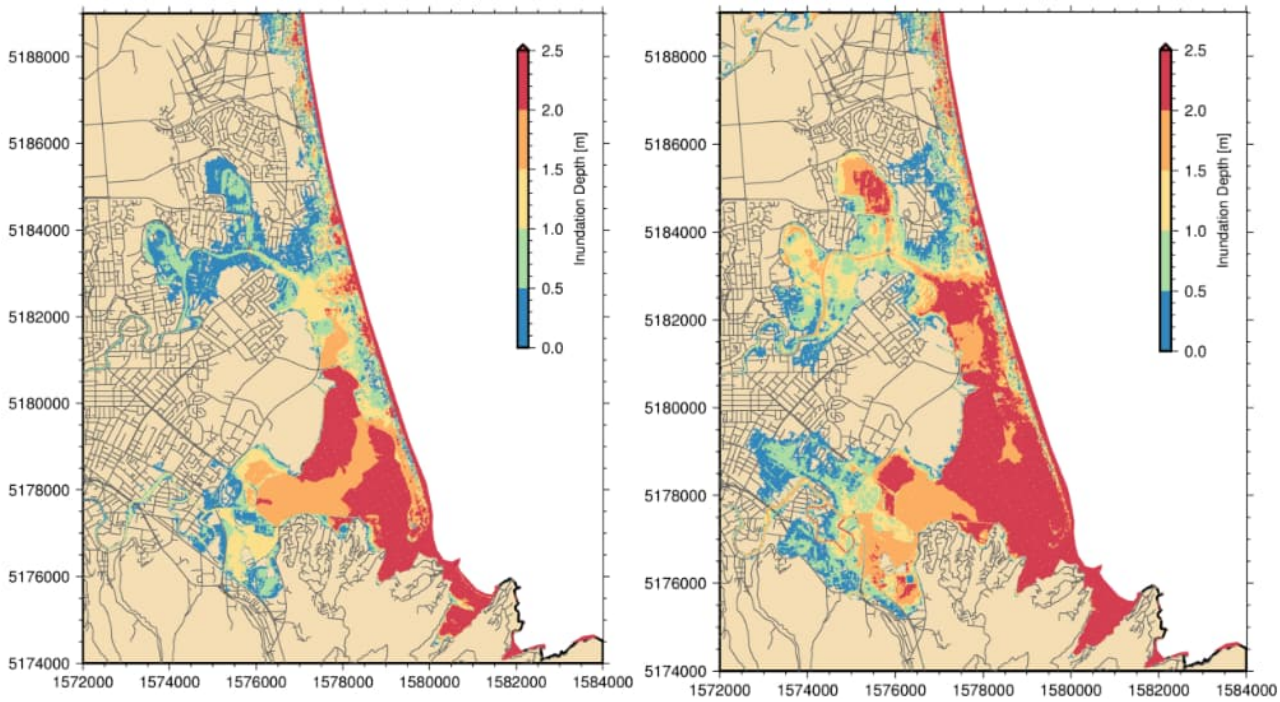


Figure 71. 0.04% AEP tsunami inundation with present day sea level (left) and 1.06 m sea level rise (right).

Table 34 summarises the main assumptions in the NIWA tsunami modelling to inform the applicability of these results and highlight the sensitivity of modelled outcomes to these assumptions.

Table 34. Key assumptions in 2018 tsunami modelling and sensitivity of outcomes to those assumptions.

Assumption	Sensitivity
Steady state sea level of MHWS applied throughout modelling.	Modelled outcomes are conservative and may be less severe if the tide is lower when each individual tsunami wave arrives.
Flood defences in the model are those in place at the time of the study.	The height of flood defences modelled are not stated but are available in the 2011 digital terrain model used. The flood defence levels for the OARC Scheme are substantially higher. Higher flood defences will increase the available storage within the Estuary and therefore tend to delay the time taken to overtop them but also tend to raise river water levels during the event. For the 0.2% AEP tsunami modelled, this additional height may have an important benefit and the extent of flooding behind the flood defences resulting from overtopping could be less than modelled, particularly in the more upstream sections of the Ōtākaro Avon River. However, in such events the flood defences are likely to be exposed to higher velocities than in flood events resulting in an increased risk of erosion and failures. For the 0.04% AEP tsunami modelled, the extent of flooding behind the flood defences is significant and the increased flood defence height in the OARC Scheme is not likely to provide any meaningful reduction in the extent of flooding.
No erosion at the estuary mouth.	The sand substrate and very high flow velocities at the estuary mouth will result in significant scour. Scour will increase the size of the opening and

	let through more water (both inflow and outflow). A higher inflow will tend to result in a greater extent of inland flooding and higher flow velocities. This modelling assumption is therefore considered to be optimistic.
No erosion at the bridges or of flood defences.	It is reasonably likely that localised erosion could occur in the 2% AEP tsunami event and significant erosion could occur in the 0.04% AEP tsunami event. Erosion will let through more water (both inflow and outflow) which will affect the propagation of flooding and may create more extreme flow velocities in localised areas. The potential velocities during tsunami events may need to be considered in designing the erosion protection methods for these structures – e.g., localised areas of rip-rap protection.
Application of sea level rise in the model	Model simulations have been performed for SLR values of 0.19 m, 0.41 m, and 1.06 m. Although the SLR is allowed for in the forcing boundaries to the model – i.e., the tsunami wave offshore – it has not been included in the initial water levels in the model, which are based on MHWS under present-day sea level. It is not clear how far this may affect the resulting inland inundation but allowing for SLR in the initial water level condition could potentially result in more extensive inundation and higher water levels in the floodplain.

Overall, it is considered that the projected maximum extents of flooding, water surface elevations, flood depth and flow velocities presented in the NIWA report are appropriate for the purposes of this assessment. We note that due to the assumptions discussed above, it is reasonably likely that effects could be greater than modelled, particularly for the 0.04% AEP tsunami event, where potential greater dune breaching and increases in cross section area of the Ihutai Avon Heathcote estuary and Waimakariri River mouths would result in greater inundation extents and depths. These additional effects were considered in 0.04% AEP tsunami modelling presented in Lane et al (2017).

7.4.2 Propagation of tsunami flooding

The NIWA simulations for the tsunami hydrograph (water level variation with time) at the estuary mouth are presented below (Figure 72) for a 0.2% AEP tsunami at present day sea level and a 0.04% AEP tsunami with 0.19 m sea level rise.

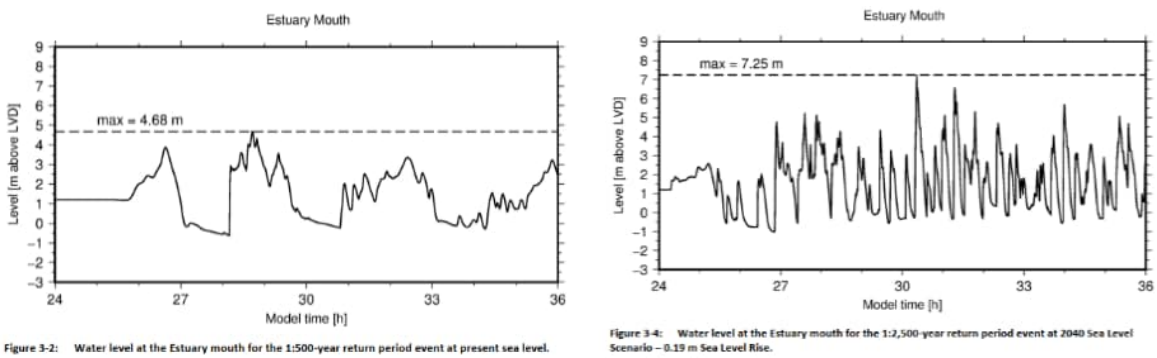


Figure 72. NIWA projections for the tsunami hydrograph.

The simulations indicate that a tsunami most likely consists of multiple waves crests and troughs which can impact how flooding occurs. The size and number of wave crest and troughs will have an effect on the tsunami propagation effects and the timing and extent to which flooding occurs, with filling associated with arrival of a tsunami wave crest then retreat associated with the tsunami wave trough. Multiple wave cycles are likely to exacerbate any breaches in flood defences that occur due to alternating high velocity flow directions.

Based on tsunami model results, we provide the following simplified description of the expected propagation of a tsunami event to assist with understanding of how it might affect flood management infrastructure. In this description, the tsunami crest is taken to arrive first, ahead of any troughs, as simulated in the modelling, however this is not always the case.

Filling

1. Inflow through estuary mouth, estuary fills.
2. The bridge at Bridge Street constricts flow so there is a water level difference between seaward and inland side of bridge, estuary fills until the top of flood defences is reached (11.4 mCDD in South Shore and South Brighton Park).
3. Overflow of South Shore and South Brighton Park flood defences occurs along the entire length, as all are at a common level. As the flood defence acts as a very long weir, this only takes a small level increase in the estuary to occur. At this stage water levels within the Ōtākaro Avon River inland of Bridge Street are lower due to the afflux, so remain within the flood defences but the river continues to fill.
4. Flooding over the estuary flood defences continues, filling the areas to the east and flowing northwards behind the flood defences on the east side of the river as there are no lateral 'bulkheads' landward of the flood defences to prevent this. The Ōtākaro Avon River will continue to fill but will stay below the estuary level and flood defence levels for the reasons outlined above.
5. Depending on the duration of the tsunami wave, flooding to the east of the flood defences continues until the floodplain fills to the top of flood defence level. Flows then re-enter the Ōtākaro Avon River from the east, as the flow constraint at the Bridge Street bridge remains. The northward extent of flooding is limited by frictional flow losses associated with surface obstructions and storage in the floodplain.
6. The Ōtākaro Avon River then overtops flood defences on the west side of the river. The west then fills to the top of flood defence level.
7. If tsunami flows continue, the water level in all areas continue to rise.
8. In parallel with tsunami propagation up the estuary and Ōtākaro Avon River, the wave will also overtop low points in the narrow dune ridge along the coastline at New Brighton or North Beach and inundate the area between the coast and the Ōtākaro Avon River. If the overtopping flows result in erosion or breaching of the dunes, this would deliver additional flow to the eastern side of the flood defences and reduce the time taken before the flood defences are overtopped and flows enter the Ōtākaro Avon River.

   Figure 73 shows the modelled tsunami inundation extents for the 0.2% AEP tsunami with 0 m, 0.41 m and 1.06 m SLR and Figure 74 shows a sample cross-section through the Ōtākaro Avon River and floodplain to the coast just upstream of Pages Road bridge. This shows that even at present-day sea level, tsunami inundation from the coastline reaches the Ōtākaro Avon River and overtops the existing flood defences. Figure 74 also shows the indicative levels of the new OARC Scheme flood defences at this location which are expected to be constructed to provide a 1% AEP standard of

protection with freeboard and allowances for future climate change and settlement. The new flood defence levels could exceed the tsunami levels in the floodplain to the east of the river and therefore obstruct the inundation flow path, raising water levels in the floodplain before the new flood defences are overtopped.

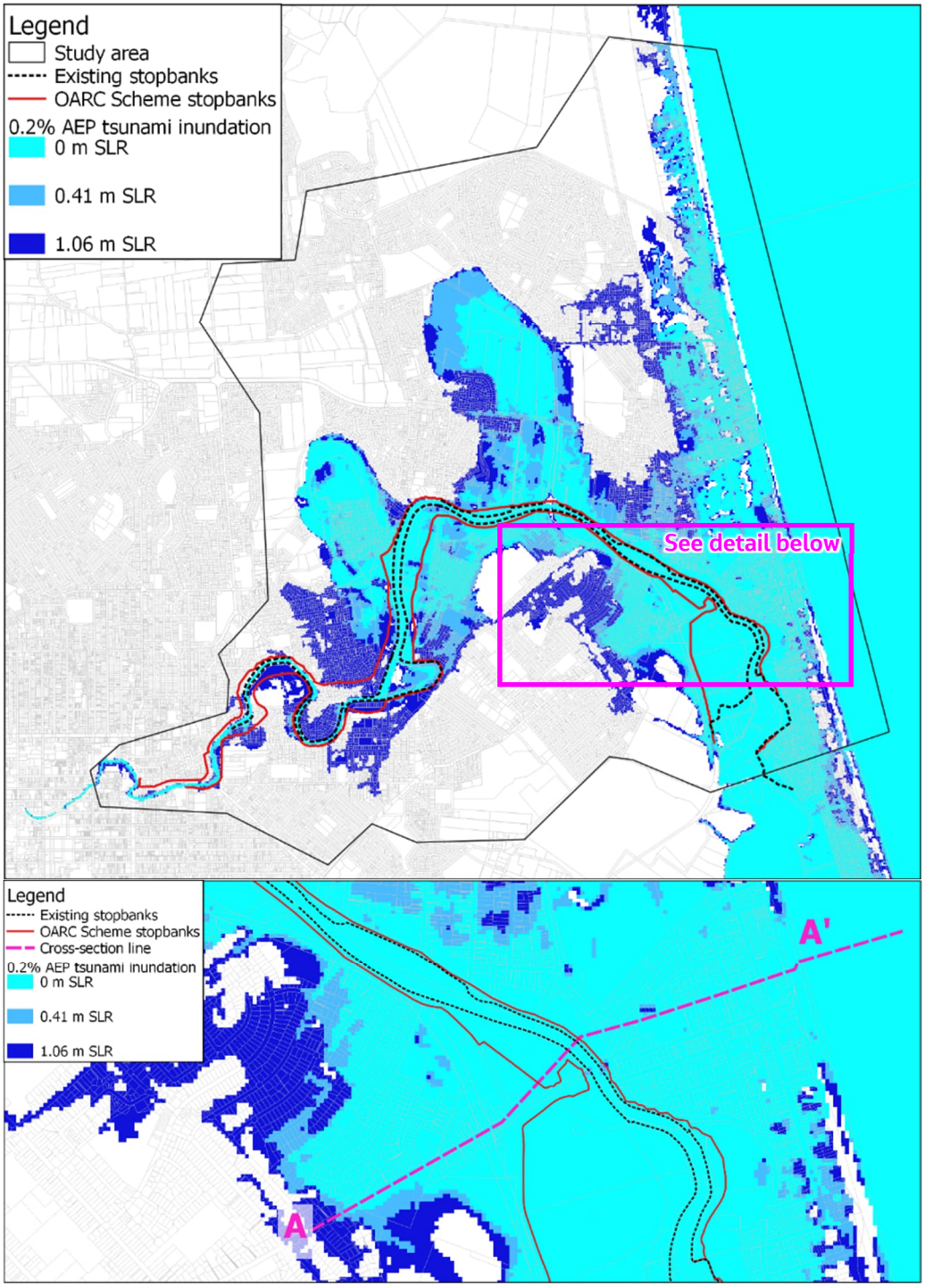


Figure 73. Modelled maximum tsunami inundation for 0.2% AEP tsunami at 0 m, 0.41 m and1.06 m SLR (NIWA, 2018) and location of sample cross-section A-A' upstream of Pages Road bridge.

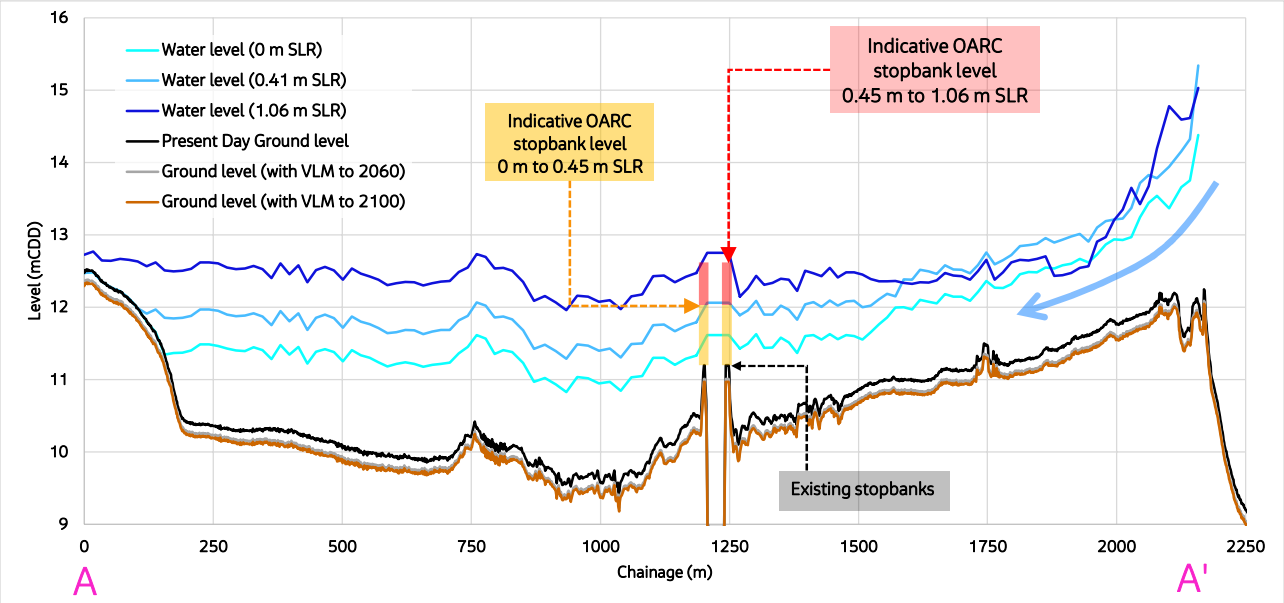


Figure 74. Sample cross-section A-A' showing maximum modelled tsunami water levels for 0.2% AEP tsunami at 0 m, 0.41 m and 1.06 m SLR (NIWA, 2018), existing stopbank levels on the Ōtākaro Avon River, indicative new OARC flood defence levels and potential change to ground levels through VLM.

Retreat

9. Sea level drops from peak to trough of tsunami wave. Inflow ceases and outflow commences. The estuary mouth constricts flow as for filling. Outflows will be of comparable flow rate to previous inflows as the driving hydraulic head is similar but may increase due to potential scour of the mouth in high velocity in and out flows.

10. As the estuary water level drops, the Ōtākaro Avon River and flooding behind flood defences drain in equilibrium to available head. The river will keep draining but flooding behind flood defences will only drain to the flood defence level unless there are breaches, in which case local drainage continues through breaches. The higher OARC Scheme flood defences will tend to maintain a higher residual ponding level in the floodplain.

Assuming the above to be a reasonable assessment of likely tsunami propagation within the estuary and Ōtākaro Avon River, the following items of interest are noted:

- The Bridge Street bridge acts as a significant hydraulic constriction throughout the tsunami propagation.
- The west abutment and land extending westwards and southwards is considerably higher than the eastern side of estuary, so will tend to force inflow through the bridge opening and to the east of the bridge.
- The overland flow path east of the bridge will be subject to high flow velocities that pose a risk to people and property.
- Any breach in the flood defence will result in a large, localised increase in inflow and outflow rate that will further erode the flood defence and further increase flows.
- Flood defences will retain impounded floodwaters between tsunami 'waves' and after cessation of the tsunami water level disturbances, potentially to the height of the flood defences, unless or until they are breached, in which case they will slow the rate of drainage of flood water.
- The scale of the tsunami event and inflow through the estuary mouth will impact the time taken and the extent to which the above occur.
- Flooding to the west of the Ōtākaro Avon River is likely to commence once the eastern flood zone is full.

All the above assume that the estuary mouth continues to provide some form of primary flow constraint, through which the tsunami waves propagate directly into the estuary.

7.4.3 Likely effects on bridges and flood management infrastructure

Based on the tsunami propagation outlined above, the following impacts may be expected on the various flood management infrastructure components:

- *Southshore flood defences* – overtopping over a long crest (approx. 2.2 km) may reduce velocities sufficiently to avoid major erosion failure in a small tsunami event, but the larger the tsunami, the more likely that significant erosion occurs.
- *South Brighton Park flood defences* – similar behaviour to the Southshore flood defences (approx. 2.0 km).
- *Bridge Street Bridge* – significant scour velocities in small tsunami event and potentially catastrophic scour in large event. Abutments at risk of eroding.
- *Flood defences north of Bridge Street* - overtopping from east into Ōtākaro Avon River over a long crest (approx. 2.1 km) may reduce velocities sufficiently to avoid major erosion failure in a small tsunami event, but the larger the tsunami, the more likely that significant erosion occurs. Similar for west flood defences when flood defences are overtopped and inflow occurs.
- *Bridges north of Bridge Street* – moderate scour velocities in small tsunami event and potentially significant scour in large event but not exposed to the same extent as the Bridge Street bridge.
- *All gravity outfalls to rivers* – likely to become blocked with sediment and debris and become inoperable.
- *All pump stations* - likely to become submerged and inoperable unless electrical components are above tsunami flood level and not located in a concentrated flow path. The pump station at Blake Street is likely to be in a concentrated flow path.

Further investigations are required to assess these effects in more detail and identify any design activities required to mitigate these risks.

7.4.4 Opportunities to improve tsunami resilience

The review of the modelling of tsunami propagation has led to the identification of several conceptual opportunities to improve the resilience of the proposed OARC flood management infrastructure:

1. Construct a floodway east of Bridge Street bridge but west of flood defence to enable flows to pass without breaching the Southshore and South Brighton flood defences. This would require it to be lower than 12.4 mCDD or require raising of Southshore and South Brighton flood defences above the floodway to divert more flow into the river.

   This would have limited benefit for a tsunami event that results in over-topping of the Southshore and South Brighton flood defences (it will only delay this occurring) but could make the difference of over-topping or not over-topping in a smaller tsunami event.

2. Construct the Southshore and South Brighton flood defences to a higher level.

   This would have limited benefit for a tsunami event that results in over-topping of the Southshore and South Brighton flood defences (it will only delay this occurring) but could make the difference of over-topping or not over-topping in a smaller tsunami event.

3. Activate the storage available in the wetland zones to be created in the red-zoned land west of the Ōtākaro Avon River. This would require:

a. Increasing the flow to the Ōtākaro Avon River sufficiently to activate the west bank storage before the Southshore and South Brighton flood defences are overtopped

b. Lowering of western flood defences sufficiently to preferentially flood into this area.

c. May require construction of a secondary bund west of the western flood defence to prevent spread of flooding to residential areas.

This would have limited benefit for a tsunami event that results in over-topping of the Southshore and South Brighton flood defences (it will only delay this occurring) but could make the difference of over-topping or not over-topping in a smaller tsunami event.

4. Create lateral 'bulkheads' landward of the eastern flood defences to compartmentalise tsunami flooding. This would benefit in an event that just overtops but may have marginal benefit in a larger event.

   This would have limited benefit for a tsunami event that results in flooding of all the eastern storage area but could reduce the impact in a smaller tsunami event that over-tops the Southshore and South Brighton flood defences.

5. Place electrical equipment at stormwater pump stations above the flood defence level, and possibly higher. This would have the benefit of enabling more rapid re-instatement of pump stations.

7.5 Interaction with earthquake hazards

Section 4 discusses the impact of modelled earthquake-induced land subsidence on future flood risk both with and without existing stopbanks and with the proposed OARC Scheme stopbanks and pump stations. With the existing stopbanks the number of properties at risk of above floor flooding in an extreme event increases by approximately 2,000 to approximately 4,700 in 2060 with the modelled settlement in ground levels from an earthquake. Potential flood damages also increase.

Modelling with the OARC Scheme indicates that land settlement from an earthquake results in a large increase in (more than double) the number of buildings where the flood level is close to, or above, floor level. This impact arises from the lowering of land and increased pluvial flood depths within the wider lower Ōtākaro Avon River catchment rather than due to increased inundation from the Ōtākaro Avon River estuary. The OARC Scheme is modelled on the basis that while stopbanks may be damaged by a future earthquake, this would be very unlikely to coincide with a severe weather event and there would be time to repair and restore the stopbanks to a suitable height prior to a severe weather event occurring. In this way the stopbanks would continue to provide protection from the flood events in the Ōtākaro Avon River. The repairs needed following an earthquake would result in additional costs to the OARC Scheme in order to maintain the design standard of protection.

The modelled scenarios show how pluvial flooding may impact the areas protected by the stopbanks in the wider lower Ōtākaro Avon River catchment. In the simulations the effect of ground settlement as a result of an earthquake is to change the distribution of pluvial flooding due to variations in the amount of settlement over the catchment. This can result in differences in which properties are affected by flooding and relatively small increases in potential flood depths. The large increase in flood damages is due to the fact that the water levels are generally close to floor levels so that even a small increase in water levels, over a large number of properties, results in a relatively large increase in flood damages.

In this section we discuss the potential impacts of future earthquakes on the stability and performance of the proposed OARC stopbanks themselves. This provides information to Council on the likely risk arising from the proposed design in future earthquakes and therefore an indication of what damage may occur and what repairs may be needed in a future event. We consider the impacts of future land subsidence, lateral spreading and seismic slope stability. It is noted that the design philosophy of the stopbanks is not that they should withstand a future earthquake without damage, but rather that when damage such as settlement or cracking occurs it can be repaired to maintain flood protection.

7.5.1 Overview

The Canterbury region has experienced a significant number of seismic events this century. In particular, the 2010-2011 Canterbury Earthquake Sequence (CES) had significant impacts on the OARC Regeneration area. The area experienced significant seismic loading, and this combined with the geology of the area and the high groundwater table resulted in severe liquefaction[41]. Furthermore, the presence of a free face on the banks of the Ōtākaro Avon River resulted in significant lateral spreading.

Looking to the future, the seismic hazard in Christchurch remains high. The seismic design criteria are summarised in Table 35 below, adopted in accordance with MBIE/ NZGS Module 1 (2021). They are based on an Importance Level 2 with a 50-year design life for seismic design.

Table 35. Seismic design criteria[42].

Design Case	Annual Exceedance Probability (AEP)	Earthquake Magnitude (Mw)	Peak Ground Acceleration (g)
Serviceability Limit State A	1/25	7.5	0.13
Serviceability Limit State B[43]	1/25	6.0	0.19
Ultimate Limit State (ULS)	1/500	7.5	0.35
ULS from NSHM[44]	1/500	Not Provided	0.41

7.5.1.1 Alpine fault

It is widely recognised that the Alpine Fault, which traverses the Southern Alps, is likely to rupture in the near future. GNS Science estimates the fault has a 75% chance of rupture in the next 50 years[45], within the lifespan of the OARC Scheme (100 years[46]). Therefore, the potential effects of this seismic event should be considered in addition to any prescribed by the MBIE/NZGS guidelines.

However, effects from this event are difficult to quantify. The latest modelling states that there is an 82% chance the fault rupture will be Magnitude 8 or above[47]. Modelling also indicates that in Christchurch, the earthquake could be between a 6 and 7 on the Modified Mercalli Intensity Scale[48]. For reference, the 22 February 2011 earthquake was between 8 and 10[49] on the Modified Mercalli Intensity Scale. In addition,

[41] Christchurch Liquefaction Viewer

[42] MODULE 1: Overview of the guidelines - Earthquake geotechnical engineering practice

[43] Module 1 of the MBIE/NZGS guidelines provides guidance for both M = 7.5 and M = 6.0 within the Canterbury Earthquake Region

[44] NSHM refers to the National Seismic Hazard Model. New standards will eventually be informed by this model.

[45] Alpine Fault magnitude 8 (AF8)

[46] Section 5.1.2 – Bexley Geotechnical Interpretive Report (BECA)

[47] https://af8.org.nz/faqs

[48] Alpine Fault Earthquake Response Framework

[49] https://www.geonet.org.nz/earthquake/felt/3468575

modelling predicts that shaking could last for around 2 minutes[50] which compares to 20 seconds[51] for the 22 February 2011 earthquake.

Therefore, given that compared to the design earthquake an Alpine Fault earthquake would likely be greater in duration but lower in intensity, further analysis would be required to give a projection on whether an Alpine Fault rupture is likely to have a more severe effect on any stopbanks than the Ultimate Limit State design earthquake.

7.5.1.2 Canterbury earthquake sequence

This section will refer to the CES, because it is so well studied and proves useful for evaluating how stopbanks may perform in future events. Where mentioned, it refers to consequences after all of the following earthquake events:

- 4 September 2010
- 22 February 2011
- 13 June 2011
- 23 December 2011

This is because some of the data collection, for example mapping settlement, was only completed after all four earthquake events. When referring to a single event, this will be made clear.

Over the course of the CES, the $PGA_{7.5}$[52] experienced at the site was greatest during the February 2011 event. This resulted in a $PGA_{7.5}$ of 0.19g – 0.36g at the Wainoni site, and 0.36g-0.43g at the Bexley site[53].

7.5.2 Liquefaction induced settlement

7.5.2.1 CES observations

Over the course of the CES, all four events caused some liquefaction, and therefore vertical settlement across most of the OARC Regeneration area. Figure 75 shows the total vertical land movement across the lower OARC from the CES. The vertical settlement is a least 0.3 m in the whole river-adjacent area but could be up to 1.5 m in some areas. In areas adjacent to the Ōtākaro Avon River, some of the vertical elevation change was likely as a result of lateral spreading.

[50] Simulation of M7.9 Alpine Fault earthquake using GMSimViz

[51] 22 February Strong Motion Data

[52] $PGA_{7.5}$ refers to the PGA scales to a moment magnitude 7.5 earthquake using the magnitude scaling factor from Idriss & Boulanger 2008

[53] GNS Shaking Layers

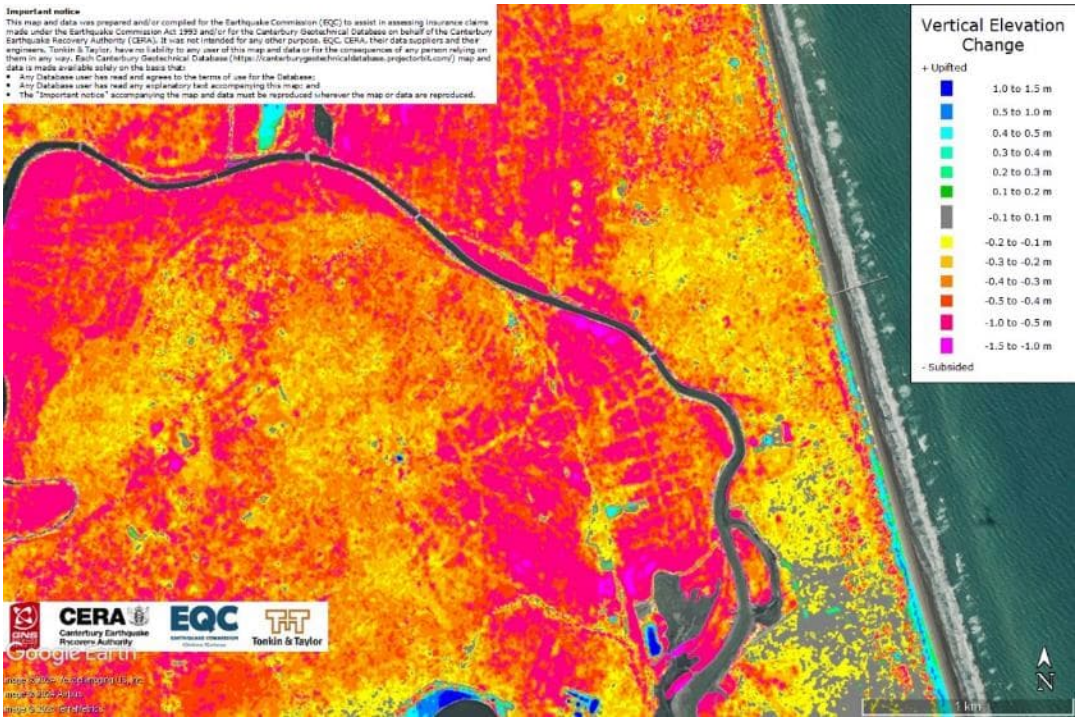


Figure 75. Total vertical land movement from the CES along the lower OARC[54].

7.5.2.2 Liquefaction assessment

Liquefaction of soils in an earthquake can cause settlement through different mechanisms. Given the proximity of this site to the Ōtākaro Avon River, lateral spreading will also be of importance. However, liquefaction induced settlements may occur where lateral spreading does not arise.

Figure 76 shows the expected liquefaction- induced settlement for a variety of Cone Penetrometer Test (CPT) data collected in the OARC Regeneration area. Table 36 shows a summary of the key points, and the intensity of earthquake corresponding to them.

Table 36. Key points in the total settlement – PGA curve for the area.

Event	PGA (g)	Approximate AEP	Comment
Liquefaction Triggering	0.08 – 0.12	greater than 1/25	Just below SLS intensity
Step change[55]	0.17-0.20	1/50 – 1/100	Liquefaction becomes severe somewhere between SLS and ULS intensity
Plateau[56]	0.3-0.35	1/500	Settlement reaches around 80% of the maximum value at this PGA

Table 36 shows that even a SLS earthquake (PGA of 0.13g to 0.19g) will trigger some liquefaction. Based on Figure 76, settlement would range from approximately 10 to 400 mm. It is around the step change where the expected settlement increases sharply, increasing to the plateau.

[54] New Zealand Geotechnical Database – Canterbury Maps

[55] Step change refers to a sudden change in total settlement with earthquake intensity

[56] Plateau refers to the total settlement flattening off despite the PGA increasing.

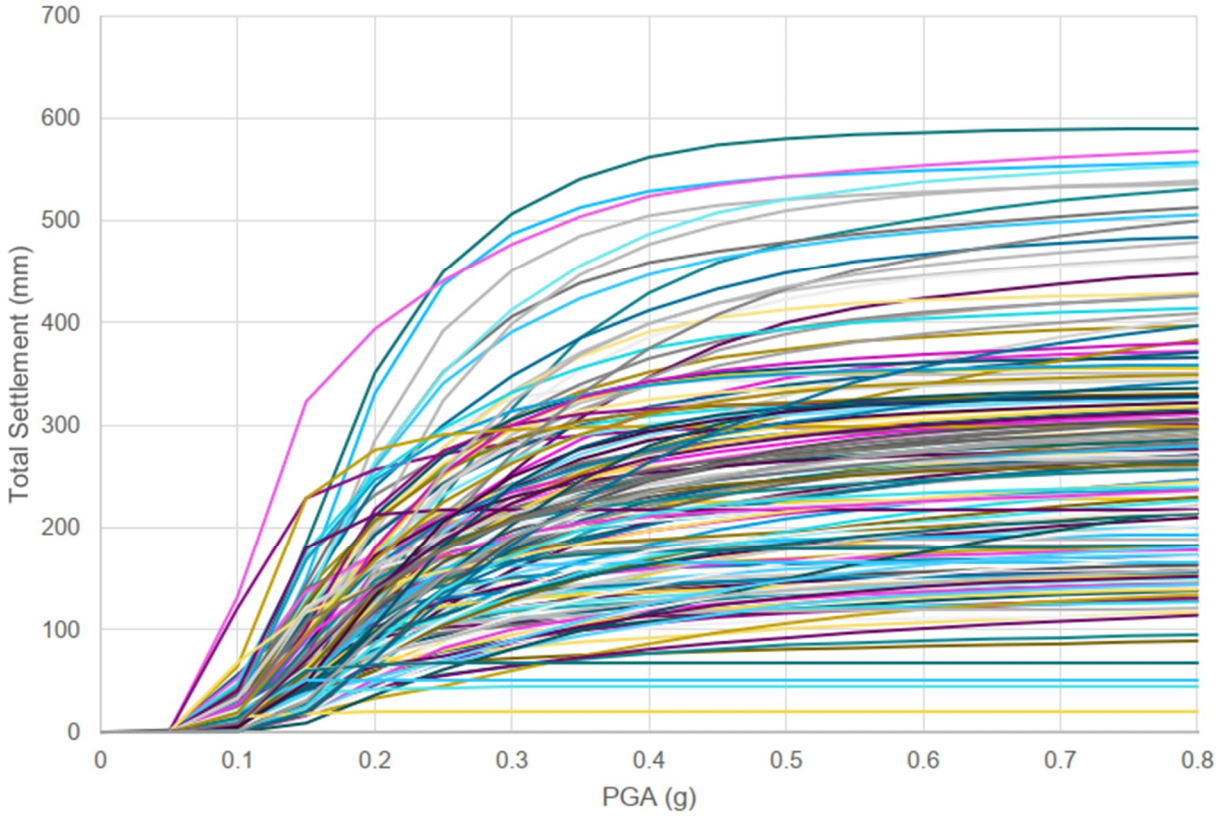


Figure 76. Estimated free field post consolidation settlement estimated from CPT data in the OARC areas with increasing PGA[57].

In summary, when considering vertical settlement alone, an SLS intensity earthquake (PGA of 0.13 to 0.19g) is unlikely to cause issues to the stopbanks. An earthquake with an intensity between SLS and ULS is likely to cause around 10 mm to 550 mm of settlement, still reasonably inconsequential given the height of the proposed stopbanks. As earthquake intensity reaches that of a ULS earthquake, settlement can be expected in the range of 10 – 600mm. An earthquake with intensity greater than ULS is not expected to cause more settlement than the ULS event.

7.5.3 Lateral spreading

Lateral spreading is defined as the horizontal movement of ground towards the free-face or downslope as a result of the liquefaction of shallow underlying soil deposits. The banks of the Ōtākaro Avon River have both a free face and liquefiable soils at shallow depths, so are susceptible to lateral spreading.

7.5.3.1 CES observations

Following each event in the CES, the liquefaction was assessed at residential properties. This was classified and mapped. Also mapped was any recorded ground cracking, which usually accompanies lateral spreading as the ground moves towards a free face.

Because lateral spreading is a difficult process to predict, past observations play a key role in determining which sections of the proposed stopbanks may be vulnerable to lateral spreading in future earthquakes. To

[57] Ōtākaro Avon River Corridor - Bexley Geotechnical Interpretive Report (BECA)

do this, the proposed location of the stopbanks have been overlayed on the maps with mapped liquefaction following the CES.

This report has assumed that if the stopbanks are located further away from the river than the recorded lateral spreading, then the stopbanks are less likely to suffer damage from lateral spreading in a future earthquake. Figure 77 shows a good example of this. The proposed stopbank location is behind the severe lateral spreading, and there are only some small ground cracks behind the proposed stopbanks.

By contrast, Figure 78 shows an area where the proposed stopbanks are in an area that experienced severe lateral spreading in the CES. There are also many ground cracks wider than 200 mm located behind and under the proposed stopbank location. Past observations therefore indicate that in this area the stopbanks may be more at risk of severe lateral spreading displacements, therefore compromising the integrity of the stopbanks.

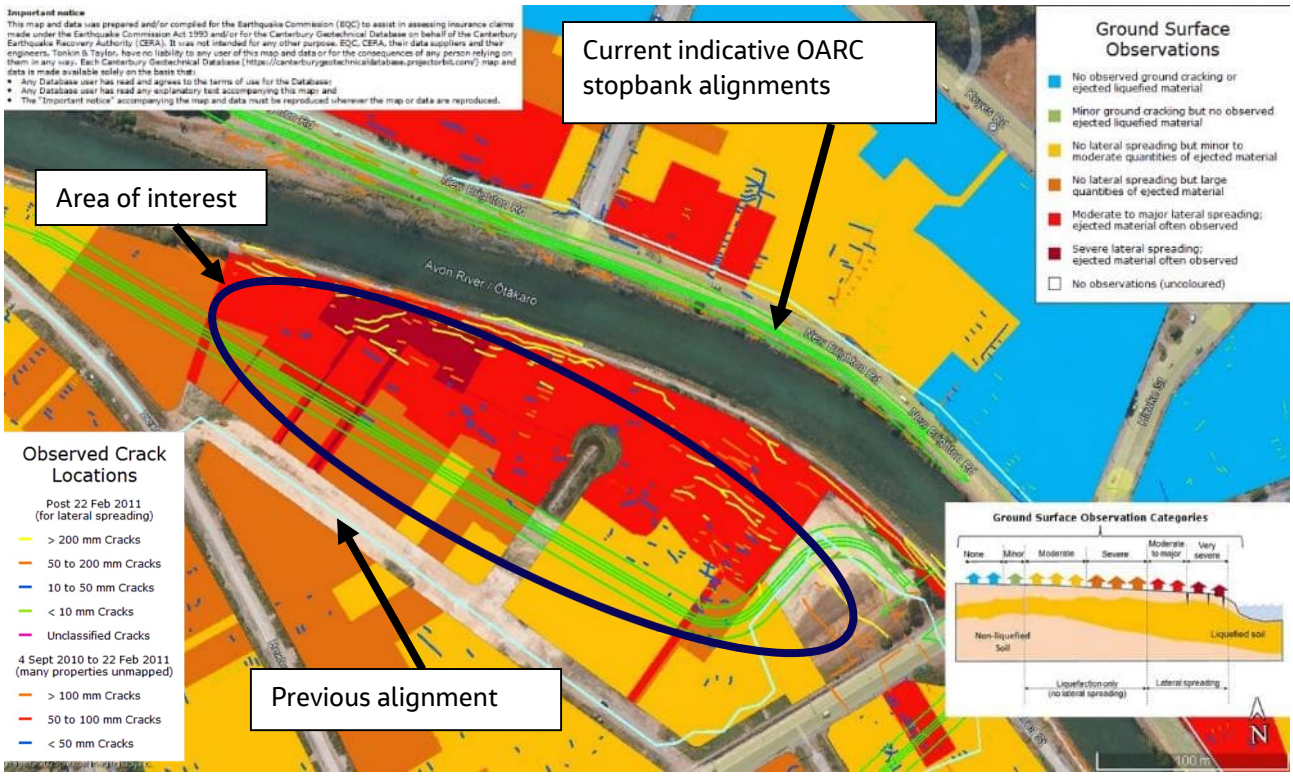


Figure 77: Liquefaction and ground cracking observations following the 22 February 2011 earthquake. Example of well-placed proposed stopbank location[58].

[58] Note that two different stopbank alignments are shown on all figures. The light blue alignment refers to a previous alignment used in flood modelling, whilst the green alignment refers to the most up to date preferred alignment at the time of writing.

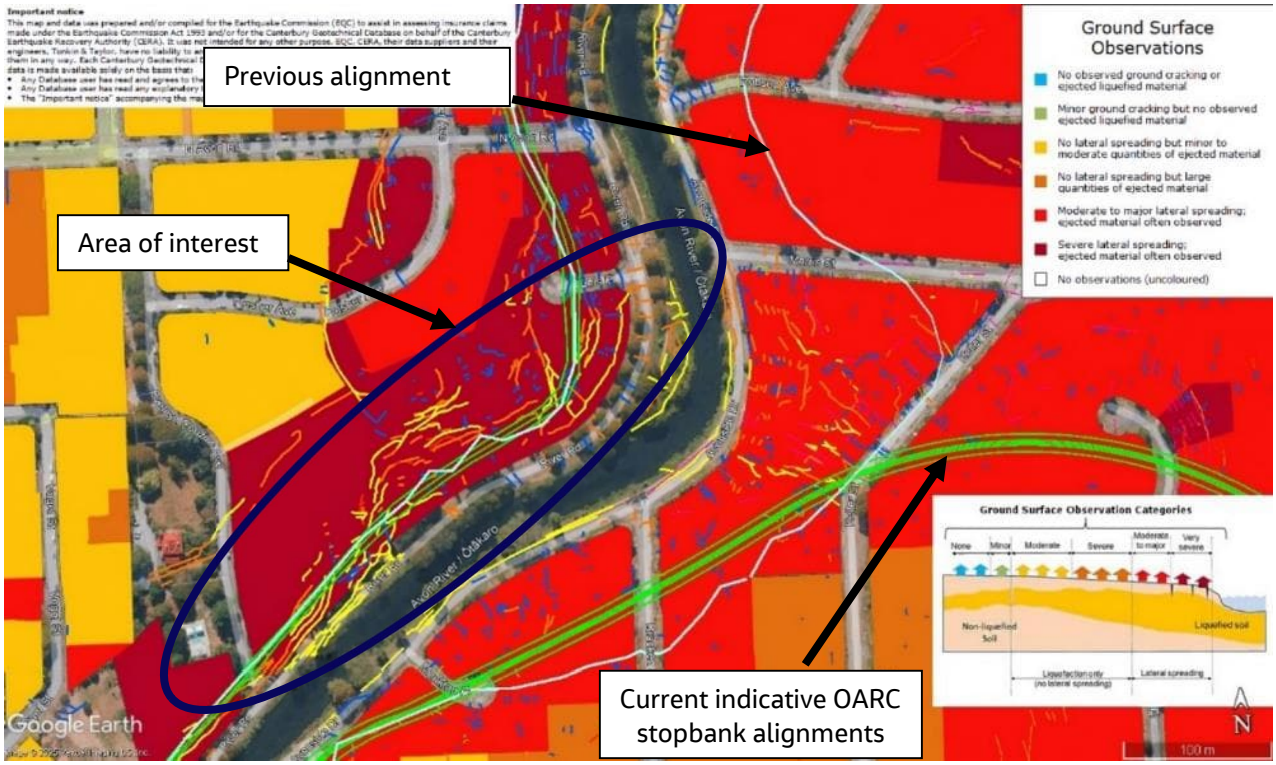
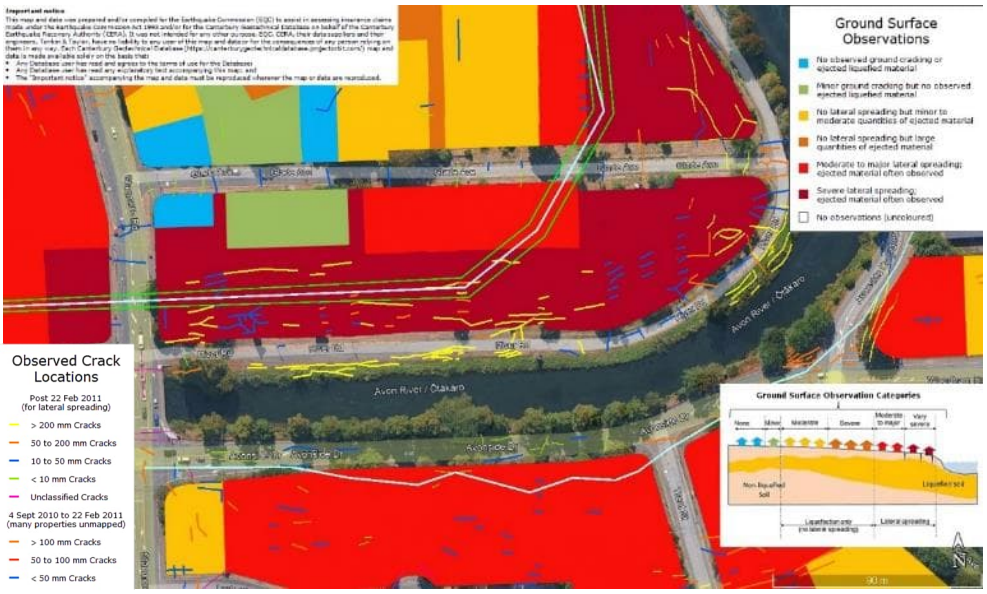
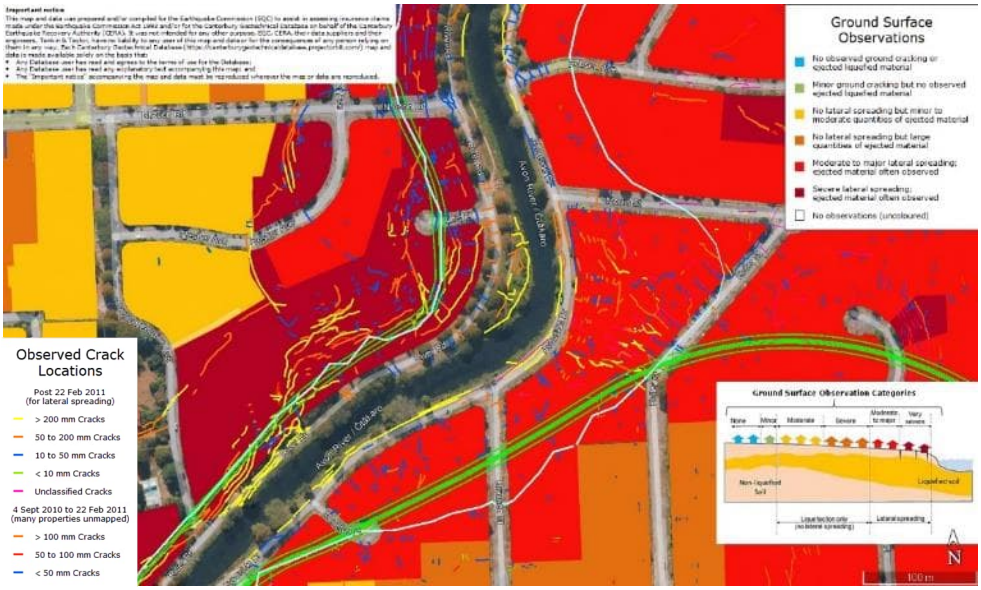


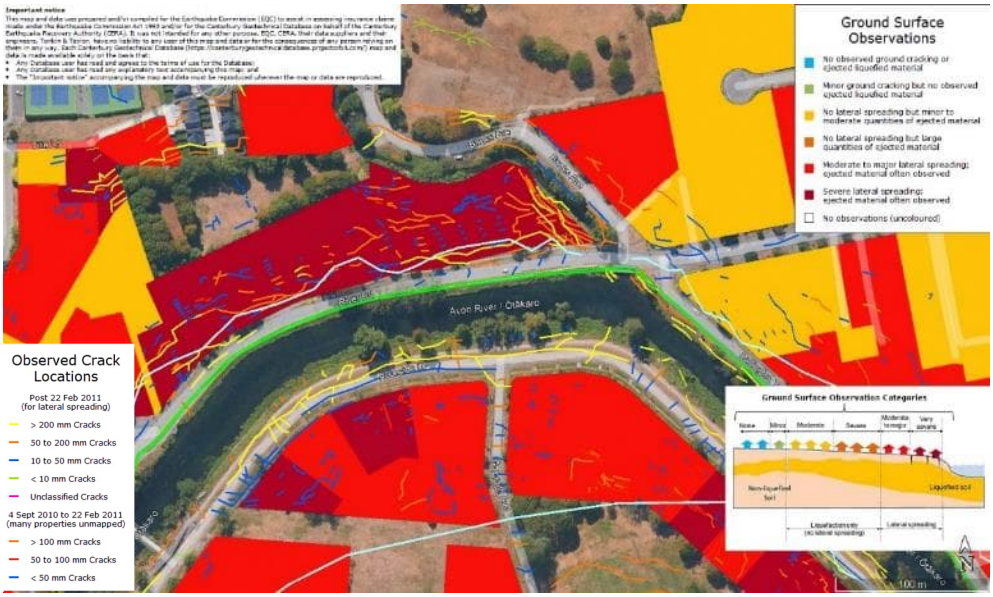
Figure 78: Liquefaction and ground cracking observations following the 22 February 2011 earthquake.

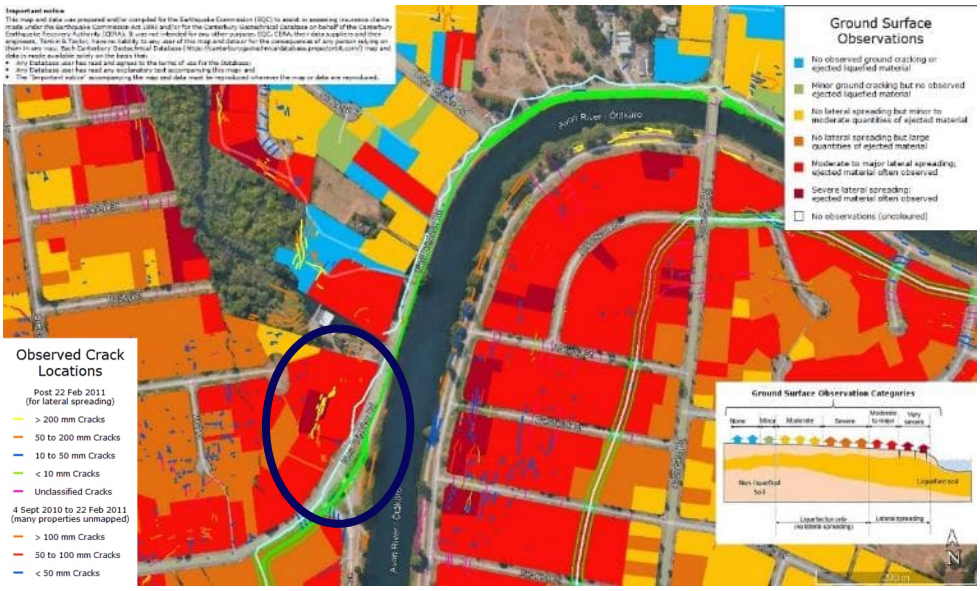
Following this logic, Table 37 identifies some of the areas where the proposed stopbank alignment is located where severe lateral spreading and ground cracking occurred during the CES. Therefore, the proposed stopbanks may not be sufficiently offset from the river to avoid future lateral spreading damage.

The examples in Table 37 only contain the extreme examples of proposed stopbanks in areas that suffered extreme lateral spreading. From a geotechnical perspective, it would be ideal for no stopbanks to be constructed in any areas that experienced lateral spreading of any kind in the CES.

Table 37: Example location where new stopbank alignment is located in areas that experienced severe lateral spreading during the CES. Note the new stopbank alignment in green and the previous alignment in light blue

	**Area 1:** Between River Rd and Glade Ave.
	**Area 2:** River Rd between Evelyn Cousins Ave and North Avon Rd.

	**Area 3:** River Rd between Medway St and Banks Ave.
	Area 4: Dallington Terrace (continued from Area 2). Avonside Drive is no longer an issue with new stopbank alignments

	Area 5: Locksley Ave near Arnst Place and Cardrona Street near Nevis Place
	**Area 6:** New Brighton Road near Goodman St

7.5.3.2 Lateral spreading assessment

In an earthquake, lateral spreading would be expected to stretch the ground towards the free face of the river, leading to cracking. The cracks potentially could then propagate through a stopbank.

In an SLS intensity earthquake, lateral spreading is not expected to be significant, likely less than 50mm. However, similar to vertical settlement, earthquakes with an AEP of 1/50 or less will result in the step change (described in Table 36), which is likely to trigger severe liquefaction and as a result, severe lateral spreading. The severe lateral spreading is expected to be concentrated within 60 m of the riverbank, and displacements are expected to be 1-3 m[59].

[59] Ōtākaro Avon River Corridor - Bexley Geotechnical Interpretive Report (BECA)

In addition, lateral spreading could result in material entering the river channel and therefore reduce the capacity of the Ōtākaro Avon River (i.e., its cross-sectional area). This has the potential to increase water levels in a flood event unless remediated prior.

7.5.4 Seismic slope stability

All slopes and stopbanks are at risk of displacement during an earthquake. There are several mechanisms through which a slope may become unstable as a result of an earthquake. Some of these methods include liquefaction and lateral spreading, already discussed previously. However, it is also possible for a slope failure to occur within the stopbanks, where the inertial load exceeds the strength of the soil.

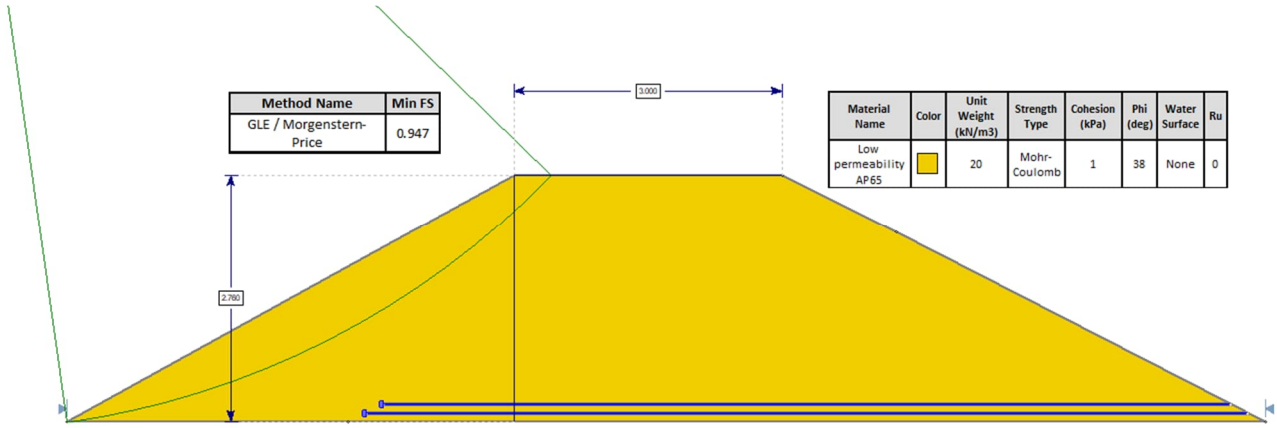


Figure 79. Analysis of seismic slope stability of the Stage B Stopbank in a ULS earthquake[60].

Figure 79 shows that in a ULS earthquake (PGA = 0.35 g), the factor of safety for the slope is below 1, meaning it would be vulnerable to collapse. However, compared to the liquefaction issues discussed above, we do not view the stability of the stopbanks themselves as a large threat to the viability of the project. This is because repairing the partial collapse of stopbanks is likely to be much easier activity than remediating stopbanks that have experienced significant lateral spreading or liquefaction. In addition, the likelihood of stopbank collapse could be decreased by reducing the slope angle of the stopbanks. The addition of geogrids could also be considered although it is understood that this option may not be preferred due to concerns around impacts on future repairability.

7.5.5 Summary of seismic hazard

As discussed, there are several ways that a future seismic event could threaten stopbanks along the OARC. Each of the three mechanisms above could reduce the ability of the stopbanks to perform their function.

Settlement of the stopbanks is possible in a seismic event, with Figure 76 showing the large possible range. However, the settlement is believed not to be a significant hazard, as a freeboard height could be added to the design, so even with the settlement the stopbanks could perform as required.

Lateral spreading however, is inferred to be a more significant hazard. Lateral spreading could result in movement of the stopbank towards the river, potentially damaging the integrity of the stopbanks. Furthermore, lateral spreading could impact the cross section of the Ōtākaro Avon River, increasing water levels. A mitigating measure would be to move the stopbank alignments away from zones where significant

[60] Page 47 HDM OARC SW Stage 1 - Wainoni Concept Design Report

lateral spreading is expected. In areas where this is not possible due to spatial constraints, an alternative solution may be required such as proposed by Beca[61], with the use of both stopbanks and sheet piles.

Instability of the slopes is also a hazard that could impact the performance of the stopbanks, by reducing their height or compromising their low-permeability design. However, this is considered less of a risk to the project compared to other hazards because of the ability to repair the stopbanks or increase their integrity.

At a high level, we believe that the key factor that will have an impact on the cost/benefit ratio of the project is the location of the stopbanks. A study on stopbank performance during the CES found that "Liquefaction is the key aspect which determines whether there will be damage or no damage, and lateral spreading is the aspect that will determine if this damage is negligible to minor or major to severe"[62].Therefore, it is our view that if the stopbanks are constructed in appropriate locations where lateral spreading is not anticipated, a ULS earthquake may still damage them. However, the relatively minor costs of these repairs mean this event would not be expected to have a large adverse effect on the overall cost/benefit ratio of the project.

However, if the stopbanks are constructed in an area that suffers extensive lateral spreading in a ULS earthquake, this could result in severe damage to the stopbanks. The cost of repairing this damage could be significant and comparable to original construction cost.

The seismic hazards discussed above could impact the stopbanks in future earthquake. They provide an indication of the more important mechanisms of damage. For the flood modelling reported in Section 4 it has been taken that any damage to stopbanks following an earthquake would be repaired prior to any flood events occurring, noting that repairs may take some time to complete. Even if this is achieved, flood risk to properties in the area benefiting from the OARC Scheme would be increased due to wider land subsidence in the lower Ōtākaro Avon River catchment. The above discussion provides an indication of the types and extent of damage that may need to be repaired with some comments on how the risk of damage could be reduced through design. Although the focus is on the risks to the stopbanks, the new stormwater pumpstations, which, in general, are expected to be located close to the stopbanks, will also be vulnerable to seismic hazards and the design of these elements of the OARC Scheme will also need to allow for these hazards.

7.6 Coastal process and changing coastal flood risk

The flood modelling for Stage 3 of the project includes simulation of inundation from the sea along the shoreline of the project area. However, apart from the inclusion of earthquake-induced ground settlement and ongoing VLM in selected future scenarios, the model ground surface does not vary from that surveyed in 2018.

It is recognised in the hazard cascades that future erosion of the coastal dunes could enhance existing pathways or open up new pathways for inundation directly from the coast into the area benefiting from the OARC Scheme. This could provide a bypass route by which areas that will benefit from the OARC Scheme are flooded from the sea, in either coastal storm events or tsunami.

Flood water can currently overtop low lying areas of the coast where the dune is absent or through gaps (accessways), which results in limited flood depths and small areas of flooding in storm events. In the future, overtopping the dunes in significant volumes, or more realistically, a breach through a point where dunes have been removed by successive events (storms) or longer-term erosion, could cause seawater to overtop the coast, and pond behind the proposed OARC flood defences. This could result in loss of some of the benefits that the flood defences will provide. This section considers scenarios of dune erosion and the extent to which gaps in the dunes or dune lowering could result in additional coastal inundation of the project area.

[61] Page 22 Bexley Geotechnical Interpretive Report

[62] https://ir.canterbury.ac.nz/items/df8ecaa5-4fe2-4301-a0ea-9e50eac9a496

It should be noted that the storm tide water level boundary adopted in the flood model does not include allowance for wave setup. The primary purpose of the model is to simulate flooding from the Ōtākaro Avon River which is influenced by tide level at the mouth of the Ihutai Avon Heathcote estuary where wave setup is less significant. However, along the open coast wave setup and wave runup is more significant and its effect on flooding is considered further in this assessment of coastal flood risk.

7.6.1 Inundation pathways

There is a risk that in the future with higher rates of sea level rise, areas that are protected by the OARC Scheme could be impacted by coastal flooding due to storm surge and wave runup through the New Brighton dune system, which protects much of the eastern coastline from direct flooding from the sea.

Coastal erosion and inundation were modelled in Council's 2021 Coastal Hazard Assessment[63] (CHA) which mapped a static extreme water level (storm surge, astronomical tide, wave setup) for three probabilities (63%, 10% and 1% AEP), at 0.2 m increments of SLR up to 1.2 m SLR and additionally at 1.5 m and 2.0 m of SLR. The coastal hazard mapping indicates that the projected coastal flood exposure in South New Brighton, New Brighton, North New Brighton, and Waimairi Beach areas is generally a result of connected flooding from the estuary and up the Ōtākaro Avon River Corridor, and that the dune system currently provides sufficient protection (elevation) to prevent water passing over the dunes and affecting property and assets along the eastern coastal boundary of the Stage 3 project area.

The CHA calculated a series of dynamic water levels, which are projections of where wave runup levels could reach in an extreme event up to 1% AEP, and therefore the elevation above the static water level which could be temporarily inundated. If the dynamic water levels are high enough, they could overtop the dune crest and create new pathways for flooding to enter the coastal suburbs. Over time, the erosion of the dune from storms and longer-term erosion trends (with SLR) could lead to a reduction in dune width (from erosion) and lowering of dune crest elevations, which will become more likely to be overtopped by dynamic water levels along the coast, and across larger areas that are not currently affected. While these dynamic water levels were calculated, they were not mapped as part of the CHA.

For Stage 3 of the multi-hazards project, coastline ground levels and water levels have been analysed to identify potential inundation pathways from coastal flooding along the dune profile, considering both static and dynamic water levels. To identify the location of these potential pathways, the dune crest elevation has been extracted from the 2018-2019 LiDAR survey data, representing the highest elevation point of the present-day dune morphology. The profile of the crest elevation along the shoreline (approximately 7.8 km in length) was compared with the static and dynamic water levels from the CHA (Table 38). We note that the storm tide levels and ground levels used in this section of the report refer to NZVD2016, to align with CCC current practise and the underlying input datasets (e.g. LiDAR, storm tides). Although the offset between NZVD2016 and CDD varies along the coast, values in NZVD2016 can be converted to CDD by adding approximately +9.411 m (+9.043 m offset to LVD37; +0.368 m offset to NZVD2016).

To align with the flood probabilities considered in the multi-hazards project, 2% AEP static and dynamic water levels have been interpolated between the 10% and 1% AEP water levels provided in the CHA. The CHA did not consider probabilities smaller than 1% AEP and therefore the outputs from that study cannot be directly used to assess overtopping for the 0.5% AEP likelihood considered in the multi-hazards project. A sensitivity test using the NIWA (2016) Coastal Calculator indicated that a 0.5% AEP would only result in potentially an additional 0.1 m elevation for both static water level and wave runup above the 1% AEP level. The following analysis therefore focuses on the 10%, 2% and 1% AEP water levels.

Note that in the dune profile figures presented in this part of the report, the probability of water levels is expressed as Average Recurrence Interval (ARI) – i.e., the average time period between exceedances of a

[63] Coastal Hazard Assessment for Christchurch District, Tonkin & Taylor, September 2021

given water level. For ARIs greater than 10 years the ARI is equivalent to the reciprocal of the annual exceedance probability (AEP) used in the body of this report

Table 38. Extreme water levels (NZVD2016 Datum) for present day (0 m SLR) from CHA (2021). The 2% AEP water level has been interpolated between the 10% and 1% AEP.

Coastal Storm Annual Exceedance Probability (AEP)	10% AEP	*2% AEP (interpolated)*	1% AEP
Static water level (m NZVD2016)	2	*2.2*	2.3
Dynamic water level (m NZVD2016)	4.2	*4.3*	4.4

7.6.1.1 Present day inundation hazard

The dune crest elevation along the open coast from South New Brighton Surf Club to Bottle Lake Forest is generally in the order of 8 m NZVD2016, with some areas being higher (up to 12 m NZVD2016), as well as gaps in the dune line where development has reduced ground levels (New Brighton Library, He Puna Tai Moana Hot Pools, Surf Clubs, beach accessways). The alongshore dune crest elevation is presented in Figure 80, with the static and dynamic extreme water levels overlaid to indicate potential pathways for seawater to flood the eastern suburbs. Figure 81 maps the pathways along the shoreline. Table 39 presents the total lengths of shoreline within the project area where the current crest elevation of the dune ridge is below the static or dynamic water levels under the three AEPs considered. Overtopping risk is most likely to be driven by dynamic inundation. The frequency of the event (or size – e.g., 10%, 2%, 1%) has minimal effect when compared to the difference between overtopping caused by static and dynamic water levels.

Table 39. Length of shoreline where elevation of the dune crest is below the static or dynamic water level during extreme events under present day sea levels (0m SLR).

	Length of Shoreline Overtopped by Water Level (% of total shoreline in project area)					
	10% AEP		2% AEP (interpolated)		1% AEP	
Scenario	**Static Water Level**	**Dynamic Water Level**	**Static Water Level**	**Dynamic Water Level**	**Static Water Level**	**Dynamic Water Level**
Present Day (0m SLR)	0 m (0%)	660 m (8%)	0 m (0%)	680 m (9%)	4 m (<1%)	722 m (9%)

Static water levels are not projected to overtop the current dune crest elevation under the 2% or 10% AEP, and only a very small area of overtopping (4 m) in a 1% AEP with present day sea levels. However, the static water levels do come close to overtopping the crest from the New Brighton Library to the New Brighton Surf Club, and also from the North Beach Community Centre to the North Beach Surf Club. Only a small amount of morphological change would need to occur along these areas to be overtopped by static inundation. As shown in Figure 80 and Figure 81, dynamic water levels could overtop the beach in four locations alongshore: From the New Brighton Library to the New Brighton Surf Club; North Beach Community Centre to the North Beach Surf Club, the Waimairi Beach Surf Club, and through a small accessway at Bottle Lake Forest at the northern end of the project area. Under present day sea levels, 660 m (10% AEP) to 722 m (1% AEP) of the eastern shoreline could be overtopped and potentially create pathways for coastal flooding. This equates to 8-9% of the shoreline within the project area.

Between the New Brighton Library to the New Brighton Hot Pools complex, the general gradient of the land behind the general line of beach dunes (e.g. landward of Marine Parade) slopes down inland to the west, hence any seawater overtopping the dune crest line would generally continue to flow into the urban area and therefore contribute to additional flooding. However, in some of the other potential overtopping locations the land behind the dune crest rises or flattens out, and therefore it is unlikely wave runup would significantly increase the flood hazard. For example, the elevation of the carpark south of the New Brighton Surf Club is in the order of 4 m NZVD2016 elevation and 40 m wide, so seawater may overtop into the carpark, but is likely to be captured by the carpark stormwater runoff system and unlikely to travel much further inland.

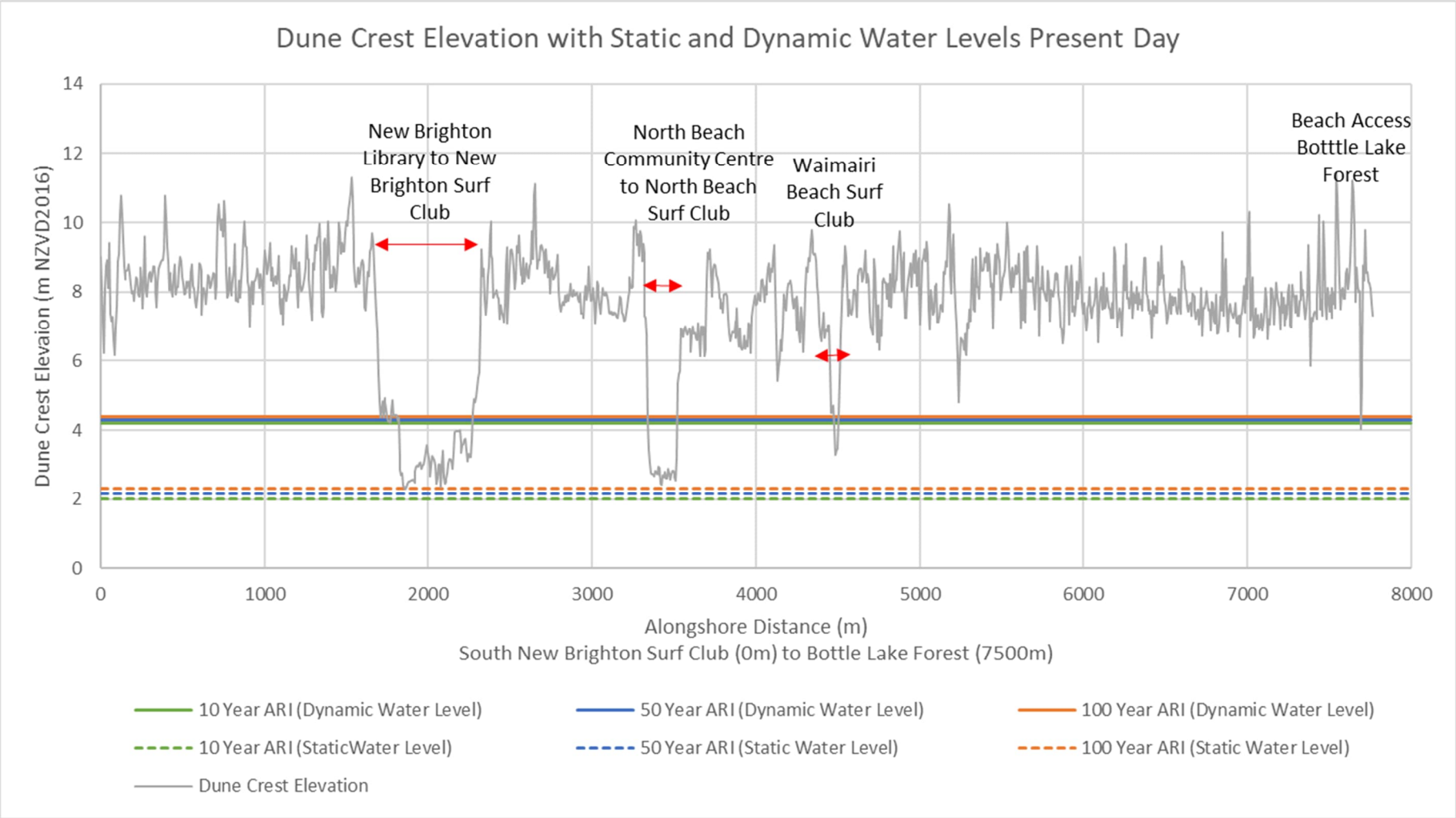


Figure 80: Alongshore profile through the existing dune crest profile compared to static and dynamic water levels with present day sea levels (0 m SLR).

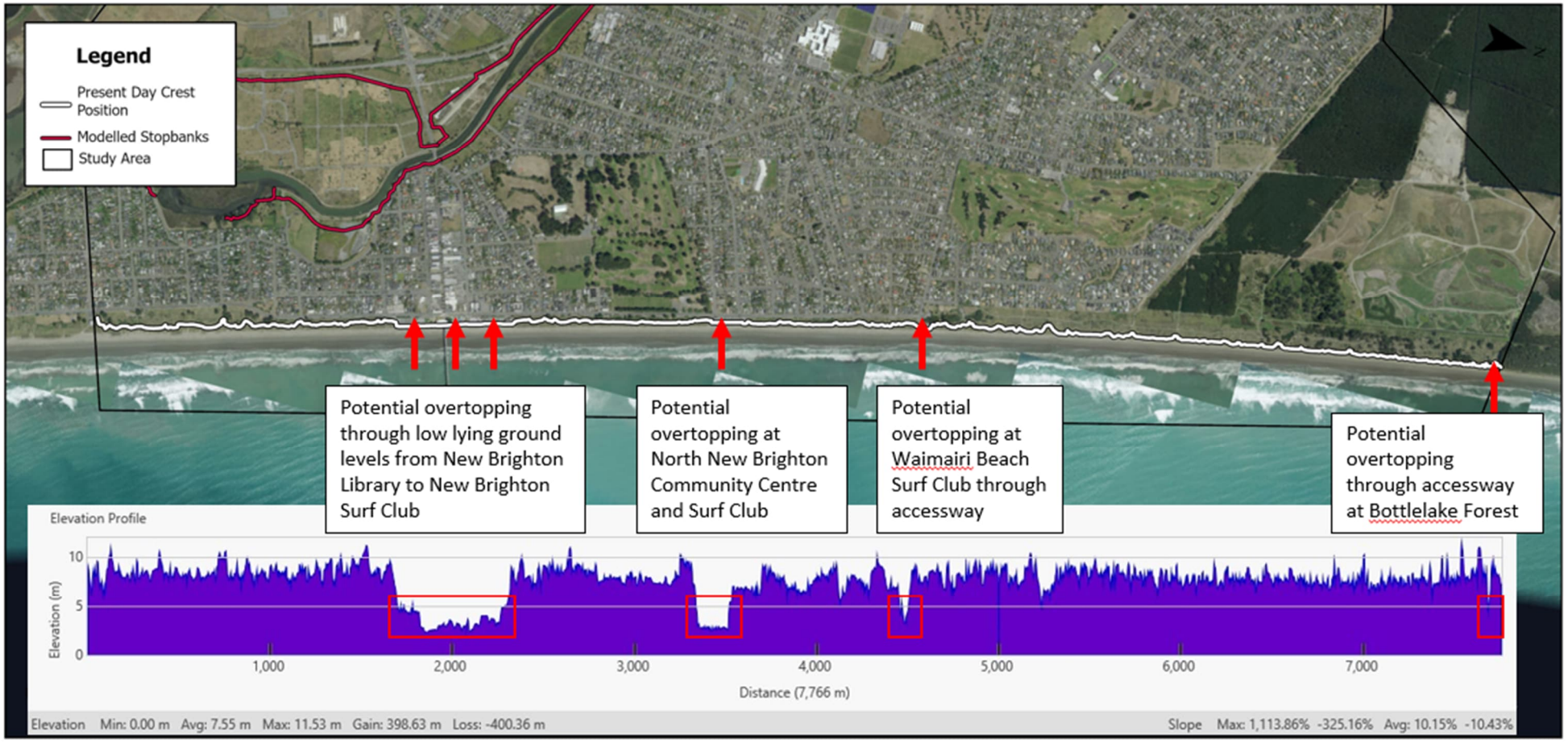


Figure 81. Annotated map showing locations of potential overtopping.

At the North Beach Community Centre and Surf Club, the elevation of the carpark landward of an existing seawall is in the order of 2.6 to 3 mNZVD2016. Due to the horizontal resolution of the LiDAR survey data, the seawall is not detected in the profile, however based on observations at the site the wall is approximately 1 m above the carpark ground elevations (i.e. 3.6 - 4 m NZVD2016), and therefore is likely to reduce direct runup into the carpark along the majority of the seawall frontage. However, there are gaps in the seawall at the North Beach Surf Club for vehicle and pedestrian access, where elevations are around 2.8 mNZVD2016 and run-up could spread to the land behind. Inland of the sea wall the land falls to a low point in Marine Parade before rising. Any runup passing through the gap in the wall or overtopping the wall could therefore pond in Marine Parade, potentially impacting transport along that road during a storm event.

At Waimairi Beach Surf Club there is a low point at the accessway, where dynamic water levels higher than 4.1 mNZVD2016 could funnel through the accessway and flow down slope to the carpark behind the beach. In Bottle Lake Forest at the northern end of the project area, there is a potential pathway for flooding through a beach access area, however the land it could potentially flow into is recreational and rural with no current development.

7.6.1.2 Future inundation hazard

Pathways for coastal inundation through the existing dune system under future sea level rise have been identified on the basis of the dune profile and crest elevations remaining unchanged, and that future storm wave parameters controlling run-up elevations (wave height and period) for a given AEP are also unchanged. This is currently a standard practice approach to assessing the potential inundation hazard (i.e. without consideration of morphological changes). A more complex analysis that considers changes in crest elevation with morphological changes is presented in Section 7.6.3.

The results of this analysis are presented in Table 40 below and shown graphically in Appendix F. This analysis uses SLR scenarios aligned with the multi-hazards project, up to a maximum of 2.4 m. Generally, the difference in the length of shoreline overtopped between the 10% AEP and the 1% AEP is small relative to the total shoreline affected (i.e. 1-2% difference in overtopping of shoreline length), so further commentary discusses only the 1% AEP event as a conservative measure of inundation.

Table 40. Length of shoreline where elevation of the dune crest is below the static or dynamic water level during an extreme event for the future scenarios considered in the multi-hazards project.

	Length of Shoreline Overtopped by Water Level (% of total shoreline in project area)					
	10% AEP		2% AEP (interpolated)		1% AEP	
Scenario	**Static Water Level**	**Dynamic Water Level**	**Static Water Level**	**Dynamic Water Level**	**Static Water Level**	**Dynamic Water Level**
0 m SLR (Present Day)	0 m (0%)	660 m (8%)	0 m (0%)	680 m (9%)	4 m (<1%)	772 m (9%)
0.19 m SLR (~2030)	0 m (0%)	719 m (9%)	13 m (<1%)	741 m (10%)	66 m (1%)	761 m (10%)
0.45 m SLR (~2060)	48 m (1%)	771 m (10%)	132 m (2%)	780 m (10%)	221 m (3%)	801 m (10%)
1.06 m SLR (~2100)	415 m (5%)	857 m (11%)	480 m (6%)	864 m (11%)	525 m (7%)	879 m (11%)

	Length of Shoreline Overtopped by Water Level (% of total shoreline in project area)					
	10% AEP		2% AEP (interpolated)		1% AEP	
Scenario	**Static Water Level**	**Dynamic Water Level**	**Static Water Level**	**Dynamic Water Level**	**Static Water Level**	**Dynamic Water Level**
1.88 m SLR (~2150)	594 m (8%)	955 m (12%)	641 m (8%)	982 m (13%)	654 m (8%)	1012 m (13%)
2.4 m SLR (>2150)	722 m (9%)	1163 m (15%)	754 m (10%)	1249 m (16%)	777 m (10%)	1340 m (17%)

The length of shoreline that could be overtopped by static water levels increases with sea level rise, from 4 m at present day, to 10% (777 m) with 2.4 m SLR. The potential pathways along the coast for future flooding by static sea levels with sea level rise are the same as those identified for dynamic water level pathways under present-day sea level (i.e., Waimairi Surf Club, North Beach Surf Club to North Beach Community Centre, New Brighton Surf Club to New Brighton Library). No new pathways for flooding from future static water levels with SLR up to 2.4 m were identified.

Assuming the dune morphology remains the same into the future, areas where dynamic water levels (i.e. wave runup) can already reach, as identified in Section 7.6.1.1, will become larger at the openings, allowing additional water volumes to travel through these lower portions of the shoreline with increases in SLR. For the highest SLR scenario of a 2.4 m, an additional 500 m of existing dune elevation lies below the projected dynamic water level, equivalent to a 7% increase in the length of shoreline potentially exposed to wave overtopping.

In addition to the areas already identified as being exposed to overtopping under present-day sea level, a new pathway at a beach accessway near Neptune Place (Waimairi Beach) could be created due to the dynamic water levels exceeding the dune crest elevation for SLR at or above 0.45 m. However, the topography inland of the accessway is such that any flooding would most likely be contained. Additional overtopping pathways also begin to occur along the shoreline between North Beach Surf Club and Waimairi Surf Club for SLR above 1.88 m.

The potential for inundation pathways occurring at present is generally around areas adjacent to built assets (e.g. near the library, surf clubs, hot pools and community centre), where the beach and dune is actively managed with plantings, artificial dune management, and sand trap fencing. In the future, there will be larger openings where water can overtop along the coast as sea levels rise, and there will also be new locations where overtopping or breaching may occur. The creation of new openings may occur in areas that are not currently actively managed, and hence dune management would need to increase in scale to cover these new areas. If these current or future pathways are not managed to the same effect as they are currently, the scale of impacts might be such that dune erosion would not be managed as efficiently as it is at the current time, and therefore the risk could be higher than what is observed in this analysis.

7.6.1.3 Effects of future vertical land movement

The potential influence of VLM on coastal flood risk has been assessed for VLM Scenarios 1 and 2 developed for Stage 3 of the project (Section 3.1.3). The purpose is to understand whether medium to long term VLM would result in large increases in overtopping volumes, or the development of new inundation pathways. The total VLM close to the shoreline over the two scenarios to 2060 (0.45 m SLR) and 2100 (1.06 m SLR) have been applied to the present-day crest levels (Section 8.6.1.1).

The length of shoreline exposed to coastal inundation from both static water levels and dynamic water levels is then identified, and a simple weir calculation has been used to estimate the potential inundation volume

and indicative depth in the project area. This analysis does not consider any future erosion of or other geomorphic changes to the dune system. As discussed further in Section 8.6.2, the combination of VLM and future coastal erosion will result in a greater increase in coastal flood risk, than VLM alone.

Table 41 shows the length of present-day dune crest that is below the 10%, 2% and 1% AEP water levels with 0.45 m SLR and 1.06 m SLR and how these lengths of shoreline increase when the crest elevation is lowered under the two VLM scenarios. These are also shown graphically in Figure 82. The analysis indicates that the distance of shoreline that could be overtopped would increase when considering VLM under the two scenarios, however as a percentage across the entire shoreline, the increase is very small (1%). The additional length of shoreline susceptible to overtopping is around areas of low-lying land already identified as being overtopped in Section 8.6.1.1 and 8.6.1.2. No new inundation pathways appear to develop due to VLM alone.

Table 41: Length of shoreline where elevation of the dune crest with no VLM, Scenario 1 and 2 VLM (for 2060 and 2100) is below the static or dynamic water level during an extreme event for the future scenarios considered in the multi-hazards project.

Scenario	Length of Shoreline Overtopped by Water Level (% of total shoreline in project area)					
	10% AEP		2% AEP (interpolated)		1% AEP	
	Static Water Level	Dynamic Water Level	Static Water Level	Dynamic Water Level	Static Water Level	Dynamic Water Level
0.45 m SLR (~2060)	48 m (1%)	771 m (10%)	132 m (2%)	780 m (10%)	221 m (3%)	801 m (10%)
0.45 m SLR (~2060) **Scenario 1 VLM**	96 m (1%)	779 m (10%)	117 m (2%)	798 m (10%)	274 m (4%)	817 m (11%)
0.45 m SLR (~2060) **Scenario 2 VLM**	147 m (2%)	794 m (10%)	235 m (3%)	815 m (10%)	317 m (4%)	833 m (11%)
1.06 m SLR (~2100)	415 m (5%)	857 m (11%)	480 m (6%)	864 m (11%)	525 m (7%)	879 m (11%)
1.06 m SLR (~2100) **Scenario 1 VLM**	467 m (6%)	869 m (11%)	520 m (7%)	880 m (11%)	542 m (7%)	892 m (11%)
1.06 m SLR (~2100) **Scenario 2 VLM**	503 m (6%)	880 m (11%)	531 m (7%)	891 m (11%)	552 m (7%)	902 m (12%)

The overtopping volume with static water levels will increase in with VLM as a result of the existing pathways becoming slightly wider and the depth of flow in the pathways increasing due to the reduction in ground level. Table 42 presents indicative overtopping volumes during a 1% AEP coastal storm event (static water levels) over a single 12-hour tidal cycle. The volumes represent the total volume of water overtopping the entire shoreline (7.8 km), both without VLM and for each of the two VLM scenarios considered (Scenario 1 and Scenario 2), for three SLR values (0 m, 0.45 m and 1.06 m). The table also indicates the potential additional depths of water that could result from the overtopping when spread over a 9.5 km^2 area between the OARC flood defences and the sea.

The analysis indicates that in both VLM scenarios there would be an increase in water volume overtopping the dune crest. However, the potential increases in flood depth resulting from the increase in overtopping volume due to VLM are relatively small in the 2060 future state – 0.01 m or 0.05 m for VLM Scenarios 1 and 2, respectively; but more significant in the 2100 future state – 0.16 m or 0.29 m for VLM Scenarios 1 and 2, respectively.

Table 42: Calculation of volume overtopping varied dune crest elevations with VLM during a 12-hour tidal cycle in a 1% AEP event.

VLM Scenario	No VLM	VLM Scenario 1		VLM Scenario 2	
Timeframe	**Present Day Crest**	**2060**	**2100**	**2060**	**2100**
0m SLR	0 m^3 0 m depth	-	-	-	-
0.45m SLR	170,860 m^3 0.02 m depth	321,192 m^3 0.03 m depth	-	546,740 m^3 0.06 m depth	-
1.06m SLR	3,482,634 m^3 0.37 m depth	-	4,991,984 m^3 0.53 m depth	-	6,311,086 m^3 0.66 m depth

In summary, VLM in isolation is unlikely to significantly increase flood risk along the coast to 2060 but will have a greater impact on flood risk over the longer term, to 2100. However, in a coastal setting, the impact of VLM is likely to be far surpassed by the impacts on flood risk caused by coastal geomorphic changes (i.e. erosion of the dune system) that will lead to the creation of more numerous and wider inundation pathways. The combined impact of VLM and coastal erosion has not been calculated as part of this study. However, VLM will result in higher rates of relative sea level rise interacting with coastal processes, which will likely speed up erosion processes where they are already occurring, or bring forward timeframes at which the accreting coastline will switch to being erosional.

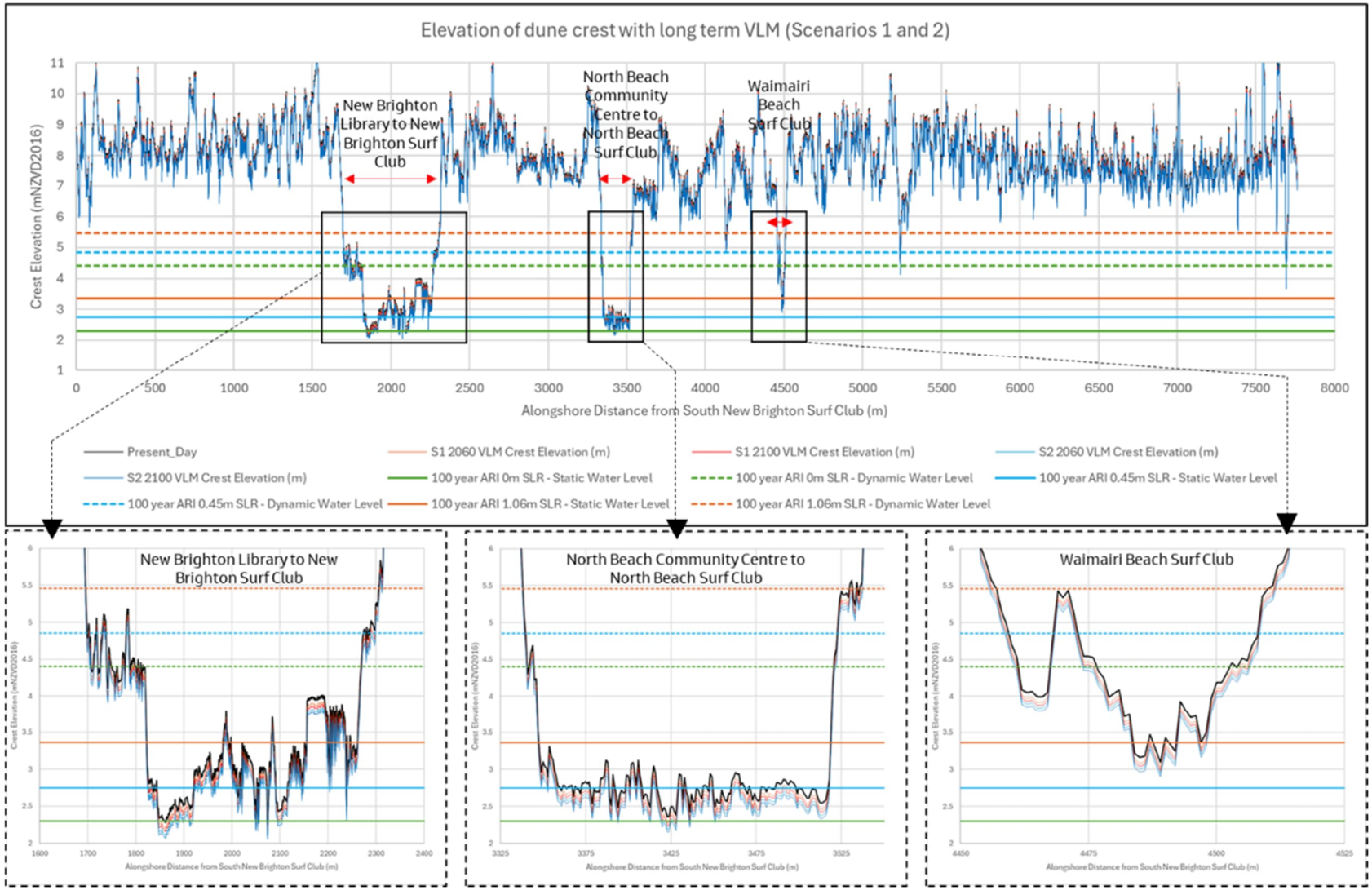


Figure 82: Alongshore crest elevation for present day, and under VLM scenarios 1 and 2 in 2060 and 2100 (with no erosion). Insets below the graph show the parts of the coastline where overtopping during a 1% AEP coastal storm with static and dynamic water levels is expected to occur.

7.6.2 Future erosion of dunes

The analysis in the previous section has established where pathways of inundation could occur along the coastline if the dune crest remains at its current level with future sea level rise. Whilst this is a common approach to undertaking coastal inundation assessments, the reality is that over time the coastal dune system is likely to change due to erosion with future sea level rise, or sooner as a result of storm clustering.

The NIWA (2018) Sand Budget Study focuses on the changes to sand supply for the coast and the impacts this may have on the long-term average beach position. The report concludes that up until 2120 the sand budget for the city should remain in surplus, and the shore should not erode, except under the worst case RCP8.5 climate change scenario. The study recognises that the results are spatially averaged along the total coastline, and a more spatially detailed assessment should be undertaken to include more localised information. The Tonkin and Taylor (2021) CHA breaks the shoreline into a series of segments to utilise more local information and capture longshore variation in shoreline responses over time, giving a more detailed assessment of future shoreline projections. Within each segment, account is taken of the different erosion causes: long term sediment supply/accumulation rates, the impacts of SLR on beach profiles, and the impacts of storms, that will affect how shoreline positions are projected into the future. Hence, the CHA shows erosion of the shoreline in earlier timeframes with SLR, due to the short-term impacts of storms on the dune system at a detailed scale, and shows progressively more erosion over long timeframes with high SLR scenarios as a result of the combined impacts of storms and erosional effects of SLR.

Considering the long-term effects of SLR and the impact of short-term storms, even with a low long term accretionary rate along most of the coast, the dunes are considered likely to become increasingly more susceptible to erosion over time. It is also important to note that the shoreline position referenced in the Tonkin and Taylor (2021) CHA is the seaward foredune toe position, with no consideration of the geomorphic response of the dune to erosion of this feature. Based on dune profile response on well vegetated dunes, the most likely geomorphic response is considered to be that the dune profile will become truncated on the seaward side rather than migrating back in uniform profile across Marine Parade. Therefore, erosion issues leading to increased flooding risk will be most prevalent where the dune is already narrow and the projected erosion extends landward of the current dune crest position.

Potential future coastal flooding pathways resulting from changes in dune crest elevation with time have been identified. The available coastal erosion mapping from the CHA has been used to understand where the shoreline, identified as the seaward foredune toe position, may be located in the future with sea level rise, and the consequent crest level at this position, derived from the current LiDAR data. The sea level rise scenarios and shoreline position probabilities adopted for this analysis are:

- 0.4 m SLR by 2050 (10% chance of exceedance)
- 0.6 m SLR by 2080 (33% chance of exceedance)
- 1.2 m SLR by 2130 (33% chance of exceedance)
- 2 m SLR by 2150 (33% chance of exceedance)

These scenarios and probabilities were adopted due to these data having been already processed for the CCC Coastal Hazards Plan Change project, and therefore the projected future position of foredune toe could be easily identified. It is noted that these scenarios differ slightly from the sea level rise scenarios and timeframes considered in the multi-hazards project but are still aligned to similar projections of sea level rise in the future as shown in Figure 83.

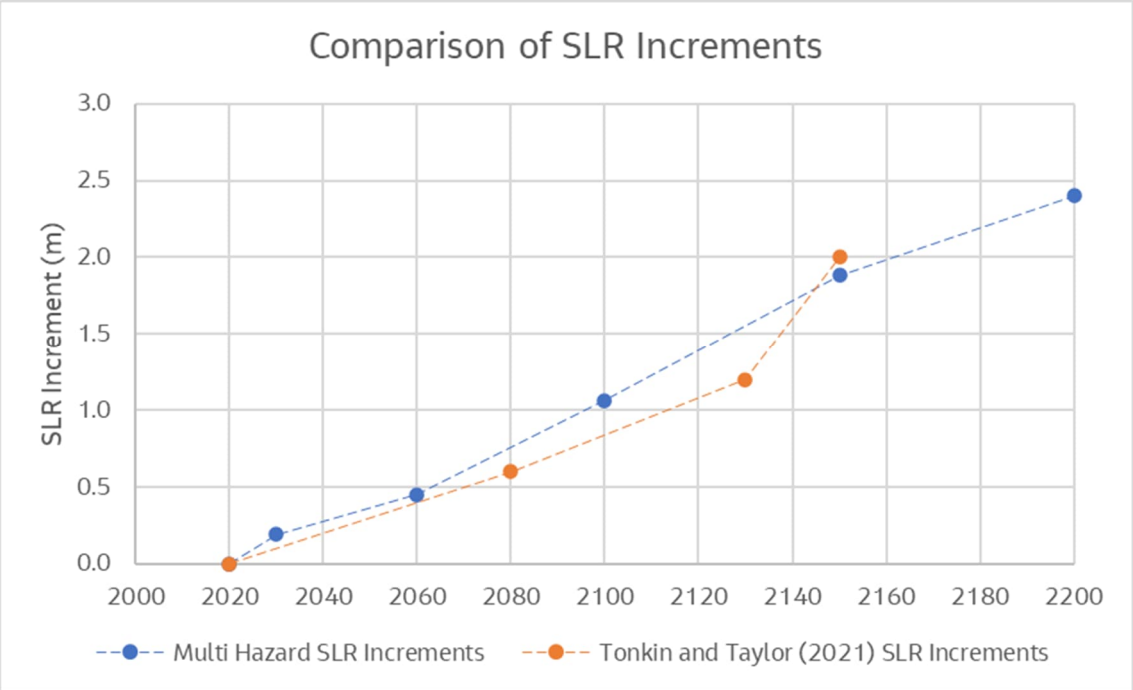


Figure 83: Comparison of available erosion mapping scenarios from CHA (2021) and the SLR scenarios considered in the multi-hazards project. Note that 2.4 m SLR increment for multi-hazards is for '>2150' and a timeframe of 2200 has been adopted for this graph.

An initial screening analysis to identify where potential future coastal flooding pathways could be created with sea level rise as geomorphic changes to the dune occur was undertaken by estimating the elevation of the dune crest if the dune toe was eroded back to the projected future shoreline position aligned with the above scenarios. For each future scenario a new dune crest elevation was determined on the basis that the dune system is managed in such a way in the future that there is no migration of the dune profile landward (i.e. the current backshore position is fixed by vegetation and infrastructure such that it does not migrate onto Marine Parade or the properties further landward).

This is considered to be a valid approach to how beaches and dunes in such situations will respond to sea level rise. The future dune crest is then taken as either the present-day dune crest position (if future accretion or small amounts of erosion are projected), or the dune level at the retreated shoreline position from the CHA if future erosion is projected (i.e. the projected dune toe position is taken as a proxy for the future 'dune crest' position). In this approach, once the future projected shoreline is landward of the current dune crest position, the new crest elevation would be lower than the current dune crest elevation due to the dunes decreasing in height in a landward direction. An along-shore profile was created along the identified new crest positions for each scenario, and water levels were then overlaid to identify where new potential pathways could open up from either dynamic or static water levels.

Figure 84 shows an example of how the identification of the future dune crest level has been undertaken. The blue profile shows a cross section through the current dune morphology (i.e. 2018-2019 LiDAR dataset). The orange profile shows a truncated dune profile under a 0.4 m SLR scenario by 2050 with 40 m of erosion at the dune toe to be at a position landward of the present-day dune crest. Under this scenario, the elevation of the dune crest is still sufficient to prevent overtopping. Further erosion by the 2080 scenario (grey profile) shows a similar situation to 2050, where the crest elevation would still be sufficient to withstand wave overtopping. However, by the 2130 scenario (yellow profile), the erosion has removed the entire dune, and the 2130 crest is located at the back of the present-day dune. At this point in time, wave overtopping (and static water levels) could overtop the entire beach into Marine Parade, and a new pathway for flooding would be created. During flood events, where there are narrow pathways for flooding, the lateral width of the

pathways will also expand due to erosion during the event, creating wider pathways and allowing more water to overtop into the backshore.

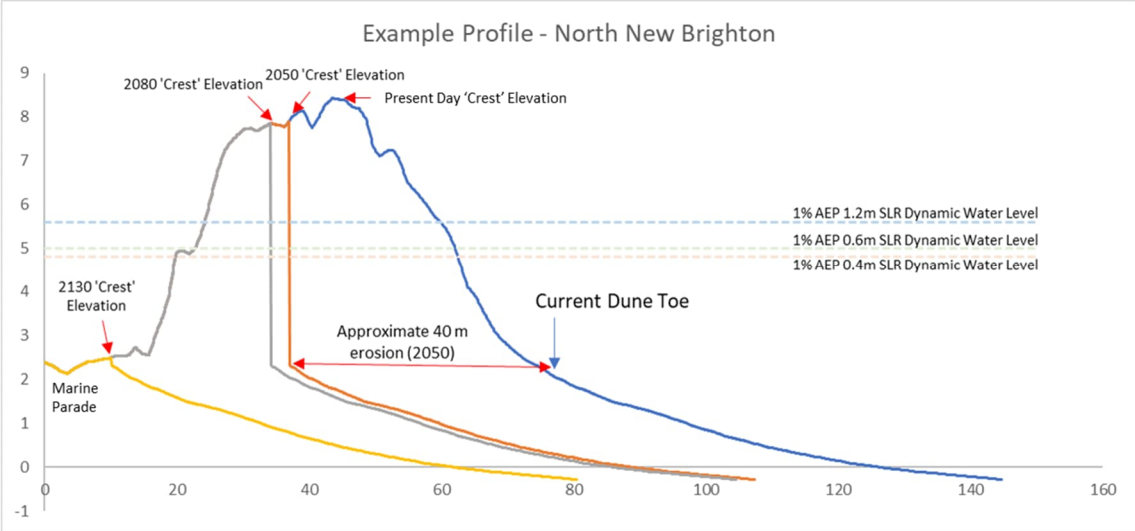


Figure 84. Example cross section from North New Brighton which shows where the assumed crest elevation is projected to be based on erosion distances from CHA (2021).

Alongshore, there are variations in dune characteristics which will also ultimately impact the creation of inundation pathways that have not been considered in this assessment. Further work to refine this analysis should have consideration for the combined impact of crest height, width, vegetation cover, and pedestrian access, as well as the impact of storms in series – which has the potential in narrow areas of the dune to have a greater impact than long term erosion with SLR.

7.6.3 Effect of dune erosion on inundation

The lengths of eroded future shoreline that could be inundated due to either static water levels or overtopped by dynamic water levels under the various sea level rise scenarios is presented in Table 43 and graphically in Appendix B. Generally, the differences in length of shoreline overtopped between the 10% AEP and the 1% AEP coastal storm event is small relative to the total shoreline length (i.e. 1-4% difference in overtopped shoreline length), so further commentary for this analysis is limited to the 1% AEP event.

Table 43. Length of shoreline overtopped by static and dynamic water levels for a modified dune profile with sea level rise.

	Length of Shoreline Overtopped by Water Level (% of total shoreline in project area)					
	10% AEP		2% AEP (interpolated)		1% AEP	
Dune Crest Profile	Static Water Level	Dynamic Water Level	Static Water Level	Dynamic Water Level	Static Water Level	Dynamic Water Level
0m SLR (Present Day)	0 m (0%)	660 m (8%)	0 m (0%)	680 m (9%)	4 m (<1%)	772 m (9%)
0.4m SLR (~2050)	0 m (0%)	805 m (10%)	8 m (0%)	822 m (11%)	12 m (<1%)	863 m (11%)
0.6m SLR (~2080)	17 m (0%)	962 m (12%)	127 m (2%)	990 m (13%)	213 m (3%)	1013 m (13%)
1.2m SLR (~2130)	1429 m (20%)	4386 m (56%)	1504 m (19%)	4523 m (55%)	1670 m (22%)	4660 m (60%)
2m SLR (~2150)	5596 m (79%)	6860 m (88%)	5890 m (76%)	6905 m (89%)	6053 m (78%)	6916 m (89%)

The results of this analysis can be summarised as follows:

- **0.4 m SLR**

The difference between the length of shoreline exposed to direct static water level coastal flooding in present day and with 0.4 m of SLR in a 1% AEP coastal storm event is small, being only an additional 8 m in isolated spots around New Brighton Library, New Brighton Hot Pools, and North New Brighton Community Centre, if existing protection was removed or failed. Length of shoreline overtopped by dynamic water levels increases from 772 m (9% of total shoreline length) in present day 1% AEP to 863 m (11% of total shoreline length) with 0.4 m SLR.

New pathways from wave overtopping of the eroded dune profile could open up between North New Brighton Surf Club and Waimairi Surf Club, and small sections north of the Waimairi Beach Surf Club. **Figure 85** identifies spatially where these additional pathways of inundation for dynamic water levels could occur in the area between the North New Brighton Surf Club and Waimairi Beach Surf Club. It is considered that this additional water from overtopping would likely pool on Marine Parade or within the first block of properties back from Marine Parade. It is important to note that the dark blue (dynamic water level) shown in Figure 85 is not the flood extent, it is the land that is below the dynamic water level. It is not anticipated that dynamic water levels would reach as far inland as shown on the map, as the dynamic water levels would be highly influenced by reduction of energy at the crest when overtopping, and attenuation distance from the shoreline.

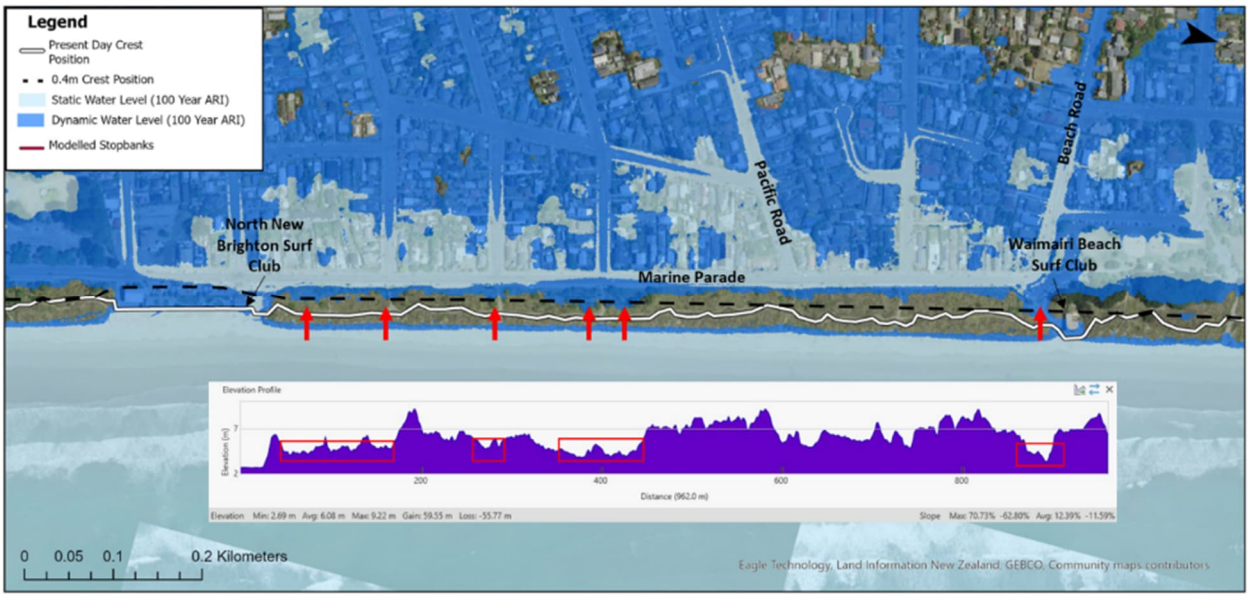


Figure 85. Shoreline between North New Brighton Surf Club and Waimairi Beach Surf Club, where the red arrows signal areas where new inundation pathways could occur if erosion under the 0.4 m SLR scenario (~2050) alters the crest position/elevation. Variations of blue represent the area of land below the static and dynamic water levels with 0.4 m SLR for a 1% AEP. The purple graph is the estimated long-shore elevation profile through the new crest position in ~2050.

- **0.6 m SLR**

There is an increase in length of shoreline that could be exposed to both static water level (up to 213 m (3%) in a 1% AEP coastal storm event) and 1013 m (13%) overtopped by dynamic water levels during the same frequency event. For static water levels, direct inundation would mostly be located around the New Brighton Library, New Brighton Hot Pools, and North New Brighton Surf Club. Potential for dynamic water level overtopping is in similar locations to those effected by 0.4 m SLR scenario, with inundation pathways from overtopping increasing between North New Brighton Surf Club and the Waimairi Beach Surf Club.

- **1.2 m SLR**

With 1.2 m SLR, 22% of the total project area shoreline (1.6 km) could be overtopped by static water levels with eroded dune profiles, and 60% (4.6 km) could be overtopped by dynamic water levels. In South New Brighton, the eroded dune would not be overtopped by static water levels, but some inundation pathways could open up by dune overtopping from dynamic water levels. Static water levels could overtop the modified shoreline either side of the New Brighton Library, and inundation from wave-run-up could occur for around 600 m frontage from south of the Library to the New Brighton Surf Club (**Figure 86**).

For approximately 1 km north of the New Brighton Surf Club the eroded dune crest would be high enough for mostly prevent overtopping from static water levels, however at Thompson Park, the dune would be sufficiently eroded to provide a direct connection for static water levels to flood the Rāwhiti Domain and surrounding properties. Along the North New Brighton Community Centre and Surf Club frontage (**Figure 87**), static water levels could directly flood through into properties both along Marine Parade and further landward. North of the Waimairi Beach Surf Club, the dunes crest elevation provides a varying level of protection from static water level flooding, however, the overtopping from dynamic water levels will connect the areas that are mapped as being flooded by the static water levels (**Figure 87**).

Using a simple weir calculation approach, 24.6 million m^3 of sea water could overtop the eroded dune crest with static water level during one tidal cycle. When this volume is spread over the project area to the east of the flood defences and ANZAC Drive (approx. 9.5 km^2 over Waimairi Beach, North New Brighton, New Brighton, and South New Brighton), it could result in an average water depth of 2.6 m. If spread over the whole project area extent east of the flood defences (approximately 21 km^2), then average water depth could be 1.2 m.

- **2.0 m SLR**

With 2 m of SLR, 86% of the shoreline (6053 m) will be directly inundated by the static water level in a 1% AEP coastal storm event, and 98% of (6916 m) could be overtopped with dynamic water levels. This would result in extensive flooding through the South New Brighton, New Brighton, North New Brighton and Waimairi Beach area. There may be some areas of dune still providing protection to the static water level at Waimairi Beach, however generally the entire shoreline would be overtopped.

Under these future time horizons, flooding will be much more impactful on a more frequent basis. As shown in Table 43, in a more frequent 10% AEP event, 79% of the total shoreline is projected to be overtopped by the static water level. Furthermore, when considering tidal flooding on a monthly basis, 33% of the shoreline could be overtopped by MHWS water levels with 2 m SLR (i.e. 2.76 m NZVD2016).

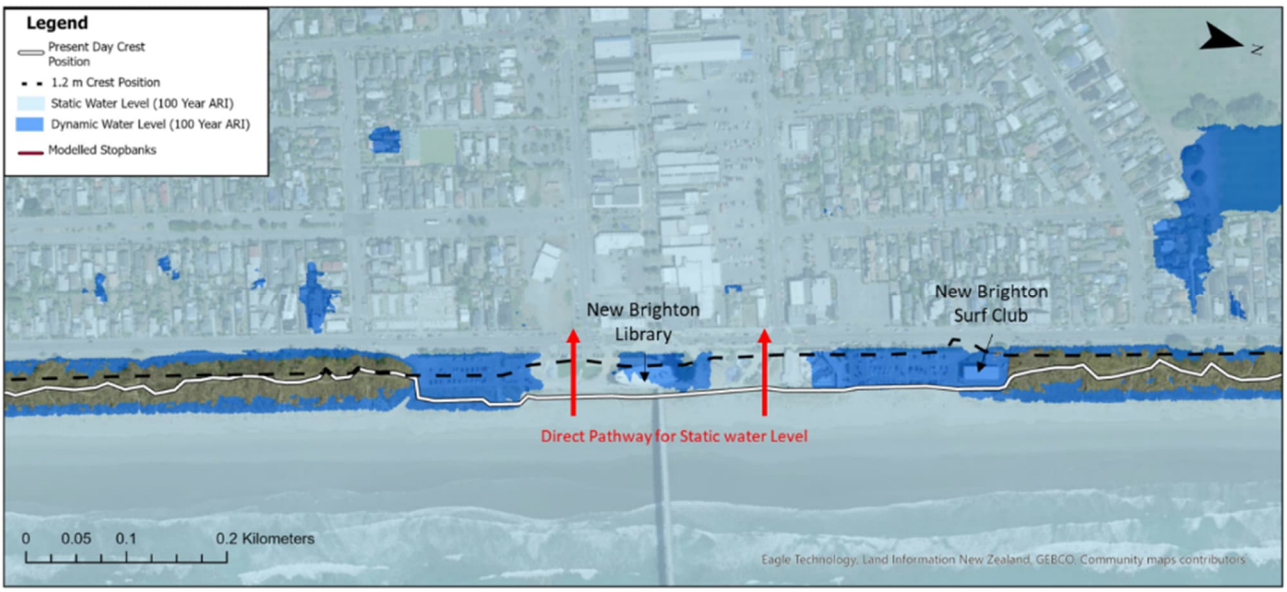


Figure 86: Future dune crest position (dashed line with 1.2 m SLR) along the New Brighton shore front overlay with static and dynamic water levels in a 1% AEP coastal storm event. Red arrows show locations where there could be direct pathways for coastal inundation from static water levels. Areas where there is overlap between the dune crest location and the water levels show where a potential inundation pathway from dynamic water levels could form.

Figure 87: Future dune crest position (dashed line) with 1.2 m SLR from North New Brighton Community Centre to Waimairi Beach, overlay with static and dynamic water levels in a 1% AEP coastal storm event. Red arrows show locations where there could be direct pathways for coastal inundation from static water levels. Areas where there is overlap between the dune crest location and the water levels show where a potential inundation pathway from dynamic water levels could form.

7.6.4 Summary

The results of this analysis highlight the importance of the New Brighton Dune system in providing protection from coastal flooding from both storm tides (static water levels) and wave run-up (dynamic water levels) and the importance of potential change in coastal morphology for future flood risk.

With present day sea levels, for the range of events considered, there are no direct pathways for static water levels to overtop the existing dune or beach front infrastructure elevations, but there are potential pathways for inundation through wave run-up at existing openings in the dune system around community assets located on the beach front (Library, Hot Pools, Surf Clubs and Community Centres). Around 8% of the study shoreline could be exposed to dynamic water level overtopping in a present-day 10% AEP coastal storm event. This is a similar sized event to the 2002 storm (10% AEP) which overtopped into the New Brighton playground site at the Pier.

If the dunes are maintained at their current profiles and elevations under sea level rise, exposure to static water inundation in a 1% AEP coastal storm event would be limited to 3% (221 m) of the shoreline length with 0.45 m SLR, increasing to 10% (777 m) with 2.4 m SLR. Under this dune morphology scenario, the length of shoreline exposed to potential dynamic water level inundation would change very little from the present-day up to 0.45 m SLR, increasing with further SLR to 17% exposure (1340 m) under a 2.4 m SLR scenario.

VLM is projected to increase overtopping volumes through wider inundation pathways and greater depths of flow, but no new inundation pathways would develop as a direct impact of VLM to 2100. Over the timeframe to 2060, the material impacts of VLM on coastal flood risk is unlikely to be significant (potential increases in flood depth of the order of 0.01 to 0.05 m) but will be greater by 2100 (potential increase in flood depth of the order of 0.16 to 0.29 m). In a coastal setting, the impacts of VLM on coastal flood risk and overtopping over the long term are likely to be far surpassed by the coastal geomorphic changes (i.e. coastal erosion of the dunes) that will lead to the opening of new inundation pathways.

Over time the dunes are projected to be more susceptible to erosion with rising sea level, with the most likely geomorphic response being that the dune profile is truncated on the seaward side rather than migrating back across Marine Parade. Future dune crest elevations are therefore likely to be lower than the current elevation due to projected erosion extending landward of the current dune crest position, and additional pathways for coastal inundation are likely to develop. These will largely be located between the North New Brighton Surf Club and the Waimairi Surf Club where the dune is the narrowest, subsequently exposing more of the shoreline to both direct static water level and indirect dynamic water level overtopping in these locations.

Under this future the analysis shows there is little change in overtopping exposure in a 1% AEP coastal storm event for SLR rise of 0.4 m to 0.6 m. However, large increases in potential exposure are likely with 1.2 m of SLR; with potential for static water levels to exceed eroded crest levels over 22% (1670 m) of the shoreline of the project area, allowing potential direct inundation of the New Brighton and North New Brighton areas, and 60% (4.6 km) of the shoreline potentially being exposed to wave run-up overtopping, which will contribute to deeper coastal flood depths.

For the highest sea level rise scenario assessed (2 m SLR), erosion with associated reduction in dune elevation is projected to expose 78% (6 km) of the shoreline to direct static water level inundation in a 1% AEP coastal storm event, increasing to 89% (6.9 km) exposure to indirect inundation from wave run-up overtopping. This is in stark contrast to the 13% (1.1 km) exposed to similar wave run-up overtopping if dune elevation were maintained at current levels.

These results indicate that although OARC Scheme flood defences will protect the areas on the true left bank of the river from combined coastal and fluvial flooding in future scenarios, under higher sea level rise scenarios (i.e., over 1.2 m), the areas from South New Brighton to Waimairi Beach could be exposed to significant increased risk from coastal flooding particularly if the projected shoreline erosion occurs. An

indication of the pathway for inundation from the coast in higher sea level rise scenarios is shown on the LiDAR land elevation map in Figure 88. The OARC Scheme flood defences will block any pathways for the overland flow from the coast to return to the sea via the Ōtākaro Avon River system where the land is lower compared to the coastal strip. The impact of this is that potential flood extents and depths on the eastern (seaward) side of the flood defences will increase with sea level rise. High water levels in the river in such events would also restrict drainage of flood water back to the river. More detailed hydrodynamic modelling would be needed to assess the impacts of the OARC Scheme under such future scenarios.

Figure 88. An indication of possible pathways for coastal inundation from the open coast towards the Avon River area.

7.6.5 Implications for the multi-hazards modelling and the OARC scheme

This analysis indicates that there is little change in exposure to a direct route for inundation through the New Brighton dunes under 0.4 m SLR and, most probably, under 0.6 m SLR. However, there is a large increase in exposure with 1.2 m of SLR. Therefore, the change in exposure could occur between around 2080 and 2130. With 1.2 m of SLR the data indicate that flow paths for coastal inundation during coastal storm events could result in inundation of areas protected by the OARC Scheme flood defence on the true left bank of the Ōtākaro Avon River. This initial assessment does not include hydrodynamic modelling of water levels, or overtopping volumes to indicate the potential extent of future coastal inundation.

Given the likely lack of change in exposure in the short to medium term this indicates that the areas protected by the proposed OARC Scheme flood defences would be unlikely to be exposed to coastal inundation during these smaller sea level rise increments. This is confirmed by the modelling undertaken in Stage 3 of the project (Section 4.2 of this report), which indicates the onset of coastal inundation in the 1.06 m SLR and more extensive inundation in higher sea level rise scenarios. That modelling does not, however, allow for future erosion of the shoreline or the effects of dynamic water level overtopping.

7.6.6 Recommendations to address coastal hazards

This analysis confirms the risk of coastal inundation to the area benefiting from the OARC Scheme in the longer term and also the benefits the dunes provide in protecting these areas from flooding. Hence, we would recommend that Council:

- Seek to maintain or improve the protection benefits provided by the dunes over the longer term.
- Work with the community through adaptation planning to discuss the importance of the benefits which the dunes provide and develop a preferred way for the dunes to adapt to sea level rise. This may for

instance include modifying land use to allow for migration of the dunes and reduce erosion impacts on elevations.

- In future, hydrodynamic modelling of the lower Avon catchment consider explicitly modelling the potential inundation route from the open ocean using alternative dune profiles in higher sea level rise scenarios. This would help clarify the volumes of water that could inundate via this route and where it could flood. This can then be considered in adaptation planning with the community.

7.7 Vertical land movement

New data, which became available since completion of the original gap analysis in Stage 1 of the multi-hazards project and the subsequent studies in Stage 2 of the project, indicate the potential for vertical land movement (VLM) to have an impact on groundwater and flood hazards in the project area. The updated hazard cascade assessment (Section 7.2) identifies VLM as an additional hazard which needs to be considered by the project and additional tasks were included in the project scope during Stage 3 to assess the implications of VLM for the multi-hazards project as follows.

- In terms of flood hazard, the effect of VLM has been explicitly simulated in the flood models using three potential future scenarios of VLM (Section 4 of this report).
- VLM will reduce the depth from the ground surface to the water table, potentially increasing the hazard posed by shallow groundwater to land use in the project area. The effect of VLM has been included in the assessment of groundwater hazards by modifying the projections of depth to groundwater at future dates by the estimated amount of VLM to those dates in each VLM scenario (Section 6 of this report).
- VLM will lower ground levels along the coastline, potentially increasing the exposure to coastal inundation and this has been considered in the assessment of coastal inundation and erosion risks (Section 7.6 of this report).
- VLM will interact with earthquake hazards, both in terms of the additional subsidence from VLM prior to an earthquake and through the expected increase in rate of ongoing VLM following an earthquake. Potential combined changes in ground levels from this interaction has been included in one of the VLM scenarios considered and the effects on flood hazard have been explicitly simulated in the flood model (Section 4 of this report).

Key outcomes from these assessments are:

- VLM has little effect on the extent of flood hazard but increases the depth of flooding and hence flood damages, particularly without the OARC Scheme in place.
- Provided the new OARC Scheme flood defence crest levels include allowance for VLM, the effect of VLM on flooding in the area benefiting from the OARC Scheme is generally small and flood damages are not significantly increased.
- Similarly, VLM does not have a significant effect on the distribution of exceedance of flood hazard PRIs.
- VLM has a greater effect on the exceedance of groundwater hazard PRIs and increases the costs of groundwater management, particularly further into the future (2100).
- VLM has little effect on the risk of coastal inundation for the range of scenarios considered.

7.8 Potential impacts of sea level rise on tidal groundwater fluctuation

In order to assess whether groundwater also poses a hazard to the OARC Scheme flood defences, the effects of tidal variation in river water levels, flood flow and sea level rise on the potential for elevated groundwater levels and seepage in proximity to the OARC flood defences have been considered. The magnitude and duration of seepage will be largely dependent on the elevation of the river stage compared to the

surrounding ground surface landward of the flood defences and is likely to be highly variable over the length of the OARC Scheme for any given scenario.

Further consideration of the potential impact of the sea level rise and flood scenarios on groundwater fluctuation has been undertaken to identify whether seepage of groundwater may be an issue requiring managing under future scenarios.

GHD (2022)[64] assessed the potential groundwater seepage of several flood defence designs at Owles Terrace, New Brighton. Modelling was undertaken to assess seepage under regular tidal cycles and flood flow, in addition to 0.4 m and 1.0 m SLR.

Three different flood defence designs were assessed including:

- A 4 m wide stopbank with mechanically stabilised earth (MSE) wall either side.
- An 8 m wide stopbank with an MSE wall landward and extended earth bund riverside.
- A concrete floodwall atop an earth bund, with cut-off walls 0.5 to 1.0 m into the bund.

Relative elevation differences between river water levels and the ground surface for the different sea level rise scenarios assessed are as follows:

- Current – no sea level rise
  - Highest low tide – below ground level
  - Highest high tide – below ground level
  - Flood flow – at or marginally above ground level.
- 0.4 m SLR
  - Highest low tide – below ground level
  - Highest high tide – at or marginally above ground level
  - Flood flow – approximately 1.0 m above ground level.
- 1.0 m SLR
  - Highest low tide – below ground level
  - Highest high tide – approximately 0.5 m above ground level
  - Flood flow – greater than 1.5 m above ground level.

The current sea level scenario did not result in any seepage to the surrounding ground surface. Under the 0.4 m SLR scenarios there was only very minor seepage associated with peak high tide and flood flow, and under the 1.0 m SLR scenarios there was seepage associated with most high tides and flood flow.

GHD (2022) investigation concluded the following:

- The modelling results were not overly sensitive to the stopbank fill hydraulic conductivity value applied, as the main seepage flow path was via the underlying sand.
- For the 0.4 m SLR scenario, modelling results indicated that seepage was expected to occur during the flood event and high tides either side of the flood event. However, no seepage was estimated for the 8 m MSE wall plus bund scenario.

[64] GHD, 2022. Owles Terrace - Preliminary Hydrogeological Assessment. Report prepared for Christchurch City Council. Project 12582768. 14 November 2022.

- For the 1.0 m SLR scenario, seepage was expected to occur at most high tides in addition to the flood event under all scenarios.
- Modelling results indicate that seepage primarily occurred in areas of low-lying ground, approximately 5-6 m landward of the stopbank, and not directly at the stopbank toe as is currently observed.

  However, it is noted that this will be largely dependent on local ground elevation. 5-6 m landward of the stopbank coincides with the lowest ground elevation along the model section, with ground elevation rising up towards the stopbank.
- Modelling results indicated that widening of the stopbank to 8 m (MSE wall plus bund scenario) reduced seepage rates by approximately 75% compared to the 4 m wide stopbank MSE wall scenario.

  It is noted that, this is effectively increasing the seepage flow path and travel time relative to the cyclic tidal fluctuations. This effect will likely become less pronounced for greater sea level rise scenarios where river levels are maintained above the surrounding ground surface.

For the 1.0 m SLR, floodwall scenario, indicative seepage rates peaked at around 2 L/s over the 450 m long flood defence section in response to the flood event. This is equivalent to approximately 33 m^3 over the tidal cycle, or 66 m^3/day for the 450 m section of flood defence assessed (0.147 m^3/day of seepage per meter of flood defence). Seepage under maximum high tide and average high tide was of the order of 0.8 l/s and 0.5 L/s, respectively (approximately 28 m^3/day and 18 m^3/day).

The base case modelling adopted a hydraulic conductivity value for the underlying sands of 2×10^{-5} m/s. However, during sensitivity analysis, hydraulic conductivity of the sand was increased up to 6.3×10^{-5} m/s and it was found that under this scenario, modelled groundwater tidal fluctuations were better matched to observed groundwater tidal fluctuations, suggesting the natural formation hydraulic conductivity is likely higher than that adopted in the base case modelling scenario. For the same 1.0 m SLR floodwall scenario, with increased sand hydraulic conductivity, modelled seepage rates were approximately 3 times greater, peaking at around 6 L/s for the flood event and ranging from 1 L/s to 2 L/s for tidal cycles.

Under the 0.4 m sea level rise scenario, groundwater seepage coincides with extreme high tide and flood events. During flood events the seepage rates are likely to be insignificant in comparison to pluvial flooding and would be managed by stormwater pump stations. Outside of flood events, any seepage would likely be diverted to stormwater detention basins and discharged back to the river during low tide.

Under the 1.0 m SLR scenario, groundwater seepage rates peak twice daily coinciding with high tide and diminishing to no seepage either side of low tide. The regular seepage would likely require management and pumping via stormwater pump stations.

Under even greater sea level rise scenarios, and once low tide elevations exceed the surrounding ground elevation, seepage would be constant and peak seepage rates would increase relative to the increased river stage/tide levels. Under these scenarios, ongoing continued management and pumping is likely to be required. For the Owles Terrace example, low tide elevations will exceed the surrounding ground surface elevation midway between the 1.06 m and 1.88 m SLR scenarios (approximately).

7.9 Performance of OARC scheme and decision making about surrounding land use in major shock events

The analyses presented in Section 7 of this report consider how various hazards could interact with the OARC Scheme flood risk management infrastructure. It is also recognised that in a major hazard shock event such as a future earthquake or tsunami there would be considerable damage to other facilities and the land that benefits from the OARC Scheme in terms of flood risk management. The scale and extent of this damage could influence any decision making around adaptation or repair of the OARC flood risk management infrastructure after such events.

Based on experience from the CES the types of damage that may occur in future earthquakes include:

- Direct damage to public and private assets including houses, commercial properties, roads, bridges pipes/in-ground infrastructure and other utilities from earthquake shaking
- Liquefaction damage to houses, roads, stormwater pipes and open waterways
- Lateral spreading and cracking impacts on waterways and pipe networks
- Land settlement impact on overall levels/flood risk and the operation of piped networks

The types of damage that could occur from tsunami includes:

- Scour of bridge abutments and direct damage to bridges
- Inundation of public and private buildings (houses, commercial and Council buildings) by tsunami waters. The flood water – which is likely to be contaminated and laden with sediment and other debris and problematic to drain – could remain ponded behind the new flood defences for a lengthy period of time hampering any repairs needed to the flood defences or other infrastructure.
- Scour and erosion from water overtopping flood defences impacting public and private assets including houses, commercial properties and utilities.

Events of this nature could trigger alternative decisions on future land use, other than restoring the flood mitigation infrastructure, given the broader damage and economic restoration costs of other infrastructure and property. It may, for example, be sensible to consider a retreat option similar to that which resulted I the creation of the Residential Red Zone after the CES.

Within this project we have specifically considered how a future earthquake shock hazard can modify the land surface and thus flood risk. This has then been included as a scenario within the analysis of when and where PRIs may be exceeded. What has not explicitly been considered is how the potential impacts on the areas benefitting from the OARC flood risk management infrastructure in an earthquake or other shock hazard may influence decision making about the exceedance of PRI's, adaptation decisions or repair of existing flood protection infrastructure. It is anticipated that in any major shock event the previously preferred response pathway will likely need to be revisited to see if the proposed OARC flood protection infrastructure pathway is still the most viable response.

8. Alternative options

Stage 3 of the multi-hazards project has assessed the performance of the specific flood management measures of new flood defences and pumpstations which are planned as part of the OARC Scheme to manage future flood risk in the lower Ōtākaro Avon River catchment. This report presents the benefits of the OARC Scheme and assesses how other natural hazards interact with the OARC Scheme.

In combination with existing measures (such as district and regional planning controls on land development), the OARC Scheme provides considerable benefits in terms of reducing flood risk to the existing land uses in the project area. However, not all of the project area benefits from the OARC Scheme and there is a residual risk of flooding in the area benefiting from the OARC Scheme which is also exposed to other types of natural hazard. Other management measures, additional to those included in the OARC Scheme, may be required in the future to maintain present day land use in the project area.

The scope of Stage 3 of the project does not include consideration or assessment of alternative flood risk management measures to those proposed in the OARC Scheme from a multi-hazard approach. The project is therefore not intended to recommend the proposed OARC Scheme as the preferred flood management approach for the catchment. A more detailed DAPP based study considering all options would be required to identify a preferred management approach.

A high-level screening assessment of a short list of alternative or complementary flood risk management options has been undertaken as an additional task on the project. The short-listed options were agreed with Council together with a simple method of assessment to understand the potential flood management benefits of these options. The intent was to provide high level information to Council to allow consideration of whether other flood risk management measures would merit further investigation as opposed to identifying a preferred option. A combination of selected short-listed options was also considered together with the implications of VLM. The assessment is included in Appendix I of this report.

The screening assessment identified that there may be value in further assessment of the following options as alternative or complementary measures to the current OARC Scheme arrangement. All the options considered would likely enable changes to be made to the flood management scheme and land use development currently envisaged under the OARC Regeneration Plan.

- **An alternative, lower cost arrangement of flood defences, built to a lower standard and with a shorter design life.** This option might have a similar level of performance as the OARC Scheme in the short to medium term but would be less readily adapted to cater for further SLR and VLM. Rebuilding would be necessary in the future, but the option could allow a change to an alternative method of risk management at lower cost.
- **Managed retreat.** Widescale retreat is very much more costly than the OARC Scheme for a similar reduction in damages and is not considered a likely option at present. A more targeted approach might be beneficial in reducing damages at a lower cost, noting that other factors not considered in the assessment such as social impacts could influence the relative viability of this option. Retreat addresses multiple hazards in one option and reduces the exposure of multiple elements simultaneously.
- **A form of accommodate.** This is probably relatively low cost but is not as robust as the OARC Scheme, has greater residual damages and doesn't address flood impacts to elements other than buildings which become particularly significant in the long term. In the short term, where flood depths are shallow, reduction in building damages relative to costs are high.
- **A combined option of protect in the short term followed by retreat in the future.** This is a more adaptive pathway that combines short term stopbanks with ongoing managed retreat once they approach the end of their design life.

Of the other high-level options considered,

- **Planning controls alone** do not address the risk to existing properties – except through re-building – or risk to other elements so provided less benefit compared to other options.
- **Under a 'tolerate' or 'do minimum'** approach, flood impacts and damages with no new flood management measures of some form are considered unlikely to be tolerable in practice.

9. Conclusions

Stage 3 of the Christchurch multi-hazards project has used and extended the information and methodologies developed in Stages 1 and 2 of the project to understand the effects of multi-hazards on flooding in the lower Ōtākaro Avon River catchment – one of the four multi-hazard project study areas – in greater detail.

Substantial investments in flood management infrastructure are being made in this catchment as part of the Ōtākaro Avon River Corridor Regeneration Plan. Under the Regeneration Plan new flood defences will be constructed along the Ōtākaro Avon River to replace the existing stopbanks which are approaching the end of their functional life. The new flood defences will be designed to provide a 1% Annual Exceedance Probability (AEP) level of service over the lifetime of the scheme by incorporating features to allow the crest level to be raised in response to future climate change, if needed. New stormwater pumpstations will also be constructed to replace existing gravity outfalls to the river.

Stage 3 of the project has assessed the performance of this new flood management infrastructure ('the OARC Scheme') in a multi-hazard environment to quantify the benefits provided and identify if and when issues related to managing flooding or other hazards could make land use in the area benefiting from the scheme less viable in the future, so reducing the value of the investments in flood protection.

The performance of the OARC Scheme has been evaluated using a set of plausible future scenarios extending from the present day to around 2150. These scenarios were defined in Stage 2 of the project and allow for the projected effects of climate change and potential future earthquake events. The scenarios were updated in Stage 3 of the project to take account of the emerging knowledge of ongoing vertical land movement (VLM) in the project area. For each of these scenarios, flooding arising from combinations of pluvial, fluvial and tidal events, including the effects of groundwater levels, has been simulated using the Avon catchment flood model, developed in parallel with Stage 2 of the project.

The assessment is based on the best knowledge of the hazards available at the time. However, uncertainty remains in the likelihood, timing and magnitudes of these future conditions and events as well as in the underlying hazard data and the models and methods used to analyse flooding and other hazards.

Performance of the OARC Scheme

Figure 89 shows the modelled 0.5% annual exceedance probability (AEP) flood extent with and without the OARC Scheme for projected climate conditions in around 2060 and 2100 – corresponding to 0.45 m and 1.06 m sea level rise (SLR) respectively. The model results include the effects of current post-seismic rates of VLM continuing for 30 years to 2050 followed by a return to the inter-seismic rate ("VLM Scenario 2"). The existing stopbanks along the Ōtākaro Avon River are not expected to function beyond around 2030 and are therefore their effects are not included in these model scenarios.

The OARC Scheme significantly reduces the extent of future flood hazards in some parts of the Stage 3 project area but not in others. As shown in Figure 89, the OARC Scheme reduces the extent of flooding in the lower lying land alongside the Ōtākaro Avon River, particularly in the suburbs of New Brighton, Aranui, Avondale, North Linwood, Avonside and Dallington. However, the OARC Scheme has little or no effect on flooding in the higher ground outside the river corridor in suburbs such as Parklands.

These results reflect differences in flood mechanisms over the Stage 3 project area. Flooding along the river corridor is a combination of overbank flow from the Ōtākaro Avon River and ponding of pluvial runoff from the sub-catchments draining to the river. The OARC Scheme flood defences will be designed to prevent tidal and fluvial flooding from the river in a 1% AEP event and will also prevent flooding in less likely events – such as 0.5% AEP – but with reduced freeboard. The new pumpstations assist in draining pluvial runoff under high river levels and reducing the duration of flooding, but the model results indicate that **flow to the pumpstations is limited by the capacity of the stormwater drainage network and overland flow paths, such**

that without improvements to the catchment drainage networks, the impact of the new pumpstations on maximum flood levels is relatively small.

As shown in Figure 89, **the OARC Scheme alone will therefore not prevent flooding in the river corridor from all sources to the same design level of service as the new flood defences (1% AEP) due to the residual pluvial flood hazard.**

Outside the river corridor, where ground levels are higher, flooding is primarily relatively shallow, local ponding of pluvial runoff which exceeds the capacity of the stormwater drainage network. This flooding is not influenced by the water levels in the floodplain or in the river and **the OARC Scheme has no effect on flooding in the more elevated parts of the project area.**

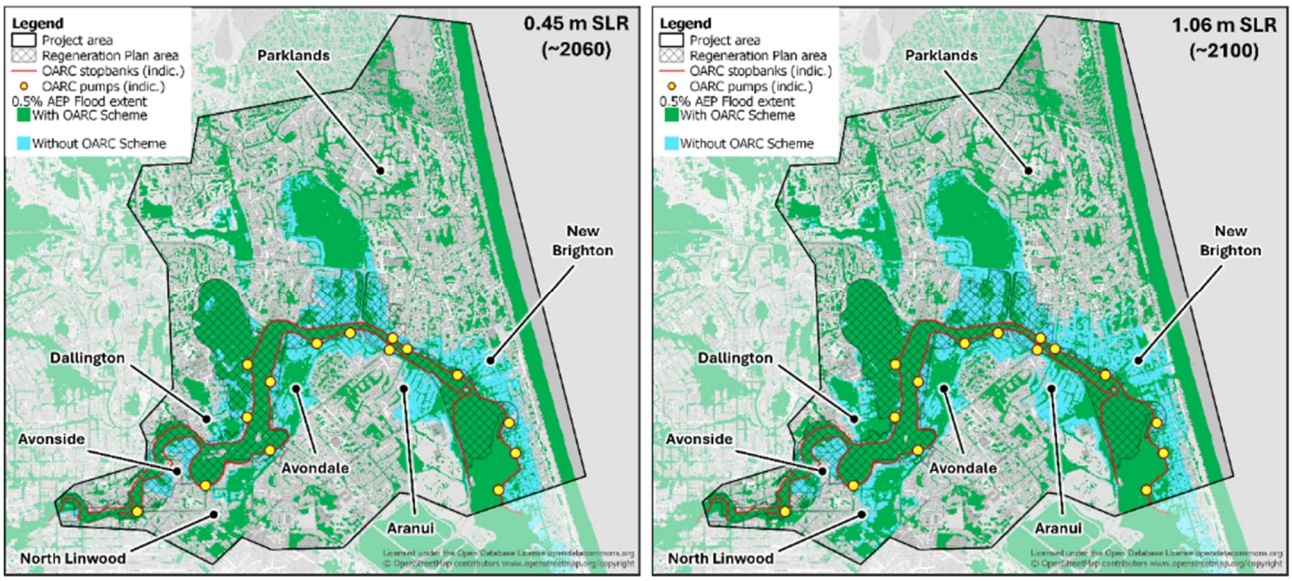


Figure 89. Extent of flooding in the Stage 3 project area with and without the OARC Scheme for 0.5% AEP with 0.45 m SLR (~2060) and 1.06 m SLR (~2100).

The OARC Scheme generally reduces the depth of flooding in the project area but increases flood levels and depths upstream and downstream of the project area. Figure 90 shows the difference between the modelled 0.5% AEP flood depths with the OARC Scheme and those without any new flood management measures together with the approximate extent of the area benefiting from the OARC Scheme in terms of a reduction in flood depth. The area benefiting from the OARC Scheme largely covers the lowest lying ground along the river corridor or in direct connectivity with it.

As shown in Figure 90, on the true right bank of the Ōtākaro Avon River and on the true left bank of the river downstream of the Anzac Drive Bridge, land use in the area benefiting from the OARC Scheme is largely residential and non-residential properties and community facilities. On the true left bank, upstream of Anzac Drive most of the area benefiting from the OARC Scheme lies within the OARC Regeneration Plan area, Travis Wetland Park, Horseshoe Lake Reserve and Clare Park and there are far fewer properties which benefit from the scheme. Depending on the nature of development within the Regeneration Plan area and the environmental consequences of more frequent flooding in the wetland areas, **there may be less value in providing flood defences along the entire length of the river on the true left bank than on the true right bank and opportunities to instead provide discontinuous flood defences and local protection from flooding while utilising wetland areas for flood storage.**

Within the new flood defences, flood depths and water levels with the OARC Scheme are higher than without the scheme due to confinement of fluvial and tidal flows within the flood defences. The design of the flood defences will allow for these water levels but the increase in water levels also extends upstream and

downstream of the new flood defences. For the scheme arrangement modelled in this assessment, this could expose additional buildings to a 0.5% AEP chance of above floor flooding – around 44 buildings in 2060 for example, compared to a reduction of above floor flooding at 2,200 buildings within the area benefitting from the OARC Scheme. **Additional flood management measures may be needed upstream and downstream of the project area to mitigate any increase in flood risk or reduce the possibility of flooding outflanking the new flood defences.**

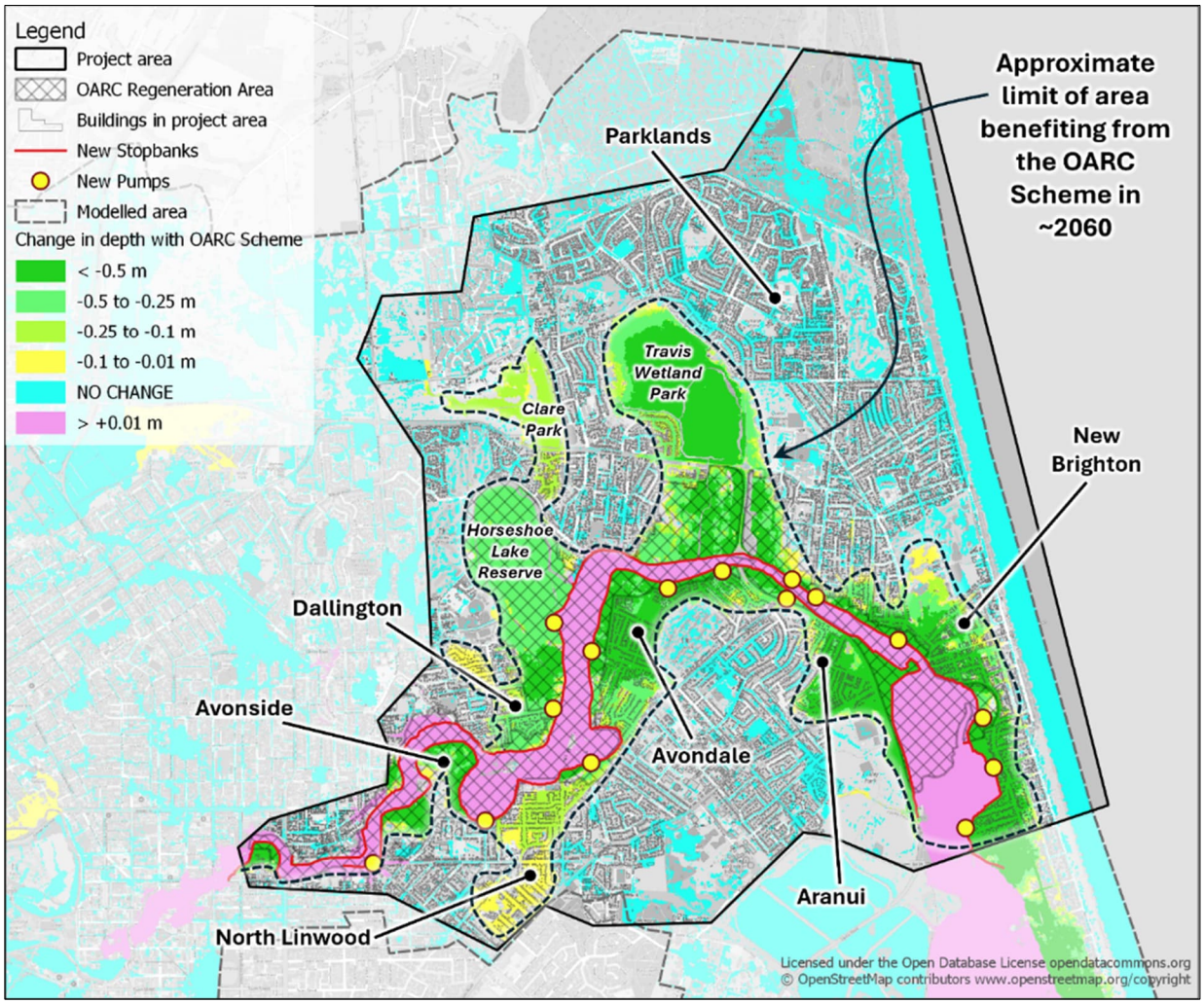


Figure 90. Change in flood depth with OARC Scheme for 0.5% AEP for 0.45 m SLR (~2060) and approximate extent of the area benefiting from the OARC Scheme.

Figure 91(a) compares the total number of buildings in the project area at risk of above floor flooding[65] and under floor flooding[66] with and without the OARC Scheme for the range of future scenarios considered by the project, referenced in terms of the rise in mean sea level. The results show that **the ORAC Scheme will substantially reduce the number of buildings in the project area at risk from deeper, above floor, flooding** – by around 63% in 2060 to 66% in 2100 for the 0.5% AEP. **Fewer buildings are protected from shallower, under floor flooding due to the residual pluvial flood hazard in the area benefiting from the OARC Scheme** – a reduction of around 23% in 2060 to 27% in 2100.

[65] model flood level within 100 mm of building floor level

[66] building footprint intersects model flood extent (50 mm minimum depth)

The financial costs of flooding in the project area have been estimated using the FloodFX damage calculation tool. Direct damages to properties are calculated using water levels from the flood model for each AEP and fragility curves for each building type. Allowances for indirect and intangible damages are included simply as fixed proportions of the direct damages. Damages for each AEP of flooding simulated (10%, 2% and 0.5%) in the scenarios are aggregated to calculate the total Annual Average Damage (AAD) from flooding in the project area for each future scenario.

Figure 91(b) compares the estimated AADs with the OARC Scheme to those without it over the range of scenarios considered together with the AAD for the OARC Scheme as a proportion of that without the scheme as a measure of the relative effectiveness of the scheme. The results indicate that **in the short-term (~10 years) the reduction in AAD with the OARC Scheme compared to the existing stopbanks is relatively small** – around 10% to 15% reduction for the whole project area. Compared to the case without stopbanks, the reduction in AAD with the OARC Scheme is more significant – around 40% to 60% in the first 10 years.

In the medium and long term (~2060 to 2100), beyond the functional life of the existing stopbanks, the reduction in AAD with the OARC Scheme is substantial – around 77% to 2060 and 87% to 2100. The total AAD from flooding in the area benefiting from the OARC Scheme amounts to around 80% to 90% of the total damage estimated for the entire project area. Within this area the OARC Scheme is estimated to reduce the total flood damage by 90% to 95%. Over this period, the damages due to pluvial flood damages increase with time since they are largely unmitigated by the scheme. These increasing damages are included in the overall damage calculations but are outweighed by the reduction in damages due to fluvial and tidal flooding from the Ōtākaro Avon River with the scheme, which increase more significantly with time.

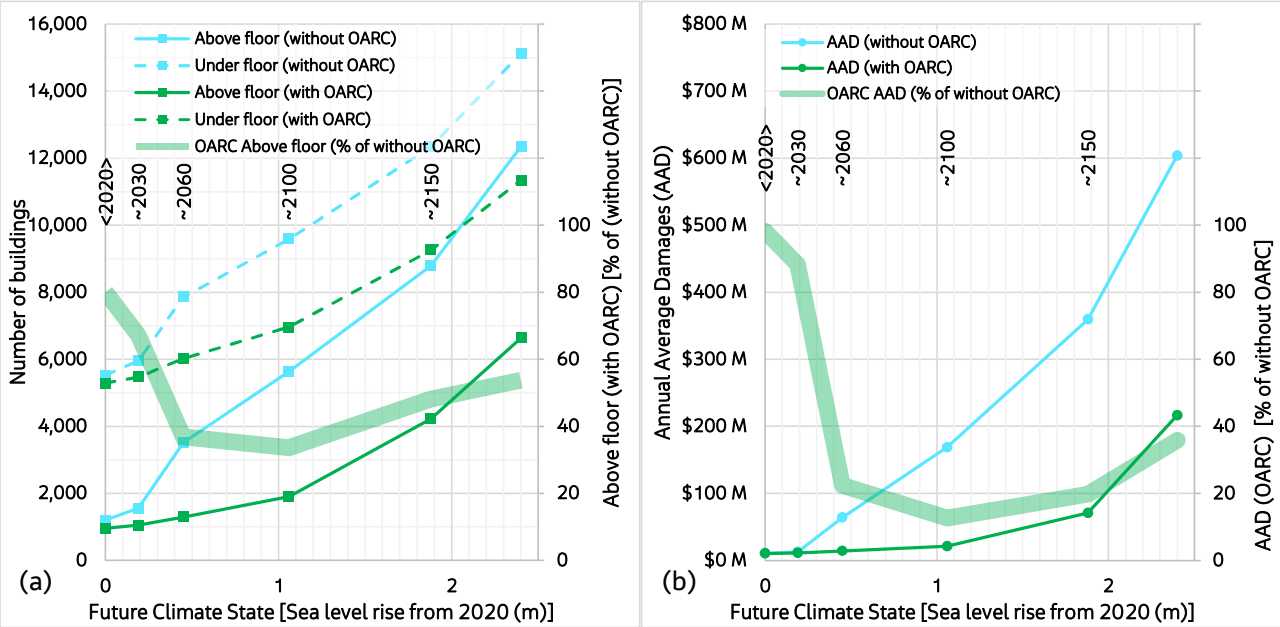


Figure 91. Effect of the OARC Scheme on (a) number of buildings affected by flooding in 0.5% AEP; and (b) Average Annual Damages, compared to a scenario without the OARC Scheme (includes existing stopbanks to ~2030 but no stopbanks beyond that time).

Further in the future, beyond 2100, the residual flood hazards with the OARC Scheme increase more rapidly and the benefits of the scheme, although still substantial, start to decline. **The relative benefits of the OARC Scheme start to reduce when SLR exceeds around 1 m, partly due to coastal inundation through the dunes along the shoreline of the project** which is likely to become significant with increasing SLR.

Although the OARC Scheme has been modelled to provide a 1% AEP level of service in all future scenarios, the lifetime of the scheme is likely to be no more than around 100 years. Depending on the amount of SLR

and other effects of climate change, it may not be feasible to manage flood risk in this way beyond this period due to the height of flood defences needed.

Indicative cumulative present values of damage from flooding, with and without the OARC Scheme, have been estimated from the AADs using a variable discount rate of 2% for the first 30 years and 1.5% thereafter and a fixed rate of 8% as a sensitivity test, as recommended by New Zealand Treasury. The present values for damages from 2020 to 2060 and 2100, the nominal lifetime of the scheme, are summarised in Table 44. The values are based on the OARC Scheme becoming operational in around 2030 at approximately the same time as the existing stopbanks reach the end of their functional life.

The cumulative cash cost of implementing the new flood defences and pumpstations is understood to be approximately $580 Million to 2060 and $690 Million to 2100 (programme level estimates, +/-50% uncertainty typically). The indicative cumulative present values of these costs are included in Table 44 based on the estimated spend profile to 2100.

As shown in Table 44, based on the method of estimating AADs from flooding and allowing for uncertainties in the timing of the scheme, **the present value of damages avoided with the OARC Scheme are likely to be greater than the present values of the costs of the scheme.** The difference between damages avoided and costs increases to 2100, reflecting the future increase in damages due to the effects of climate change and the reduction in discount rate further in the future. Although the present values of damages and costs are much lower **with a higher discount rate, the damages avoided are still likely to be greater than the costs.**

Table 44. Indicative cumulative present values of damages and costs from 2020 for the OARC Scheme.

	Cumulative Present Values (variable discount rate) $ Million		Cumulative Present Values (sensitivity test – high fixed discount rate) $ Million	
	To 2060	To 2100	To 2060	To 2100
Flood damages without OARC Scheme	990	2850	300	350
Flood damages with OARC Scheme	360	660	150	160
Damages avoided	630	2190	150	190
Costs of flood defences and pumpstations (~+/-50%)	380	420	110	110

Consequences of other hazards for the OARC Scheme

The anticipated likelihood and consequence of the cascade of non-flood hazards to fluvial and pluvial flooding within the overall multi-hazards study area was assessed in Stage 1 of the project. The cascade assessment has been updated in Stage 3 to include any new or additional information and consider the consequences of cascading hazards specifically within the Stage 3 project area of the lower Ōtākaro Avon River.

The hazard cascades with the highest consequences for fluvial and pluvial flooding in the project area, including the area benefiting from the OARC Scheme, are:

- Future coastal erosion (due to sea level rise)
- Future coastal inundation (due to sea level rise)
- Future high groundwater levels (due to sea level rise)
- Earthquake (Local, Regional, Distant Alpine Fault)
- Vertical land movement (VLM)
- Distant source tsunami

Future coastal erosion and inundation

Widespread inundation from the sea long the coastline of the project area is unlikely for SLR of less than around 1 m given present day ground levels along the coast and allowing for VLM. Erosion of the dune ridge along the coastline with SLR is considered likely and would tend to increase the likelihood of inundation in storm events. However, this is not considered likely to be significant until SLR exceeds around 0.6 m to 1.2 m. Given current projections of SLR, this means that **coastal inundation is unlikely to pose a significant hazard to the project area or the area benefiting from the OARC Scheme over its expected lifetime**. Further into the future, coastal inundation is likely to become a more important source of flood risk to the project area and an important consideration in future flood risk management.

Future high groundwater levels

Present day groundwater levels are relatively shallow within the project area, particularly in the lower lying land in the area benefiting from the OARC Scheme. Groundwater levels are expected to rise with SLR and are very likely to reach levels where some form of hazard management is needed in some locations for current land use to remain viable. Figure 92 shows the locations of buildings within the area benefiting from the OARC Scheme for which the groundwater and surface water "response indicators" developed in Stage 3 of the project (Project Response Indicators or PRIs) are exceeded in approximately 2060. The groundwater PRIs are defined by the 85th percentile groundwater levels so they could be expected to be exceeded at least 15% of the time. Mapping of PRI exceedances for other aspects of land use – such as roads – shows that these often coincide with PRI exceedances for buildings.

Within the area benefiting from the OARC Scheme, groundwater hazard PRIs for buildings are very likely to be exceeded for around 25% of the buildings by 2060 and around 42% of buildings by 2100.

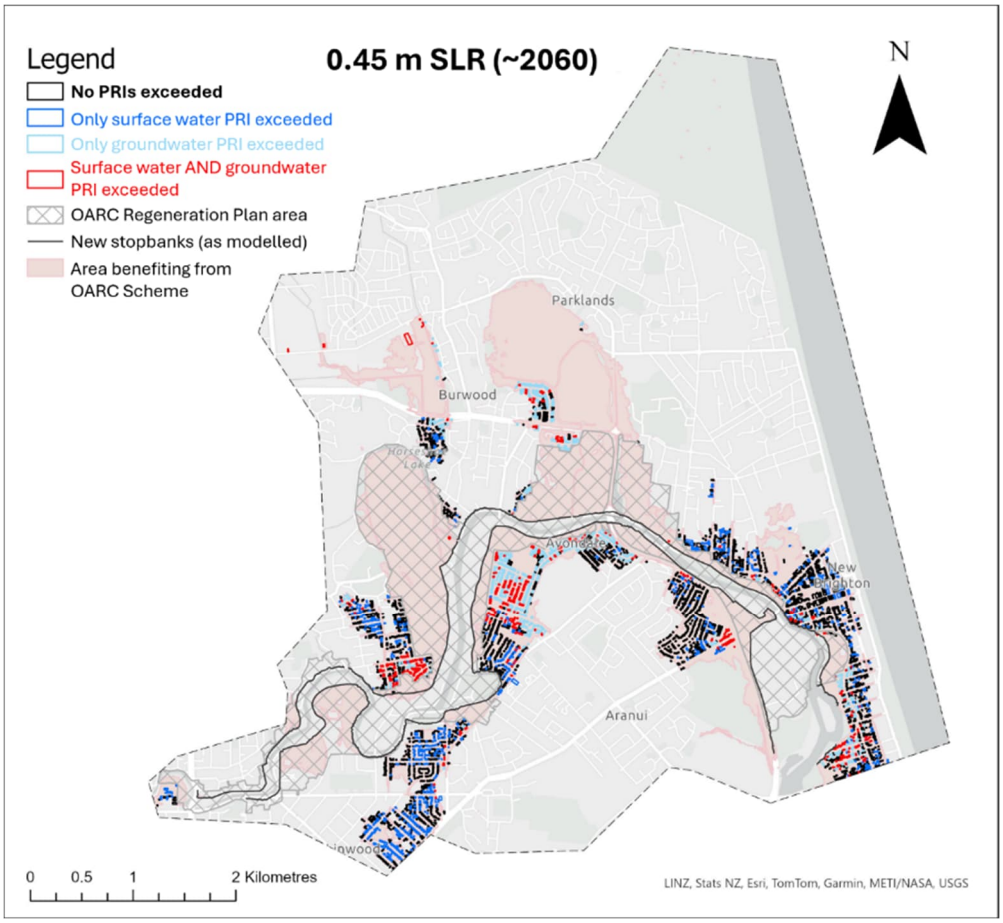


Figure 92. Buildings within the area benefiting from the OARC Scheme for which groundwater or surface water PRIs are exceeded with the OARC Scheme for 0.45 m SLR (~2060).

Without a response to groundwater, it is likely that land use in some parts of the area benefiting from a reduction in flooding from the OARC Scheme will become unviable. The feasibility and costs of managing groundwater levels in these areas are uncertain. Indicative cash costs for one approach to controlling groundwater levels – through pumping – are estimated to be in the order of $130 to $300 Million in 2060, rising to over $600 Million by 2100 (excluding operating costs). The cost of managing groundwater hazards could therefore be comparable to, or potentially even greater than, the cost of the new flood defences and stormwater pumpstations.

Financial damages from chronic groundwater hazards, which will occur with or without the OARC Scheme, have not been evaluated and further assessment is needed to understand these effects together with the feasibility, costs and benefits of managing groundwater hazards alongside flood hazards. As an initial assessment of the effect of groundwater hazards relative to the benefits of the OARC Scheme, Table 45 compares the flood damages avoided with the OARC Scheme (presented in Table 44) to the corresponding values if any benefits to buildings where the groundwater PRIs are exceeded are excluded. The results show that the total present value damages avoided with to the OARC Scheme is reduced by around 40% in 2060 and by around 60% in 2100. This reflects the fact that the buildings exposed to the largest flood depths, and which therefore benefit most from the OARC Scheme, tend to be in areas susceptible to the shallowest groundwater and so contribute disproportionately to the benefits of the scheme. In 2060 the reduced benefit of the scheme is however comparable to the cost of the new flood defences and in 2100 the reduced benefit is approximately double the costs. **This suggests that the OARC Scheme is still likely to be beneficial overall even if properties affected by residual groundwater hazards are excluded, particularly in the longer term when flood damages without the scheme become substantial.**

The PRI exceedance maps show that PRIs for other elements of land use which are needed to access or provide essential services to buildings, such as roads, are often exceeded in the same areas as buildings. However, some of these elements may also be affected by groundwater in areas where building PRIs are not exceeded, so indirectly impacting on their use and reducing the value of the OARC Scheme in reducing flood damages to the buildings.

Table 45. Effect of excluding buildings where groundwater PRIs are exceeded on flood damages avoided through the OARC Scheme (variable discount rate applied to calculate present values).

			2060	2100
Annual average damages ($ Million)	All buildings	without OARC Scheme	64	169
		with OARC Scheme	14	21
	Excluding buildings in area benefitting where groundwater PRIs exceeded	without OARC Scheme	34	51
		with OARC Scheme	11	15
Cumulative present values from 2020[67] ($ Million)	All buildings	without OARC Scheme	990	2850
		with OARC Scheme	360	660
		Damages avoided	630	2190
	Excluding buildings in area benefitting where groundwater PRIs exceeded	without OARC Scheme	710	1410
		with OARC Scheme	340	560
		Damages avoided	370	850
	Costs of flood defences and pumpstations (~+/-50%)		380	420

Earthquake

The likelihood of an earthquake within the lifetime of the OARC Scheme is relatively high – an earthquake resulting from rupture of the Alpine Fault, has been estimated to be at least 75%, for example. It is hard to predict the effects of earthquakes from the different possible sources (local, regional, distant Alpine Fault). **However, it is expected that an earthquake will cause widespread land settlement over the project area and increase the rate of ongoing VLM, resulting in additional future land settlement.**

The new flood defences and other components of the OARC Scheme will be designed to meet appropriate earthquake resilience standards but **damage to the infrastructure from an earthquake is likely, with lateral spreading posing the greatest risk. The proposed alignment of the new flood defences intersect areas of higher lateral spreading risk in some locations.**

Land surface changes from future earthquakes will not necessarily increase the extents of fluvial flooding markedly but are likely to increase depths of flooding and redistribute flooding according to spatial variations in settlement.

Damages from future flooding with a lowered ground surface following an earthquake are likely to be significantly higher than for present day ground levels - estimated to be approximately double. Provided that the new flood defences are repaired and restored to design level where needed prior to any future flood events, **the OARC Scheme has the potential to provide additional benefits following an earthquake in terms of avoiding the increase in damages from fluvial flooding due to ground settlement over the project area, assuming that existing land use continues after such an event.**

The damage caused by an earthquake to the stormwater drainage network may require significant investment over many years to restore the level of service for pluvial flooding such that **the residual risk and damages**

[67] Present values are calculated on the basis that the OARC Scheme becomes operational in around 2030 at approximately the same time as the existing stopbanks reach the end of their functional life.

from pluvial flooding in the area benefiting from the OARC Scheme are likely to increase following an earthquake.

There is a wider risk that areas benefiting from a reduction in flood risk from the OARC Scheme may be abandoned due to the damage caused by an earthquake, so reducing the potential benefits of the scheme relative to the cost. Table 44 shows that the estimated present value of the cumulative flood damages avoided to 2060 are greater than the estimated present value costs of the OARC Scheme that time based on the climate change scenario adopted in the damages assessment. This suggests that **the cost of investment in flood protection could be offset by the damages avoided within a few decades, depending on the programme of construction and the rate of climate change effects. The likelihood of an earthquake occurring before the benefits of the investment outweigh the costs is therefore less than the likelihood of an earthquake occurring over the full lifetime of the Scheme.**

Settlement of the ground surface as a result of an earthquake and the subsequent increased rate of ongoing VLM will reduce the depth to groundwater, increasing the extent of PRI exceedances, the area over which some form of management measures may be needed and the costs of these measures, assuming that existing land use continues following an earthquake. **For the example method of pumping, the costs of managing groundwater within the area benefiting from the OARC Scheme could increase by around 30% as a result of earthquake-induced land settlement.**

Vertical land movement (VLM)

The effects of VLM on flooding have been explicitly included in the flood model scenarios which show that **the projected future lowering of ground levels has little effect on the extents of flooding but generally increases the depths of flooding and hence flood damages, particularly without the OARC Scheme in place.**

Provided the new OARC Scheme flood defence crest levels include allowance for VLM, the effect of VLM on flooding in the area benefiting from the OARC Scheme is generally small and flood damages are not significantly increased.

VLM does not have a significant effect on the distribution of exceedance of PRIs for residual flood hazard, but **VLM increases the exceedances of groundwater hazard PRIs and the corresponding potential extent and costs of groundwater management measures that may be needed, particularly further into the future (2100).**

VLM has little effect on the risk of coastal inundation to the area benefiting from the OARC Scheme for the range of scenarios considered.

Tsunami

Distant source tsunami pose a greater hazard (larger wave height) to the project area than local source tsunami for a given probability of occurrence. Modelling of large distant source tsunami undertaken in Stage 2 of the project indicates that even under present-day sea level, **tsunami inundation from the coastline at New Brighton and North New Brighton is likely to reach the area benefiting from the OARC Scheme and the resulting water levels in the Ōtākaro Avon River downstream of Anzac Drive are likely to overtop the new flood defences. The OARC Scheme is therefore unlikely to provide protection from a large distant source tsunami.** The new, higher, flood defences also have the potential to impound tsunami inundation in the floodplain following an event to a deeper depth and for longer than the existing stopbanks.

Tsunami have the potential to damage the new flood defences and other infrastructure along the Ōtākaro Avon River, especially in the lower reach, which could lead to breaching and uncontrolled inundation. This

would require repairs to the OARC Scheme and therefore additional costs. **Depending on the severity of tsunami damage and how quickly it could be repaired, the area benefiting from the OARC Scheme could be exposed to increased risk of flooding following a tsunami.**

In the long term (e.g., to 2100), the additional cost of reinstating the OARC Scheme following a tsunami – even if at full replacement cost – is unlikely to exceed the benefits of doing so in terms of reduced flood damages (Table 44). In the short to medium term (e.g., to 2060) this may not be the case. However, the likelihood of a distant source tsunami of the probabilities modelled (0.04% AEP and 0.2% AEP) occurring during the lifetime of the OARC Scheme is relatively low (1% and 6% to 2060, 3% and 13% to 2100) compared to that of a 0.5% AEP flood (14% to 2060, 30% to 2100), for example.

Summary

Without new flood risk management measures, the number of buildings in the project area at risk of above floor flooding in a 0.5% AEP event is estimated to increase from around 1,200 at the present to around 3,500 in 2060 and 5,600 by 2100. The cumulative present value of damage from flooding is estimated to reach almost $1 Billion by 2060 and nearly $3 Billion by 2100. Land settlement from an earthquake could increase the present value of flood damages by the order of 50% by 2100.

The OARC Scheme will significantly reduce the number of properties at risk of above floor flooding (estimated to be by around 2,200 in 2060 and 3,700 in 2100 for the 0.5% AEP) and the cumulative damage from flooding (estimated to be by around $600 Million to 2060 and around $2 Billion to 2100). Present value costs of the flood defences and pumpstation components of the OARC Scheme are estimated to be around $380 Million to 2060 and $420 Million to 2100.

The OARC Scheme will provide a high standard of protection (1% AEP or better) from fluvial and tidal flooding from the Ōtākaro Avon River but will not provide the same level of protection from the residual pluvial flooding in the river corridor. "Project response indicators" for surface water flooding are estimated to exceed for around 30% of the buildings within the area benefiting from the OARC Scheme by 2100. Elsewhere in the project area, outside the area benefiting from the OARC Scheme, around 900 buildings are estimated to be at risk of above floor flooding to 2100.

The area benefiting from the OARC Scheme is potentially susceptible to coastal inundation, groundwater hazards, earthquakes, vertical land movement and tsunami.

The dunes along the coastline of the project area currently protect large areas of lower lying land from direct inundation by the sea such that coastal inundation is unlikely to significantly contribute to flooding in the area benefiting from the OARC Scheme over its expected lifetime (to around 2100). Erosion of the dunes could increase the likelihood of inundation and Council should consider measures to maintain the health, function and height of the dunes with the community given their importance as a defence against inundation under rising sea level.

Rise in groundwater levels through sea level rise is an emerging hazard, physically and in terms of public awareness, across New Zealand, including in Christchurch. Project response indicators for groundwater hazards are very likely to be exceeded for around 25% of the buildings in the area benefiting from the OARC Scheme by 2060 and around 42% of buildings by 2100.

To date, Christchurch City Council have not needed to develop adaptation approaches or solutions for widescale groundwater hazards. The OARC Scheme provides no protection from groundwater hazards. Sea level rise and a lowering of land ground levels due to VLM will increase the hazard posed by groundwater. The feasibility of controlling groundwater levels through pumped drainage, for example, is uncertain and capital costs could be comparable to, or potentially even greater than, the cost of the new flood defences and stormwater pumpstations.

Given this hazard will impact not only the area benefiting from the OARC scheme but also more widely over the project area and other parts of the city, it is recommended that Council start to consider how they and the community could respond to the changing hazard and start to gather monitoring data on whether high groundwater levels are impacting specific assets. This information could include correlating reports of damp or mouldy houses to areas in which high groundwater levels are predicted or rates of inflow to wastewater pipes. This information could assist Council and the community assess tolerance of this hazard and adaptation approaches.

An earthquake is considered likely over the lifetime of the scheme and, depending on the damages incurred to the OARC Scheme, could result in substantial repair costs to restore the design level of service. If existing land use was to continue following an earthquake, flood damages without the OARC Scheme are expected to increase substantially due to earthquake-induced ground settlement and it is likely that the additional flood damages avoided through restoring the serviceability of the OARC Scheme would exceed the costs of doing so. However, this excludes the costs, and additional damages from pluvial events, that would result from damage to the stormwater drainage network.

Provided the new OARC Scheme flood defence crest levels include allowance for future vertical land movement, the effect of VLM on flooding in the area benefiting from the OARC Scheme is generally small and flood damages are not significantly increased.

Most of the area benefiting from the OARC Scheme is susceptible to tsunami inundation. The OARC Scheme is not expected to provide protection from such an event and it is important that communities in tsunami hazard zones in the area benefiting from the OARC Scheme understand this and are aware of the continued need to evacuate under current procedures. Although a large tsunami is considered unlikely to occur over the lifetime of the OARC Scheme, it could result in extensive damages and the need for substantial repairs to the OARC Scheme. In common with other authorities, Council has not historically sought to protect land use from tsunami and risk management has been through evacuation and civil defence response. The OARC Scheme is not likely to reduce the flood damages caused by a tsunami and could potentially impound flood water behind the new flood defences. As for an earthquake event, it is likely that the benefits of restoring the design level of service, in terms of the future flood damages avoided, would exceed the costs of repairs (excluding impacts on the stormwater drainage network), if existing land use was to continue following a tsunami.

Recommendations

1. The Multi-Hazards study has considered how a range of hazards can impact flood management in the lower Ōtākaro Avon River. To further develop councils understanding of these hazards and their potential management options, the following recommendations are made within the report and summarised here: The area benefiting from the OARC Scheme is exposed to other natural hazards. These are principally residual pluvial and fluvial flooding from local drainage catchments, shallow groundwater, earthquakes and tsunami. The direct effects of these are not mitigated by the OARC Scheme. These other hazards may affect the performance of the OARC Scheme or the value of providing protection from river flooding to areas where the residual risk from other hazards is significant. These factors should be considered by Council when making decisions on the planned flood protection investment.

2. The communities in the area benefiting from protection from river flooding should be made aware that the flood defences will not provide protection from tsunami and that civil defence managed evacuation remains the primary means for managing this hazard.

3. A future tsunami has the potential to effect bridges and flood management infrastructure, however there are opportunities to improve tsunami resilience. Further investigations are required to assess these effects in more detail and identify any design activities required to mitigate these risks.

4. Direct long-term monitoring of groundwater levels within areas where PRIs are predicted to be exceeded over time would be valuable to understand the trends in changing groundwater levels over time. This can inform the community on how the hazard itself is changing over time and when PRIs may be approached. This monitoring however does not provide information on whether the impacts of the changing hazard are occurring. Future ATs may be more likely to be based on changing impacts rather than just the changing hazard. For example: functionality of the stormwater system or cost to maintain that functionality rather than just its exposure to groundwater. Therefore, monitoring of impacts on assets should also be considered. Possible examples of monitoring of impacts to wastewater, stormwater, buildings and road assets is provided in section 6.6.

5. Recommendations for monitoring of changing flood hazard impacts on assets are also provided.

6. The seismic hazards identified could impact the stopbanks in future earthquake. For the flood modelling analysed it has been taken that any damage to stopbanks following an earthquake would be repaired prior to any flood events occurring, noting that repairs may take some time to complete. Even if this is achieved, flood risk to properties in the area benefiting from the OARC Scheme would be increased due to wider land subsidence in the lower Ōtākaro Avon River catchment. This report provides an indication of the types and extent of damage that may need to be repaired with some comments on how the risk of damage could be reduced through design. Although the focus is on the risks to the stopbanks, the new stormwater pumpstations, which, in general, are expected to be located close to the stopbanks, will also be vulnerable to seismic hazards and the design of these elements of the OARC Scheme will also need to allow for these hazards.

7. Future earthquakes are likely to damage flood infrastructure, primarily through lateral spreading. The proposed alignment of the new stopbanks intersects areas of higher lateral spreading risk in some locations and there could be value in considering alternative alignments.

8. Within this project we have specifically considered how a future earthquake shock hazard can modify the land surface and thus flood risk. This has then been included as a scenario within the analysis of when and where PRIs may be exceeded. What has not explicitly been considered is how the potential impacts on the areas benefitting from the OARC flood risk management infrastructure in an earthquake or other shock hazard may influence decision making about the exceedance of PRI's, adaptation decisions or repair of existing flood protection infrastructure. It is anticipated that in any major shock event the previously preferred response pathway will likely need to be revisited to see if the proposed OARC flood protection infrastructure pathway is still the most viable response.

9. There is a risk of coastal inundation to the area benefiting from the OARC Scheme in the longer term. The dunes provide benefits in protecting these areas from flooding at present. Hence, we would recommend that Council:

    a. Seek to maintain or improve the protection benefits provided by the dunes over the longer term.

    b. Work with the community through adaptation planning to discuss the importance of the benefits which the dunes provide and develop a preferred way for the dunes to adapt to sea level rise. This may for instance include modifying land use to allow for migration of the dunes and reduce erosion impacts on elevations.

    c. In future, hydrodynamic modelling of the lower Avon catchment consider explicitly modelling the potential inundation route from the open ocean using alternative dune profiles in higher sea level rise scenarios. This would help clarify the volumes of water that could inundate via this route and where it could flood. This can then be considered in adaptation planning with the community.

10. The alternative flood management screening assessment identified that there may be value in further assessment of the following options as alternative or complementary measures to the current OARC Scheme arrangement. All the options considered would likely enable changes to be made to the flood management scheme and land use development currently envisaged under the OARC Regeneration Plan.
    a. An alternative, lower cost arrangement of flood defences, built to a lower standard and with a shorter design life.
    b. Managed retreat.
    c. A form of accommodate.
    d. A combined option of protect in the short term followed by retreat in the future.
11. On the true left bank, upstream of Anzac Drive most of the area benefiting from the OARC Scheme lies within the OARC Regeneration Plan area, Travis Wetland Park, Horseshoe Lake Reserve and Clare Park and there are far fewer properties which benefit from the scheme. Depending on the nature of development within the Regeneration Plan area and the environmental consequences of more frequent flooding in the wetland areas, there may be less value in providing flood defences along the entire length of the river on the true left bank than on the true right bank and opportunities to instead provide discontinuous flood defences and local protection from flooding while utilising wetland areas for flood storage.
12. Without a response to groundwater, it is likely that land use in some parts of the area benefiting from a reduction in flooding from the OARC Scheme will become unviable. The feasibility and costs of managing groundwater levels in these areas are uncertain. Financial damages from chronic groundwater hazards, which will occur with or without the OARC Scheme, have not been evaluated and further assessment is needed to understand these effects together with the feasibility, costs and benefits of managing groundwater hazards alongside flood hazards.
13. While it may be possible to manage the effect of shallow groundwater on buildings within the area benefiting from the OARC Scheme, through pumped drainage for example, such a solution could have other effects including changes in the salinity of groundwater which would need to be investigated further. The feasibility of obtaining planning consent for such a method of managing groundwater also needs to be investigated since it may not be provided for under current planning policies.
14. To date, Christchurch City Council have not needed to develop adaptation approaches or solutions for widescale groundwater hazards. The OARC Scheme provides no protection from groundwater hazards. Sea level rise and a lowering of land ground levels due to VLM will increase the hazard posed by groundwater. Responding to groundwater hazards to maintain current land uses in the area benefiting from the OARC Scheme could amount to the order of $300 Million by 2060 and $500 Million by 2100 in terms of present value costs. Given this hazard will impact not only the area benefiting from the OARC scheme but also more widely over the project area and other parts of the city, it is recommended that Council start to consider how they and the community could respond to the changing hazard and start to gather monitoring data on whether high groundwater levels are impacting specific assets. This information could include correlating reports of damp or mouldy houses to areas in which high groundwater levels are predicted or rates of inflow to wastewater pipes.
15. New research conducted since the completion of the multi-hazards project in relation to groundwater in the project area should be reviewed. Updated groundwater modelling of future SLR scenarios,

building on the work of Weir et al (2023)[68], should be considered. The findings of ongoing and future studies and broader research on land drainage should also be reviewed and considered in assessing this hazard and developing management solutions. Collectively this information could assist Council and the community assess tolerance of this hazard and adaptation approaches.

[68] Weir, J; Rutter, H; Dudley Ward, N; Hatley, G. (2023): APP Network - Data Analysis Update. Christchurch City Council. Aqualinc Research Ltd.

Appendix A. Analysis of baseline flood modelling memo

Analysis of baseline flood model results

Date:	18 January 2024
Project name:	LDRP97 Multi Hazards Stage 3
Project no:	IZ084400
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Document no:	IZ084400-NW-MEM-0007
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1. Background

Stage 3 of the Christchurch Multi Hazards project examines the flood hazards in the Ōtākaro Avon catchment over a range of future scenarios. The future scenarios take account of the effects of the new flood management measures which have been agreed for the lower Ōtākaro Avon catchment – setback stopbanks and stormwater pumping – as part of the Ōtākaro Avon River Corridor (OARC) Regeneration Plan.

To assess flood hazards, the assessment makes use of the new Avon City Wide Model ('Avon CWM'), a detailed flood model of the Avon catchment. Results of simulations of flooding in the catchment with the current flood management infrastructure are available for the 13 scenarios listed in Table 1.

An initial review of these model results for scenarios with the current infrastructure was presented in the document IZ084400-NW-RPT-0003 Stage 1 and 2 Summary Report (15/11/2022).

Table 1. Modelled scenarios for the Ōtākaro Avon River catchment.

Sea level rise and indicative timing	Land settlement from earthquake	Existing Temporary Stopbanks	Groundwater levels	Scenario No.
0 m (2020)	no	Up	85th percentile	1
	no	Down	85th percentile	2
0.19 m (2030)	no	Up	85th percentile	3
	no	Down	85th percentile	4
0.45 m (2060)	no	Up	85th percentile	5
	no	Down	85th percentile	6
	yes	Up	85th percentile	7
	yes	Down	85th percentile	8
1.06 m (2100)	no	Down	85th percentile	9
	yes	Down	85th percentile	10
	no	Down	50th percentile	11
1.88 m (2150)	no	Down	85th percentile	12
2.4 m (>2150)	no	Down	85th percentile	13

In Task 1 of Stage 3 of the project we have undertaken further analysis of these baseline model results and this memorandum presents the results of these analyses as follows:

- Provide further understanding of the current flood mechanisms to inform subsequent tasks.
  - We have assessed the magnitudes of modelled flood velocity in the Ōtākaro Avon catchment to understand whether velocities are likely to be high enough, as defined by the hazard rating method of the Australian Rainfall and Runoff (AR&R) Guideline[1], over a sufficient extent to warrant consideration as an additional factor in determining flood hazards, rather than using water depth alone, for simplicity of analysis.
  - For 18 of the baseline scenarios (one for each epoch and AEP), we have quantified the total area falling under each hazard rating as an additional metric for assessing flooding and the performance of protection measures.
  - We have assessed the influence of preceding and successive storm tides on flooding in the catchment to understand whether there is any significant accumulation of flood water from one tide to the next and therefore whether sufficient tidal cycles are included in the model simulations to accurately estimate maximum flood levels.
- Provide a quantitative assessment of the effects of flooding for the current flood infrastructure in terms of financial damages for comparison with new flood protection options.

  We have calculated the number of properties flooded and financial flood damages using the FloodFX[2] tool. This allows a quantitative assessment of the effects of flooding under different scenarios using financial metrics – estimated Annual Average Damage (AAD) for individual model scenarios and Present Value Damages for a set of potential future scenarios of climate change and earthquake-induced land settlement.

  It is important to note that the purpose of this damage assessment is to enable a comparison of the relative performance – e.g., 'better' or 'worse' – of the existing flood protection measures and the agreed new measures in the future scenarios simulated with the flood model to be made within the Multi Hazards project. The results of the damage calculations are sensitive to the method and parameter values adopted for several key aspects of flood damage in the FloodFX tool. The approach adopted in the tool is based on comprehensive research undertaken at the time of its development. However, it is acknowledged that considerable uncertainty remains in some aspects of the calculations and some of the values adopted are subject to change for economic reasons. These limitations must be recognised should the results be considered for use in any other purpose.

  In particular, we note that:

  - In the short term, underfloor damages comprise a large proportion of the direct flood damages. This reflects the general nature of flooding outside the area of the OARC Regeneration Plan, i.e., extensive but relatively shallow flooding affecting a large number of properties but with a smaller proportion experiencing above floor flooding, particularly for higher probability events (e.g., 10% AEP) which are significant for the AAD calculation. These underfloor damages are calculated in a simple way in FloodFX and there is uncertainty in the current costs of such damages.
  - Intangible damage values represent a large proportion of the total damages – approximately 50% – but there is considerable uncertainty in the valuation of this component of damage. Since these damage values are calculated as a proportion of the direct damages, uncertainty in the underfloor damages is further escalated through the intangible damage calculation.
  - The Riskscape fragility curves used to calculate damage to individual buildings are capped to the value of the property. However, as agreed with Council, we have not capped Present Value damages

[1] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

[2] FloodFX is a Christchurch City Council tool (developed by Jacobs) that identifies impact of flooding on building assets. It utilizes flood modelling outputs and a database of house floor levels and types to identify properties at risk of flooding and estimate damages (based on intangible and tangible factors).

to properties. This allows for buildings to be repeatedly repaired or re-built after multiple flood events which might be unrealistic. Whilst we have not assessed the effect of capping present value damages of individual properties, an initial review of average property damages suggests the extent to which damages would be capped may be limited, reflecting the generally shallow, though extensive, nature of flooding in the near future. It should be noted that further intensification within the project area is not allowed for within the assessment. This may to some degree counterbalance the effect of Present Value damages to properties being uncapped.

We recommend that the sensitivity of the results to these factors, and the corresponding outcomes, are considered further if the data or method are to be used for any other purposes.

- Assess the sensitivity of flooding to the choice of statistical frequency of groundwater levels.

  Results of model simulations using the 50th percentile groundwater surface instead of the 85th percentile surface adopted for the study show that the differences in maximum flood depths is very small – generally less than 10 mm to 50 mm – for the scenario tested (1.06 m sea level rise without any earthquake subsidence). As a result, the difference in total number of properties affected by flooding is very small, 0.1% to 0.7% depending on the AEP. The difference in overall Annual Average Damages for this scenario due to the difference in groundwater surfaces is also very small (0.5%). These results justify use of a single groundwater surface frequency for the assessment and indicate that the 50th percentile simulations could be excluded from the simulations of flooding with the OARC Scheme.

2. Flood hazards and flood mechanisms

2.1 Flood hazard

2.1.1 Effect of velocity of flood water

In Stage 3 of the Multi Hazards project, the impacts of flooding are quantified primarly through reference to the depths of flood water in each of the scenarios considered:

- The FloodFX tool calculates the number of flooded properties and financial cost of flood damage to properties using modelled water depths.
- The performance of flood management measures in relation to other effects of flooding – for example, public safety or access to properties – is assessed relative to performance thresholds of water depths, as developed under Task 2 of the project and detailed in the project memorandum for Task 2[3].

It may be of value to the project to also consider flood hazard as an additional metric of the impact of flooding. Flood hazard is generally recognised to depend not only on the depth of water but also, primarily, on the velocity of the water, together with other factors such as debris load.

The AR&R Guideline (Book 6, Chapter 7) provides a suggested combined set of hazard vulnerability curves, shown in Figure 1, which can be used as a general method for classifying flood hazard on a floodplain. Six classes of hazard vulnerability are defined by the curves through relationships of water depth and velocity. The curves reference thresholds to the safety of people, vehicles and buildings derived from scientific studies.

The raw baseline model results, comprising 186 individual simulations covering a range of storm durations, three annual exceedance probabiities (AEP), six climate change scenarios, two flood defence scenarios and two earthquake scenarios have previously been processed to produce 'maximum of maximum' water depth grids for each AEP and each scenario. Although raw time varying water velocity vector results are available for each individual simulation, without re-running the models considerable processing would be need to derive time varying scalar velocities and combine these with time varying depth to determine the time varying and

[3] Initial Project Response Indicators for Groundwater and Flood Hazards (IZ084400-NW-MEM-0006 – Final, 20 December 2023)

hence maximum flood hazard for each individual storm duration and hence maximum hazard grids for each AEP and climate change scenario.

Given the large number of scenarios, size of datsets involved and the nature of flooding in the catchment – generally slower moving water outside the main watercourses – we have inspected sample baseline model results to assess whether modelled velocities need to be considered in addition to water depth to quantify the flood hazard for assessing the performance of flood management measures or whether, instead a simpler approach, using the available maximum depth grids can be used to quantify hazard.

It can be seen from Figure 1 that the classification of hazard in the AR&R Guideline method depends only on water depth if the velocity is less than 0.5 m/s. For shallower depths of flooding, less than 0.5 m, the hazard classification is independent of velocity for velocities less then 1.0 m/s.

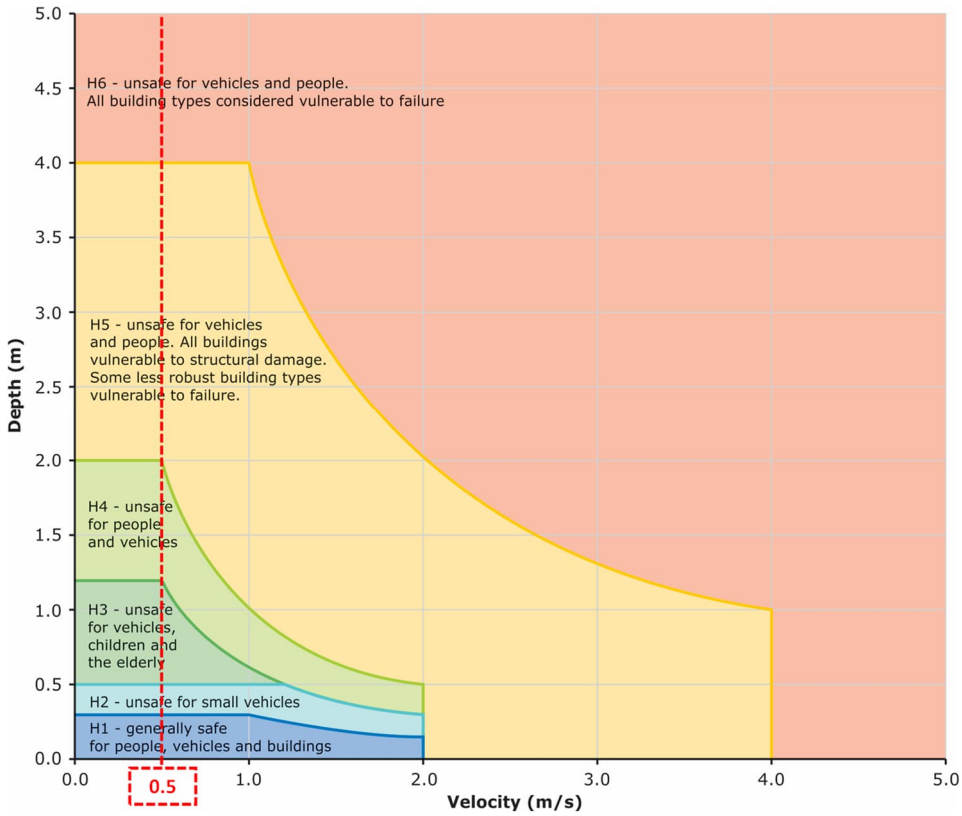

Figure 1. Combined flood hazard curves for safety and stability thresholds of people, vehicles, and buildings (Figure 6.7.9 of the AR&R Guidelines)

We have used the baseline Avon CWM model results to derive indicative maximum velocity values over the model flood extents. The values are indicative because the raw model results provide instantaneous values of the orthogonal components of velocity rather than the total velocity, or speed of flow, over the period simulated. For our assessment we have calculated maximum total velocity values by from the vector product of the maximum values of the orthogonal components. Since these may not occur simultaneously, the calculated values will tend to overestimate total velocity.

The indicative maximum model velocities for two magnitudes of tidally dominated flooding – 2% and 0.5% AEP – and for two scenarios – 'present day' or '2020', and with 0.45 m of sea level rise, nominally '2060', both with the existing flood management infrastructure in place – are mapped in Figure 2 and Figure 3.

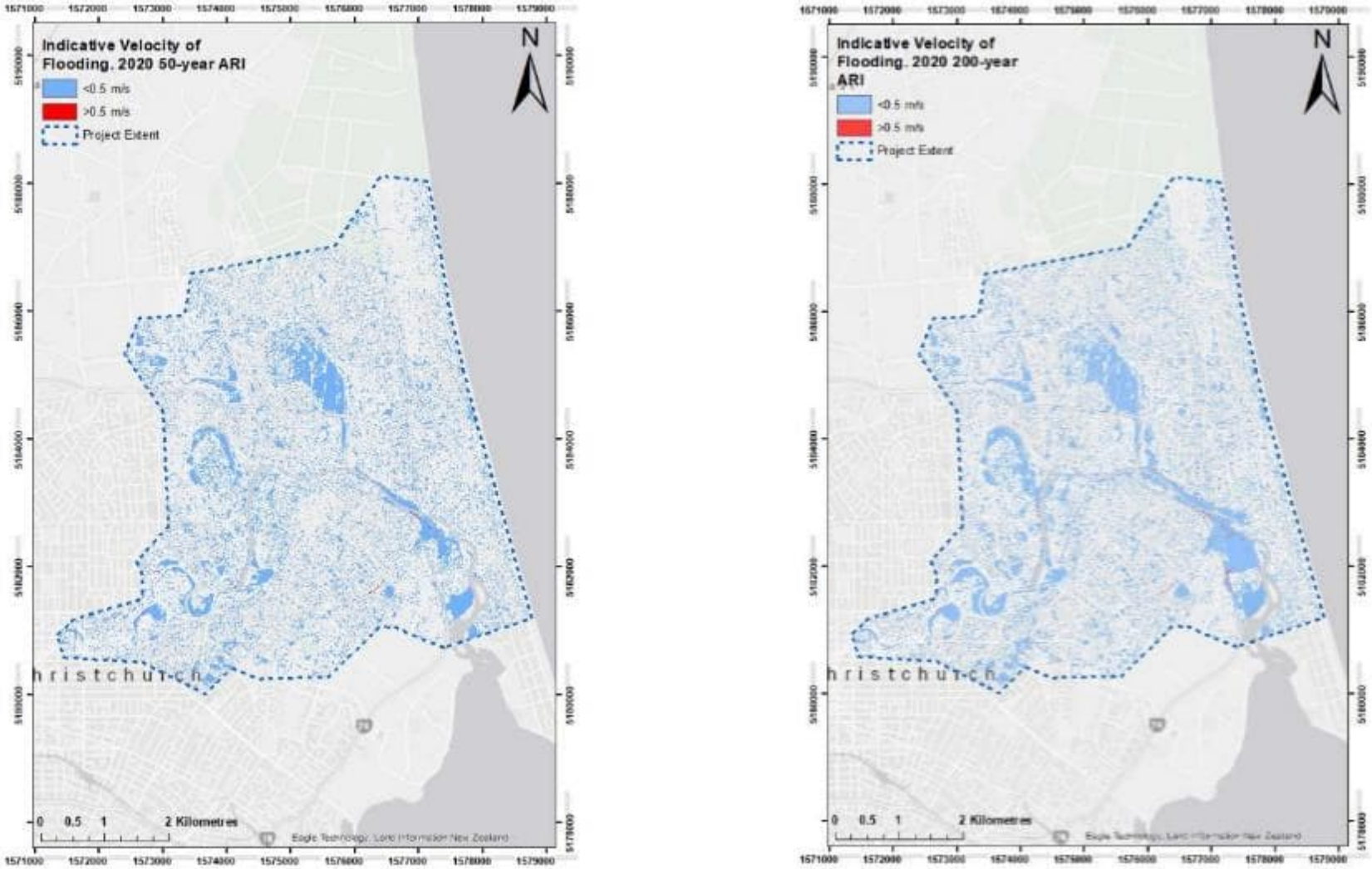

Figure 2. Indicative maximum velocity of flooding in 2020 for 2% AEP (left) and 0.5% AEP (right).

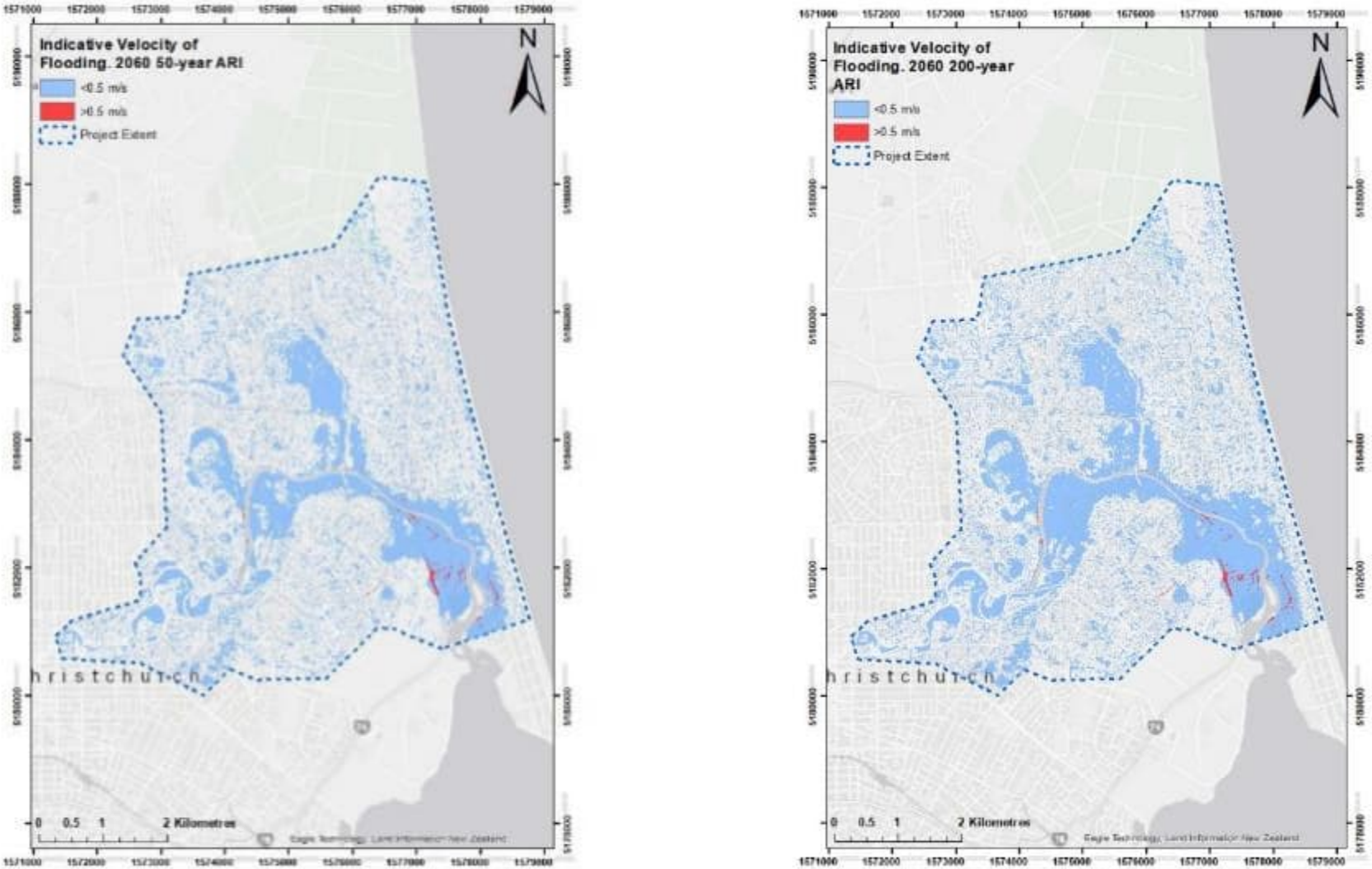

Figure 3. Indicative maximum velocity of flooding in 2060 for 2% AEP (left) and 0.5% AEP (right)

The maps show that for these modelled flood events the indicative maximum velocities are less than 0.5 m/s over the majority of the flooded area (between 98.4% and 99.8% of the area). Given that the indicative values are conservative, the results show that for the purpose of this stage of the Multi Hazards project, flood hazard in the types of flood event simulated in the project can be adequately quantified in terms of water depth alone.

2.1.2 Baseline flood hazard assessment

To provide a metric of flood hazard in addition to the assessment of financial cost of damages, we have used the AR&R Guideline hazard classification system to calculate the total area subject to each class of flood hazard. We have computed the flood hazard areas in the project area for each of the three modelled AEPs in each of six modelled scenarios shown in Table 2, with the existing flood management infrastructure in place for scenarios up to and including 0.45 m sea level rise (SLR) and without earthquake-induced land settlement.

Table 2. Distribution of AR&R Guideline flood hazard categories classified by depth.

Scenario	AEP	Area in each flood hazard class (km^2)						
		ALL	H1 (< 0.3 m)	H2 (0.3 m to 0.5 m)	H3 (0.5 m to 1.2 m)	H4 (1.2 m to 2.0 m)	H5 (2.0 m to 4.0 m)	H6 (> 4.0 m)
S1 0 m SLR (~2020)	10%	5.7	3.4	0.6	0.5	0.5	0.5	0.3
	2%	8.3	4.6	1.3	1	0.5	0.6	0.3
	0.5%	11	5.4	2.1	1.9	0.6	0.6	0.4
S3 0.19 m SLR (~2030)	10%	6	3.5	0.6	0.5	0.5	0.6	0.3
	2%	9.2	4.8	1.5	1.5	0.5	0.6	0.4
	0.5%	12.1	5.3	2.1	2.9	0.7	0.7	0.4
S5 0.45 m SLR (~2060)	10%	7.8	4.2	1.2	1	0.5	0.6	0.4
	2%	11.9	5.3	2.1	2.6	0.8	0.8	0.4
	0.5%	14.3	4.8	2.4	4.6	1.2	0.8	0.5
S9 1.06 m SLR (~2100)	10%	13.5	3.8	1.9	4.7	1.5	1	0.5
	2%	15.9	4.2	1.9	5.4	2.5	1.3	0.6
	0.5%	17.6	4.3	2.2	5.7	3.4	1.4	0.6
S12 1.88 m SLR (~2150)	10%	18	3.2	1.7	4.8	5	2.5	0.7
	2%	20.1	3.4	1.6	5.2	5.7	3.4	0.9
	0.5%	21.7	3.6	1.7	5.4	5.9	4.2	0.9
S13 2.44 m SLR (~2150+)	10%	21.8	3.2	1.7	4.9	5.7	5.4	1
	2%	24	2.9	2	5.5	5.7	6.8	1.2
	0.5%	25.4	2.9	2	5.6	5.8	7.8	1.3

Figure 4 shows the distribution of flood hazard for a sample future scenario – S5, 0.45 m SLR (approximately 2060) with existing flood management measures – for the 10% AEP and 0.5% AEP. It can be seen that most of the higher hazard areas (class H3 and above) lie within the OARC Regeneration Plan area or in areas of open land or beach. Flood hazard over developed areas in this scenario are generally in the lower classes (H1 and H2).

Figure 5 shows the distribution of flood hazard class, excluding the beach area, for future Scenario 1 (~2020), Scenario 5 (~2060) and Scenario 9 (~2120). In Scenario 1 and Scenario 5 the majority of the project area lies within hazard classes H1 and H2 – i.e., less than 0.5 m depth above ground level. Much of the deeper flooding is located with the OARC Regeneration Plan area.

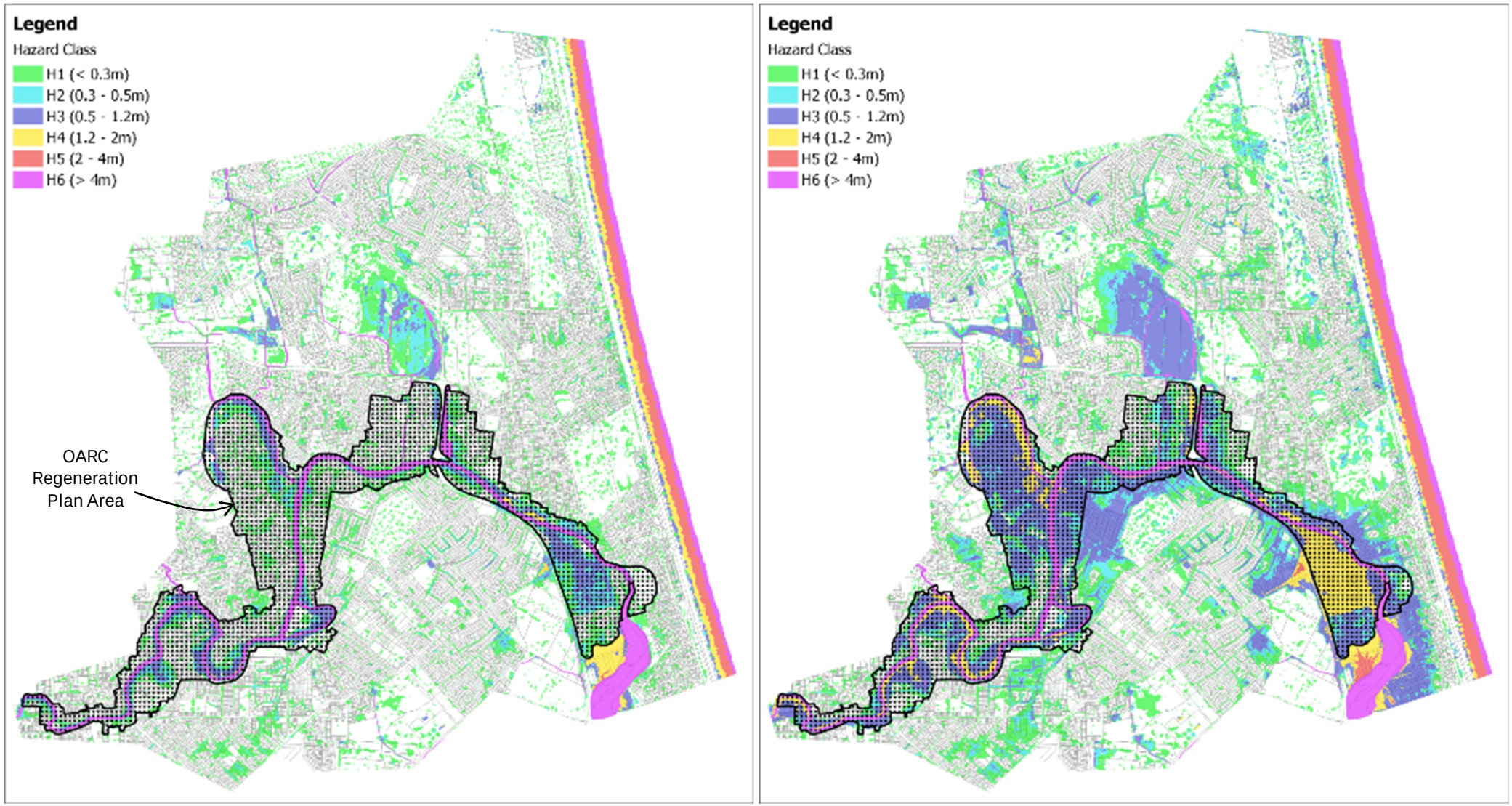

Figure 4. Flood hazard using the AR&R Guideline classification for flooding in 2060 with existing flood management measures for 10% AEP (left) and 0.5% AEP (right)

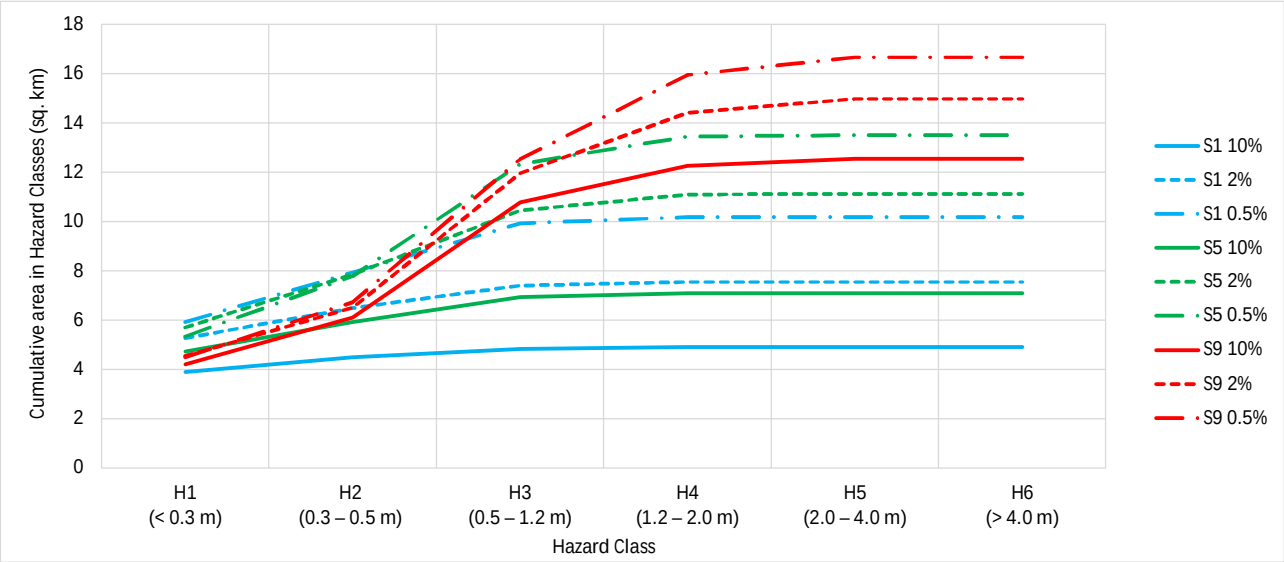

Figure 5. Distribution of AR&R Guideline flood hazard categories classified by depth, excluding beach area

2.2 Accumulation of flood water from successive tides

The duration of the baseline simulations undertaken with the Avon CWM for tidally dominated events at each AEP is generally either 24 hours or 30 hours. This is a sufficient period of time to capture the peak flows and water levels resulting from the coincident pluvial and fluvial flows in these events (an 18-hour rainfall duration is simulated). However, in a storm tide event, tidal high-water levels are usually elevated above the astronomical levels for several tides before and after the tide of maximum high water due to the relatively long duration of the atmospheric events which causes these tides.

This can result in an accumulation of flood water from successive high tides where additional overtopping or prolonged impedance of the drainage of flood water occurs over multiple high tides. Figure 6 shows an example of the tidal water level time series specified for the coastal boundary of the Avon CWM together with the period simulated with the model for that scenario. In some scenarios, e.g., those with large values of SLR or without stopbanks, it is possible that flood levels in the catchment could be higher than those simulated in the model due to the effects of high tides outside the period simulated.

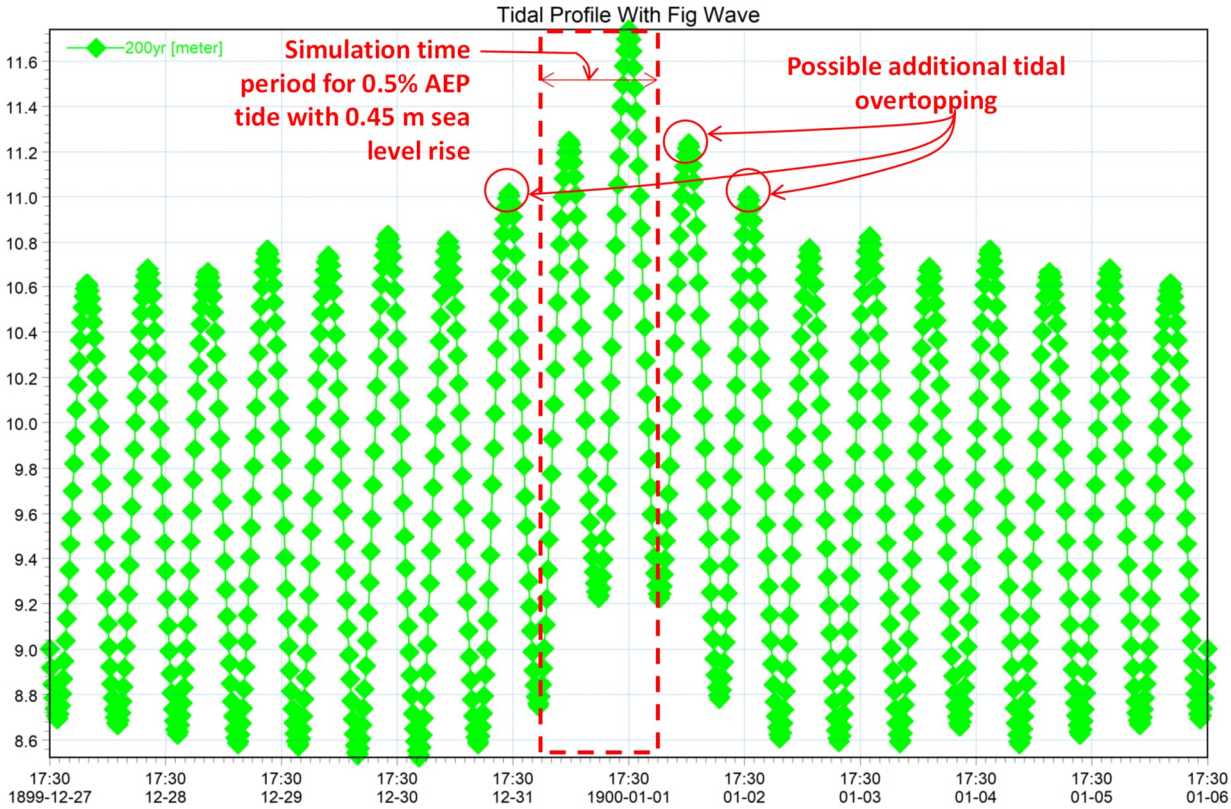

Figure 6. Baseline model tidal water level boundary for 0.5% AEP storm tide with 0.45 m SLR (~2060).

We have assessed the potential for preceding and successive storm tides to exacerbate flooding in the catchment beyond that simulated by inspecting model results for the 2% AEP and 0.5% AEP tidally dominated events for SLR scenarios of 0 m (~2020), 0.45 m (~2060) and 1.06 m (~2100). These events also include the effects of coincident rainfall and river flows (14% AEP and 8% AEP respectively) based on a previous joint probability assessment of storm tide and rainfall events[4]. For the first two sea level rise scenarios we have considered results with the existing stopbanks in place. For the third scenario simulations were only performed without stopbanks.

We have extracted time series water level data from the model results at ten sample locations along the Ōtākaro Avon River as shown in Figure 7. Figure 8 and Figure 9 compare the water levels at these points to the tidal water level at the model coastal boundary offshore of the Avon-Heathcote estuary and the simulated water level at the mouth of the Ōtākaro Avon River, downstream of Bridge Street. The minimum crest level of the existing stopbanks between Gayhurst Road and Bridge Street (11.2 mCDD) is also shown as an indication of when overtopping of the stopbank occurs, noting that in tidally dominated events, the water levels in the river between Gayhurst Road and upstream of Avondale Road are lower than at Bridge Street.

[4] Christchurch City Council, LDRP097 Multi-Hazard Baseline Modelling, Joint Risks of Pluvial and Tidal Flooding, GHD, February 2021

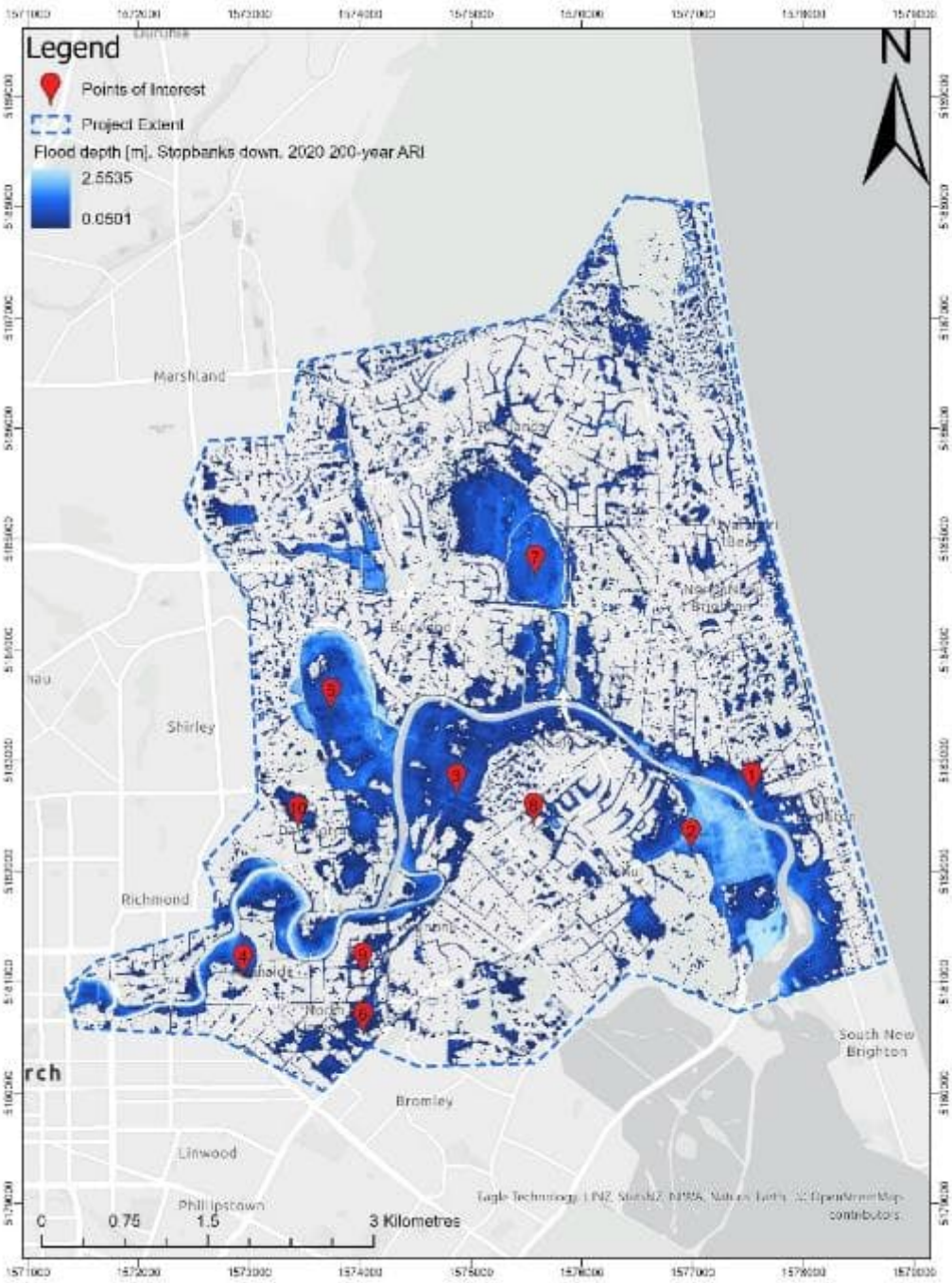

Figure 7. Location of points of interest for assessment of the effect of successive high tides on flood levels in the lower Ōtākaro Avon River catchment (present day 0.5% AEP flood depths shown for context).

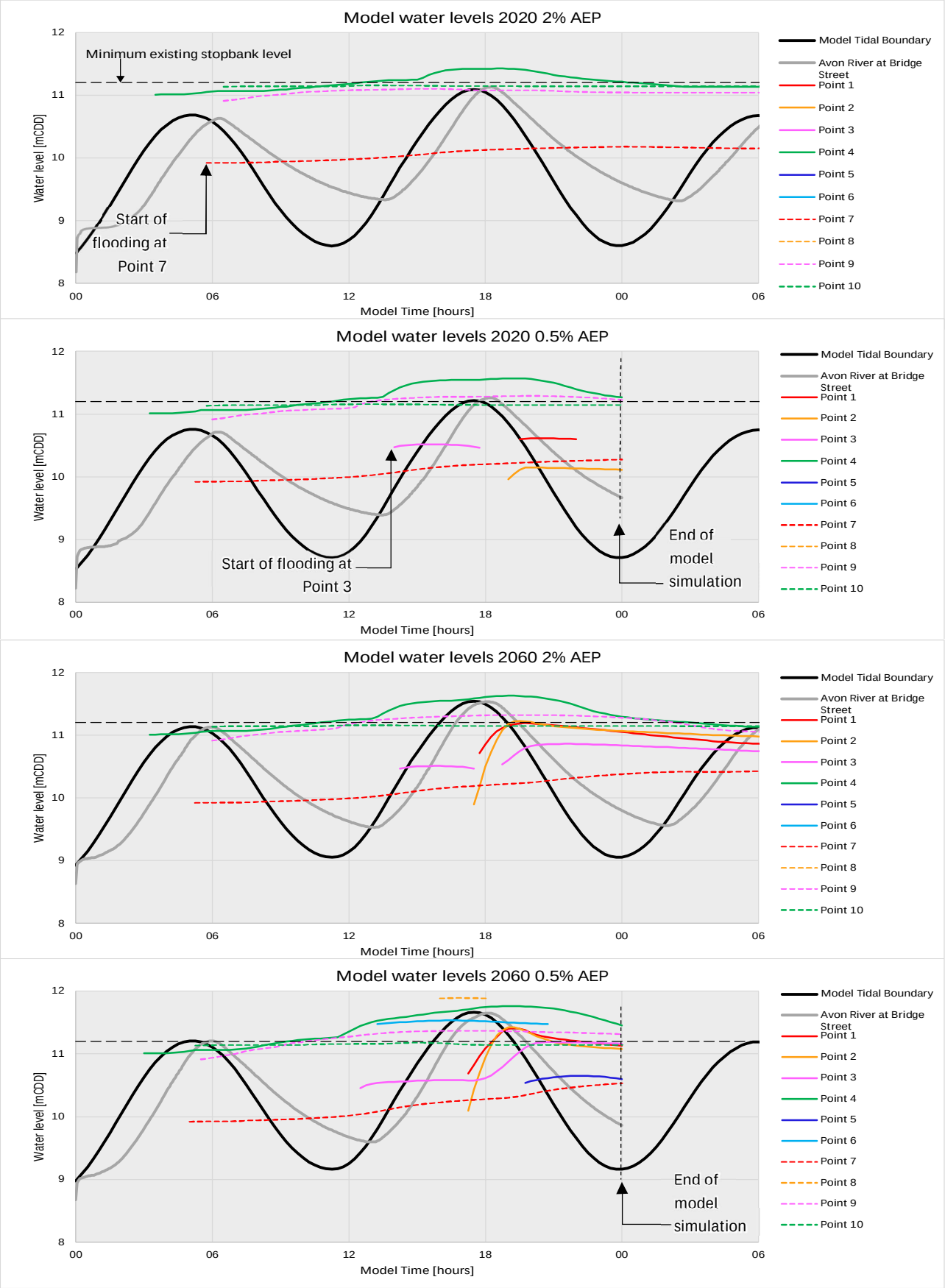

Figure 8. Baseline water levels at selected points (~2020 and ~2060, 2% and 0.5% AEPs, stopbanks up)

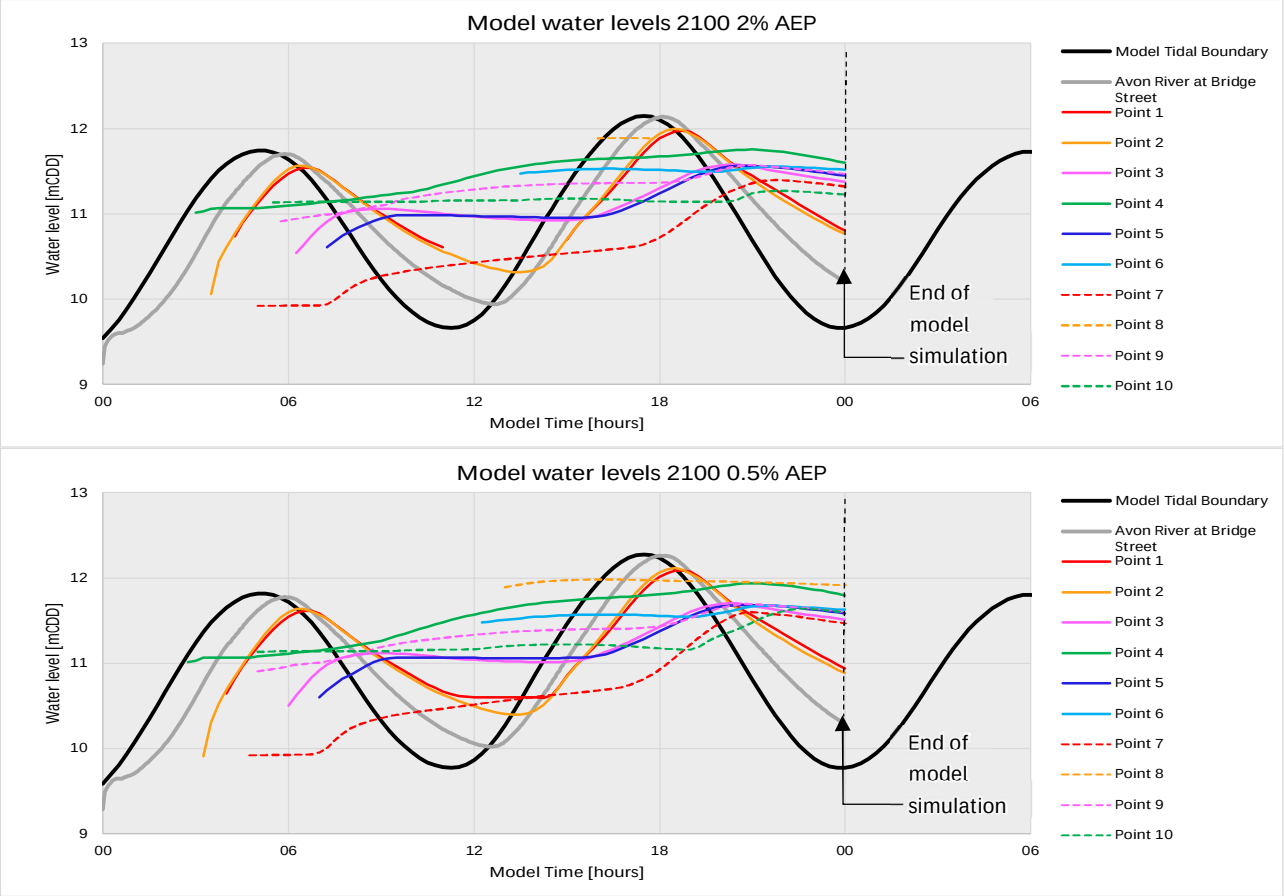

Figure 9. Baseline water levels at selected points (~2100, 2% and 0.5% AEPs, stopbanks down)

The model results presented in Figure 8 and Figure 9 indicate that:

- For 0 m SLR (present day ~2020):
  - There is little if any overtopping for 2% AEP and only for the highest tide for 0.5% AEP. Flooding is primarily from local catchment runoff and impedance of drainage to the river. At all locations water levels have reached peak values in the simulation. For 0.5% the water level at Point 7 (Travis Wetland) has not reached a maximum level within the simulation period. However, since the level here is not affected by the initial high tide it is unlikely to be further elevated by further high tides so any further increase in level is likely to be very small and there are no properties affected by flooding in this area.
- For 0.45 m SLR (~2060):
  - Overtopping contributes to flooding for both AEPs. However, there is little contribution to flooding from the tide before the highest tide and therefore unlikely to be further contribution from successive tides. In both AEPs the water level at Point 7 has not reached a maximum level at the end of the simulation. However, the results for the 2% AEP, in which the simulated period is longer, indicate that any further increases in level due to successive tides are likely to be very small.
- For 1.06 m SLR (~2100, no stopbanks):
  - At locations closest to the river (e.g., Points 1 and 2) the water levels are similar to the river levels and maximum level occurs at the highest tide. Water levels at most locations show effects from the first tide in the simulation and are therefore likely to be affected by successive tides as well. Water levels at Points 3, 5 and 7 are most affected by the initial tide and are more likely to be further influenced by successive tides. Although water levels have reached peaks during the simulation period, some further increase is possible on the third tide. However, water levels on tides following the highest are unlikely to rise above those tide levels and therefore any further increase is likely to be small.

In conclusion, from an inspection of the baseline model results for a selection of scenarios, the simulated water levels will generally encompass the highest water levels resulting from the storm tide sequence developed for the model boundary condition. At a few locations water levels do not reach maximum values within the period simulated but we expect that any further increase in level due to continued ponding of water or additional tidal contributions would be small. Worst case water levels at these locations are likely to arise from rainfall dominated events in which effect of tides is less significant. Therefore, we consider the results appropriate for assessment of baseline flooding effects.

For the simulations performed in Stage 3 of the Multi Hazards project, the model includes the new set back stopbanks and stormwater pumpstations to be implemented under the OARC Regeneration Plan. The stopbanks are set high enough to prevent overtopping so successive tides will not contribute to flooding through overtopping. The effect of the tides on flooding due to impeded drainage is likely to be less significant due to the provision of additional pumping. However, we for longer duration rainfall events (as in the tidally dominated events) a longer simulation time – e.g., 30 hours – could be considered.

3. Properties flooded and flood damages

3.1 Method

We have used the baseline flood model results and the FloodFX tool to make a quantitative assessment of the effects of flooding for the current flood infrastructure in terms of the number of properties affected by flooding and the financial damages for comparison with new flood protection options. The assessment is restricted to the project boundary of the lower Ōtākaro Avon catchment, as indicated in Figure 7.

Detailed descriptions of the FloodFX calculation methods are provided in the FloodFX User Guide[5] and Calculation Theory Report[6]. Further details of the input datasets and calculation parameters adopted for the Multi Hazards project are provided in the FloodFX Methodology and Parameters memorandum for the project[7].

3.1.1 Property counts

Counts of properties affected by flooding are computed in FloodFX as follows:

- ‘Buildings subject to overfloor flooding’: the number of building footprints in which the modelled flood level is within 100 mm of the building floor level as defined in the FloodFX database, a composite of surveyed and inferred floor levels.
- ‘Buildings subject to underfloor flooding’: the number of building footprints which intersect the modelled flood extent.

3.1.2 Flood damages

In FloodFX, flood damages are calculated as Annual Average Damages (AAD) for each building affected by flooding using calculations of the damages to the building for individual probabilities of flooding (10% AEP, 2% AEP and 0.5% AEP in the Multi Hazards project). Damages in each event are calculated using the NIWA Riskscape method capped at the property value for the purposes of calculating AAD.

The total damages are the sum of direct damages, indirect damages and intangible damages. In the FloodFX calculations, indirect damages and intangible damages are calculated as a proportion of direct damages. For

[5] Stormwater Infrastructure Economic Tool, Christchurch City Council, FloodFX User Guide, IZ057301-NCM-GL-0001 Rev 2, 19 October 2016

[6] Stormwater Infrastructure Economic Tool, Christchurch City Council, Calculation Theory Report, IZ057301-OEC-RP-0002 Rev 2, 19 October 2016

[7] FloodFX Methodology and Parameters, IZ084400-NW-MEM-0005, 10 April 2023

the calculations reported in this memorandum, values of 6% and 100%, respectively, of direct damages have been used. These values are based on research on flood damages available when developing FloodFX but are subject to relatively high uncertainty. For comparison, flooding resulting from Cyclone Gabrielle in early 2023 resulted in around 13,000 insurance claims in Hawkes Bay worth over $481m[8]. Capital losses including damage to fencing/machinery/buildings/orchards/vines etc was up to $1B[9]. Farm revenue loss was estimated as $500m-$1B and Westpac revised down their forecast of 2023 exports by $1.2B to account for the cyclone[10]. This provides some support for allowing for a relatively large proportion of indirect and intangible damages relative to direct damages, noting however that there are key differences in the land uses between the area affected by the cyclone in Hawkes Bay and the Christchurch Multi Hazards project area.

Direct damages are calculated in FloodFX for both underfloor flooding and overfloor flooding. Overfloor flood damages are calculated once the flood level exceeds the building floor level using the NIWA Riskscape damage calculation method and fragility curves for specific types of property. Underfloor damages are calculated from the total building footprint area and a flat damage rate if any part of a building footprint intersects the modelled flood extent.

Due to the 'rain on grid' approach to the flood modelling, the raw model results include some areas of very shallow water depths which are unlikely to result in damage to buildings. For the FloodFX analysis we have used the processed model water depth grids, which exclude flooding of less than 50 mm in depth.

3.2 Scenarios

We have used FloodFX to calculate the number of properties affected by flooding and the AAD for each of the 13 modelled scenarios defined and agreed in Stage 2 of the project[11] and simulated with the baseline model as set out in Table 1.

We have used the AAD values calculated by FloodFX for the modelled scenarios to calculate the Present Value of flood damages over 100 years from 2020 for six future scenarios of climate change and permanent, earthquake-induced, land settlement set out in Table 3. To calculate Present Values we have used a discount rate of 5% and interpolated AADs linearly between the modelled scenarios. For the period beyond 2100 we have adopted a constant value equal to the AAD at 2100 because the modelled scenarios beyond 2100 (2150) do not include allowance for earthquake-induced land settlement, which may have previously occurred in some scenarios. These damages (2100 to 2120) do not contribute significantly to the Present Value due to the substantial discounting of damages in the far future. We have not capped the total present value of damage to a property to the property value. This allows for properties to be repaired or rebuilt multiple times in the future rather than relocating or removing buildings. However, further intensification has not been allowed for within the assessment, which may to some degree counterbalance the impact of Present Value damages to properties being uncapped.

The 'stopbanks up' scenario used in this assessment assumes that the temporary stopbanks will be structurally sound over the scenario period. This would require significant repairs and maintenance costs, which have not been included in this evaluation, and could significantly reduce the 'gap' between the 'stopbanks up' and 'stopbanks down' scenarios. For example, $7.2M was spent on the strengthening of the temporary stopbanks as part of the LDRP 507 project which aimed to secure a 20-year additional life out of the earthquake emergency stopbanks.

[8] Insurance Council of New Zealand (ICNZ), 'Provisional Cyclone Gabrielle Claims Reach $890m', March 2023

[9] New Zealand Foreign Affairs & Trade, 'Cyclone Gabrielle's impact on the New Zealand economy and exports', March 2023

[10] New Zealand Foreign Affairs & Trade, 'Cyclone Gabrielle's impact on the New Zealand economy and exports', March 2023

[11] Christchurch Multi-Hazards, Christchurch City Council, Stages 1 & 2 Summary Report, IZ084400-NW-RPT-003 Rev A, 15 Nov 2022

Table 3. Future scenarios from 2020 to 2120 for assessment of baseline Present Value flood damages.

Scenario	2020	2030	2060	2100	2120
Up1	<---------- With Existing Stopbanks ---------->			<--------- No Stopbanks ---------->	
Up2	<---------- With Existing Stopbanks ---------->			No Stopbanks + Earthquake settlement	
Up3	<- With Existing Stopbanks -->		Existing Stopbanks & Earthquake settlement	No Stopbanks + Earthquake settlement	
Down1	<---------- No Stopbanks ---------->				
Down2	<---------- No Stopbanks ---------->			<-------- No Stopbanks + Earthquake settlement ------->	
Down3	<------- No Stopbanks ------>		<----- No Stopbanks + Earthquake settlement ---->		

3.3 Results

3.3.1 Number of properties flooded

The number of properties affected by flooding in the three AEPs for each of the 13 modelled scenarios are presented in Table 4 in terms of the total number of building footprints intersecting the modelled flood extent, the number of those properties where the flood level is within 100 mm of the floor level and the number of properties where the flood level is above floor level. We have checked the FloodFX property count for a sample scenario by way of an alternative GIS calculation to confirm the validity of the outputs, as detailed in Annexure A of this memorandum.

The results at an individual property or building are subject to high uncertainty due to the nature of the inferred floor level data set, however, the overall analysis is considered sufficiently robust for the purposes of this study. An extensive floor level survey would be required to increase certainty in the output, but this is not practicable within the current assessment.

Table 4. Approximate number of buildings subject to flooding under each scenario

					Total building footprints intersecting modelled flood extent			Buildings where flood level within 100 mm of floor level			Buildings where flood level above floor level		
SLR and indicative timing	Land settlement from earthquake	Stopbanks	Groundwater levels	Scenario	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP
0 m SLR (2020)	no	Up	85th percentile	1	3018	4375	5528	410	693	1203	112	217	458
	no	Down	85th percentile	2	3291	4978	6092	539	1186	1840	203	533	1075
0.19 m SLR (2030)	no	Up	85th percentile	3	3133	4559	5954	441	764	1560	114	267	809
	no	Down	85th percentile	4	3800	5419	6567	766	1627	2256	319	943	1464
0.45 m SLR (2060)	no	Up	85th percentile	5	3725	6014	7291	576	1862	2827	180	1116	1915
	no	Down	85th percentile	6	4629	6333	7565	1410	2296	3118	836	1574	2175
	yes	Up	85th percentile	7	4210	6295	7561	1782	3621	4657	888	2461	3378
	yes	Down	85th percentile	8	4851	6560	7800	2631	3902	4941	1700	2741	3652
1.06 m SLR (2100)	no	Down	85th percentile	9	6358	8011	9177	2921	4030	4993	2303	3239	4042
	yes	Down	85th percentile	10	6699	8351	9480	4372	5832	7007	3445	4655	5733
	no	Down	50th percentile	11	6344	8002	9171	2904	4023	4985	2287	3230	4036
1.88 m SLR (2150)	no	Down	85th percentile	12	9556	11153	12336	6341	7828	8790	5559	6938	7894
2.4 m SLR (>2150)	no	Down	85th percentile	13	12506	14144	15121	9570	11237	12341	8733	10387	11453

Figure 10 shows how the number of buildings affected by flooding in the 0.5% AEP increases with time in each of the six future scenarios defined in Table 3. Figure 10(a) shows that the total number of building footprints flooded does not differ greatly between the stopbanks up and stopbanks down scenarios. Similarly, earthquake-induced land settlement does not greatly increase the total number of buildings affected by flooding. However, the number of buildings where the flood level is close to, or above, floor level – Figure 10(b) and Figure 10(c) – differs more between the stopbanks up and stopbanks down scenarios and increases significantly in the land settlement events.

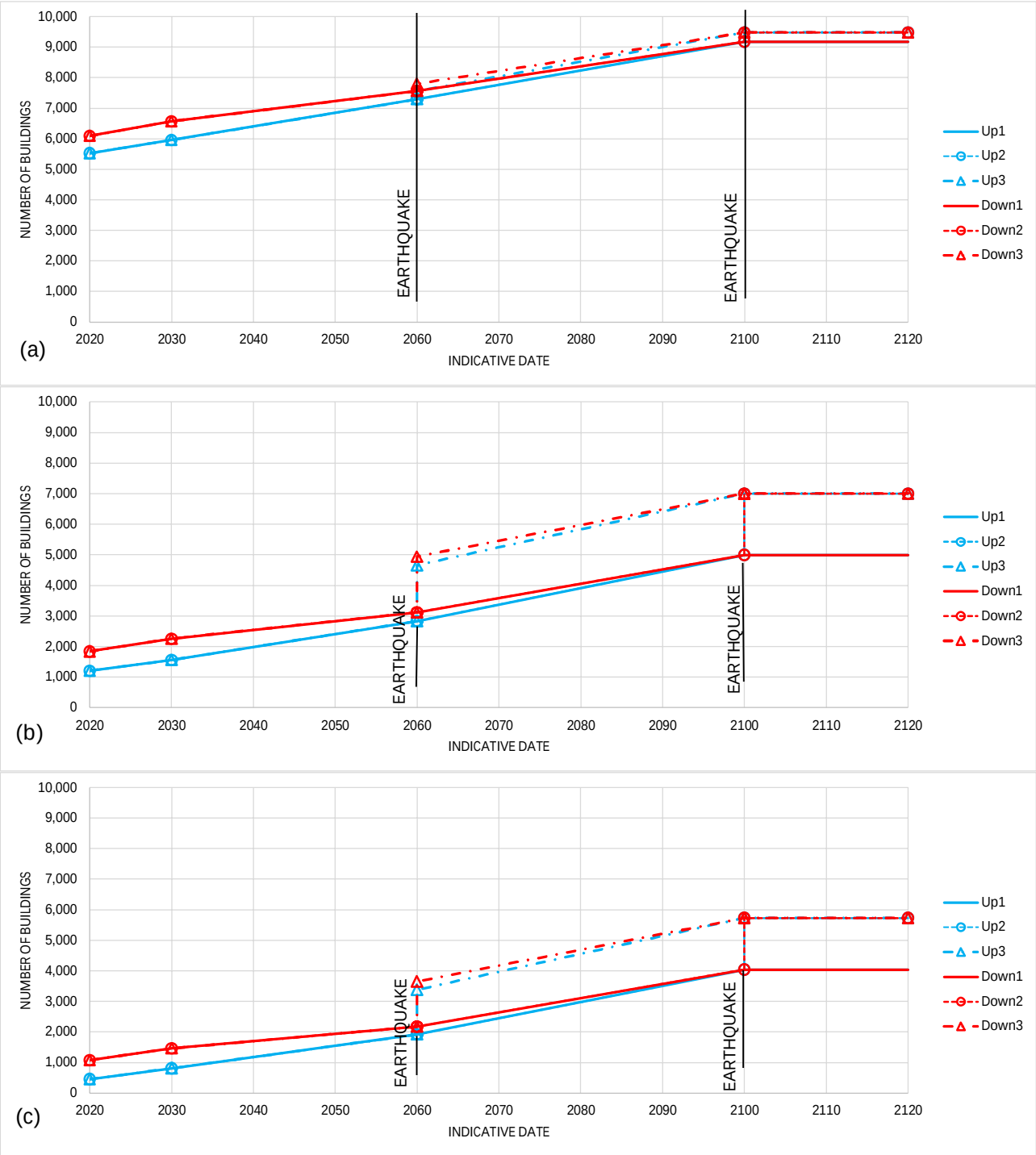

Figure 10. Number of properties in the project area affected by flooding in the 0.5% AEP for each scenario – (a) total number of building footprints affected by flooding; (b) number of buildings with water level within 100 mm of floor levels; (c) number of buildings with water level above floor level.

3.3.2 Flood damages

The total AADs calculated for each of the 13 modelled scenarios are presented in Table 5. Figure 11 shows how the AADs are used to define the change in AAD with time for each of the six future scenarios defined in Table 3. AAD values are interpolated between those calculated at each modelled scenario. Where a scenario includes the shock hazard of earthquake-induced land settlement, a step change in AAD is applied from the AAD value without land settlement to the AAD with land settlement at the time of the shock hazard.

Table 5. Total AADs for the scenarios simulated for the Ōtākaro Avon River catchment

Scenario No.	SLR and indicative timing	Land settlement from earthquake	Stopbanks	Groundwater levels	Total AAD
1	0 m SLR (2020)	no	Up	85th %ile	$10.8 M
2		no	Down	85th %ile	$17.6 M
3	0.19 m SLR (2030)	no	Up	85th %ile	$12.8 M
4		no	Down	85th %ile	$27.0 M
5	0.45 m SLR (2060)	no	Up	85th %ile	$31.0 M
6		no	Down	85th %ile	$50.1 M
7		yes	Up	85th %ile	$69.4 M
8		yes	Down	85th %ile	$90.2 M
9	1.06 m SLR (2100)	no	Down	85th %ile	$134.9 M
10		yes	Down	85th %ile	$202.0 M
11		no	Down	50th %ile	$134.2 M
12	1.88 m SLR (2150)	no	Down	85th %ile	$359.4 M
13	2.4 m SLR (>2150)	no	Down	85th %ile	$603.5 M

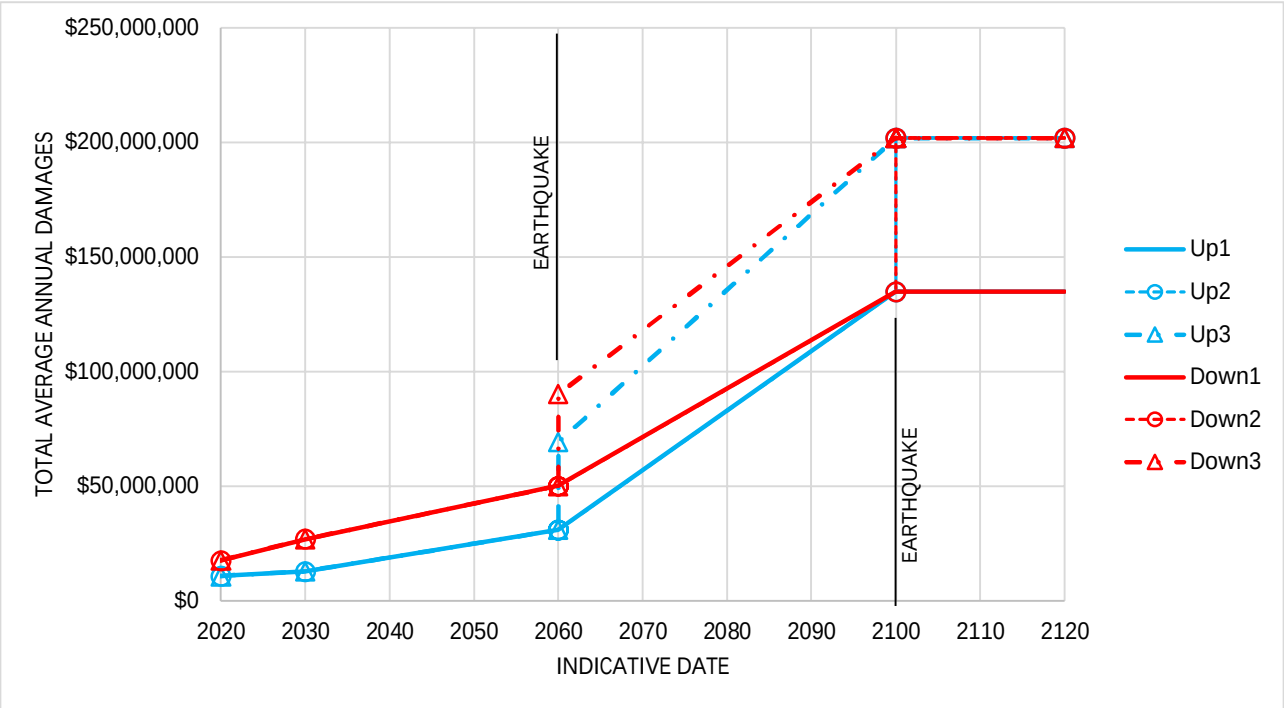

Figure 11. Average Annual Damages (AAD) through time for each of the six future scenarios considered

We have used the AAD time series for each future scenario in Figure 11 to calculate the cumulative present value of total flood damages with time using a discount rate of 5%. The cumulative present values at selected indicative dates are presented in Table 6 and illustrated in Figure 12.

Table 6. Cumulative present value total flood damages for six future scenarios using a discount rate of 5%.

	Up1	Up2	Up3	Down1	Down2	Down3
2020	$11 M	$11 M	$11 M	$18 M	$18 M	$18 M
2030	$102 M	$102 M	$102 M	$190 M	$190 M	$190 M
2060	$292 M	$292 M	$292 M	$532 M	$532 M	$532 M
2100	$458 M	$458 M	$577 M	$729 M	$729 M	$850 M
2120	$491 M	$507 M	$626 M	$762 M	$778 M	$899 M

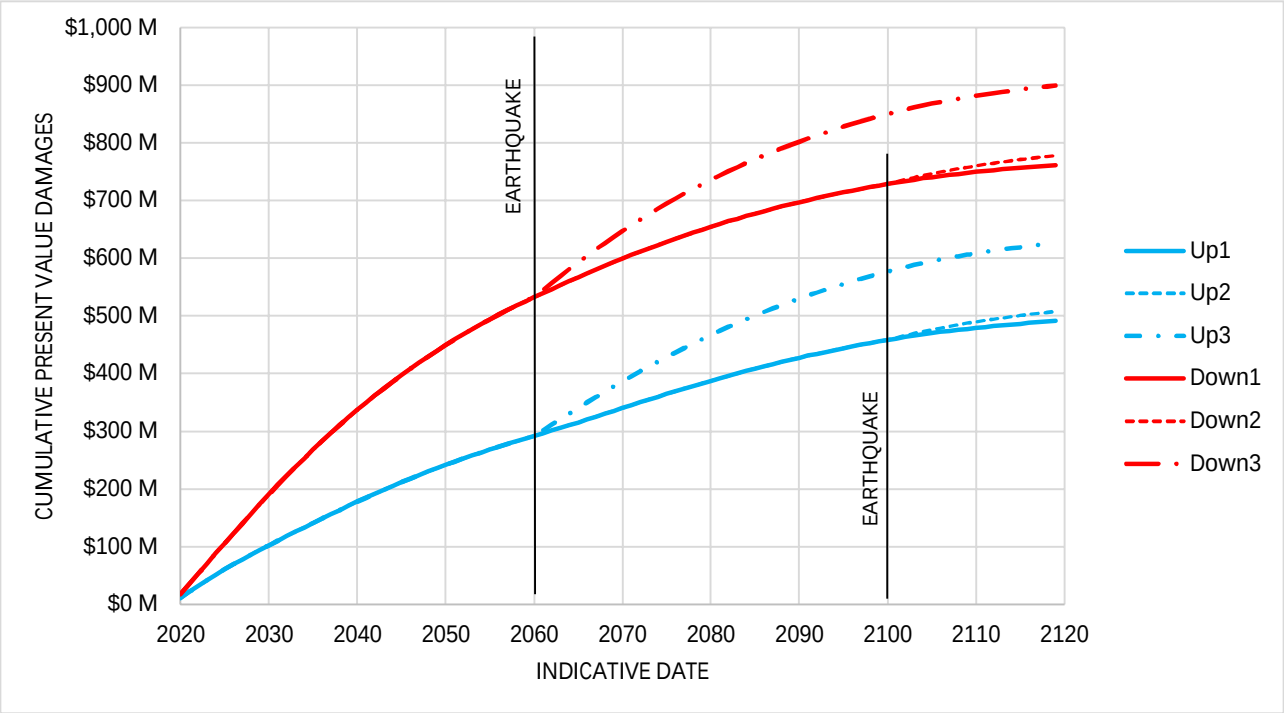

Figure 12. Cumulative Present Value of total flood damages through time for each of the six future scenarios using a discount rate of 5%.

The results presented in in Table 6 and Figure 12 indicate a relatively large AAD in the first decade of the assessment ($11M increasing to $13M, with modest climate change effects) for the future scenario with the existing stopbanks up. The calculated present value damages over the first 10 years amounts to around $100M. In the early years of these scenarios around 50% of the total damages is due to underfloor flooding, both in terms of direct damages (calculated as $60 per m^2 over the full footprint of every building intersecting the modelled flood extent) and through its contribution to intangible damages (100% of the direct underfloor damage). Underfloor damages also contribute to indirect damages, but this forms only a small proportion of the total damage (6% of the direct damages).

Figure 13 shows the composition of the cumulative present value total damages for the six future scenarios together with the approximate total damages if underfloor damages are excluded. The difference in damages is significant in the shorter term – e.g., for scenario Up1 present value total damages including underfloor damages is calculated as $292M in 2060 whereas if underfloor damages are excluded the corresponding value is approximately $170M. These differences could be relevant when considering the relative costs and benefits of alternative options for managing flood risk – e.g., property-scale versus catchment-scale – or the sensitivity of damages and benefits to the basis of calculating the underfloor damage contribution. Given the significance of underfloor damages, it would be worth considering testing the sensitivity of outcomes to the value adopted for the unit rate of underfloor damage and the minimum depth of flooding considered.

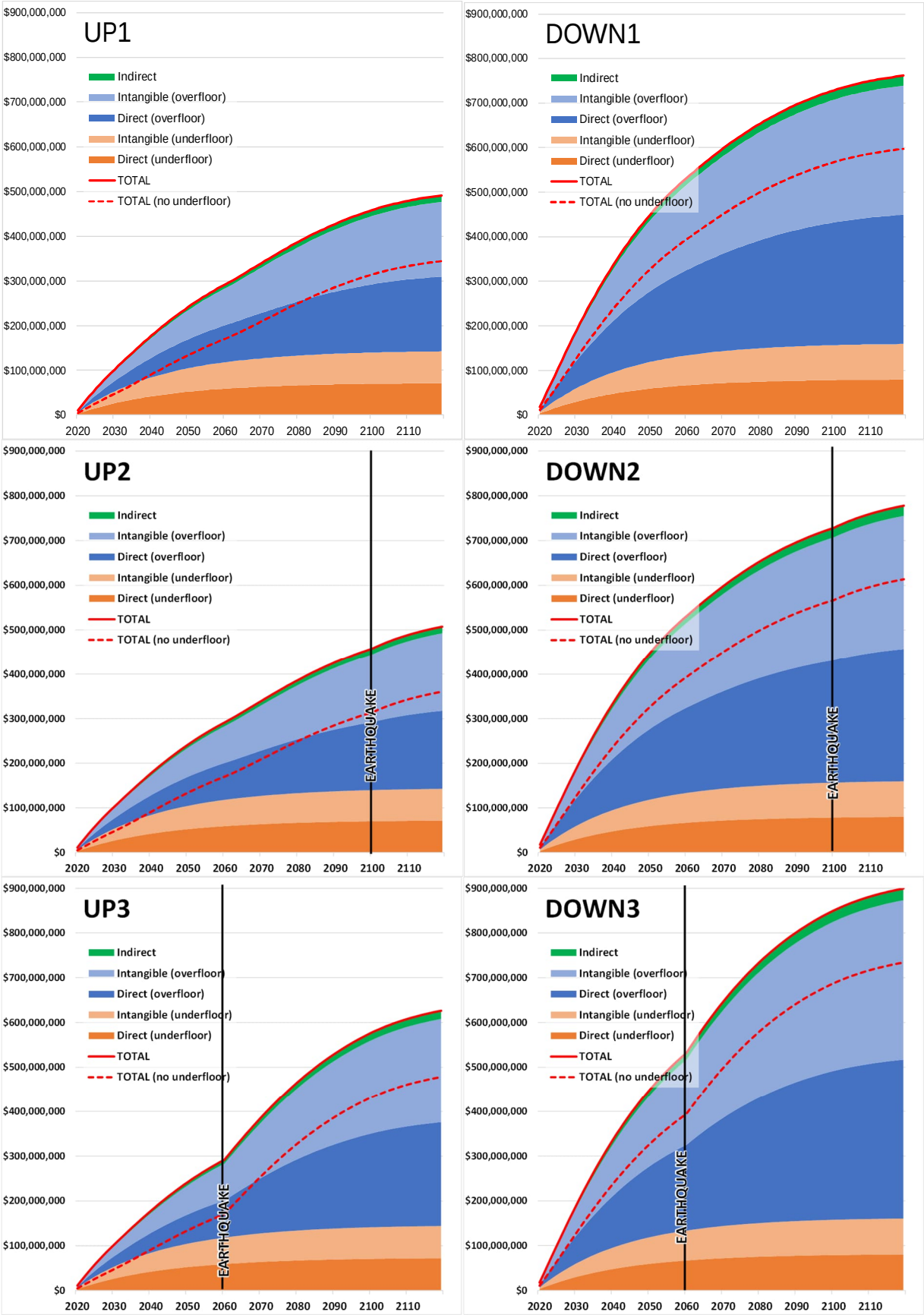

Figure 13. Composition of cumulative present value damages for each of the six future scenarios

In calculating the present value total flood damages presented in Table 6 and Figure 12, the present values of damage to individual buildings have not been capped at the building value. This allows for buildings to be repeatedly repaired or re-built after multiple flood events which might be unrealistic, particularly for uninsured properties. We have not assessed the effect of capping present value damages of individual properties on total damages in the project area in detail. However, as an initial assessment, Figure 14 shows the average present value of direct damages per flooded building for each of the six future scenarios, calculated as the total present value of direct damages (underfloor and above floor) divided by the total number of buildings intersecting the flood extents, as shown in Figure 10(a). Given the value of buildings in the project area (estimated typical values of $0.75 M for residential and $2.4 M for non-residential buildings) the results suggest that the extent to which damages would be capped may be very limited, reflecting the generally shallow, though extensive, nature of flooding, particularly in the near future (Table 2, Figure 4, Figure 5). Further, additional intensification has not been allowed for within the assessment, which may to some degree, counterbalance the impact of Present Value damages to properties being uncapped.

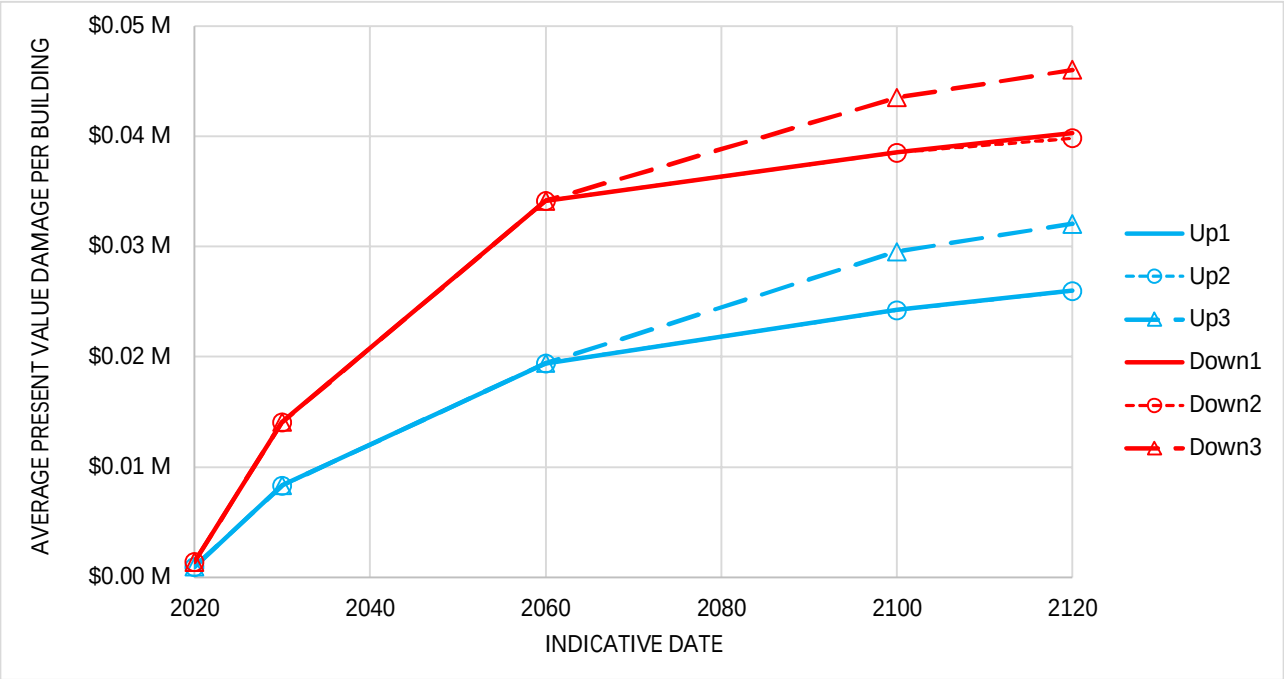

Figure 14. Average cumulative Present Value direct flood damages per building through time for each of the six future scenarios using a discount rate of 5%.

4. Sensitivity of flooding to groundwater levels

The Multi Hazards model simulations allow for the effect of groundwater level on the infiltration of rainfall during the simulations of storm events. The depth of storage available for infiltration in the soil is determined from the groundwater levels and the ground surface levels specified in the model. The soil storage depth and rate of infiltration are together used to calculate the surface runoff resulting from the rainfall.

For each modelled scenario, the groundwater levels used in the simulations are the estimated 85th percentile levels, derived from statistical analysis of observed levels and groundwater modelling. To understand the sensitivity of the simulated flooding to the values of the groundwater levels adopted for the project, the baseline model simulations also include a scenario with 50th percentile groundwater levels (Scenario 11 in Table 1). This is the same as Scenario 9 (~2100 with 1.06 m SLR, stopbanks down and no earthquake settlement) except for the groundwater levels (Table 7).

Table 7. Scenarios for assessing the sensitivity of modelled flooding to model groundwater levels.

Scenario No.	Timeline and SLR	Earthquake	Stopbanks	Groundwater levels
9	2100 1.06 m SLR	No	Down	85th percentile
11		No	Down	50th percentile

Figure 15 shows the differences in maximum flood depths between the two scenarios. As expected, the flood depths for Scenario 9 (85th percentile groundwater surface) are slightly greater than those for Scenario 11 (50th percentile groundwater surface). However, the differences in depths are generally very small – less than 10 mm over much of the project and only exceeding 50 mm in small areas of lower lying ground.

As a result, the difference in total number of properties affected by flooding (Table 8) is very small – 0.1% to 0.7% of the total, depending on the AEP. The difference in overall Annual Average Damages between these two scenarios (Table 9) is also very small – 0.5% of the total damages.

Table 8. Approximate number of buildings subject to flooding under both scenario 9 and 11, as well as the difference totals and percentage difference between the two scenarios.

	Total building footprints intersecting modelled flood extent			Buildings where flood level within 100 mm of floor level			Buildings where flood level above floor level		
Scenario No.	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP
9	6358	8011	9177	2921	4030	4993	2303	3239	4042
11	6344	8002	9171	2904	4023	4985	2287	3230	4036
9 - 11	14	9	6	17	7	8	16	9	6
(% diff)	0.2%	0.1%	0.1%	0.6%	0.2%	0.2%	0.7%	0.3%	0.1%

Table 9. Total AADs for simulated scenarios 9 and 11, and the difference between the two scenarios.

Scenario No.	SLR and indicative timing	Land settlement from earthquake	Stopbanks	Groundwater levels	Total AAD
9	1.06 m SLR (2100)	No	Down	85th %ile	$134.9 M
11		No	Down	50th %ile	$134.2 M
9 - 11					$ 0.7 M
(% diff)					0.5%

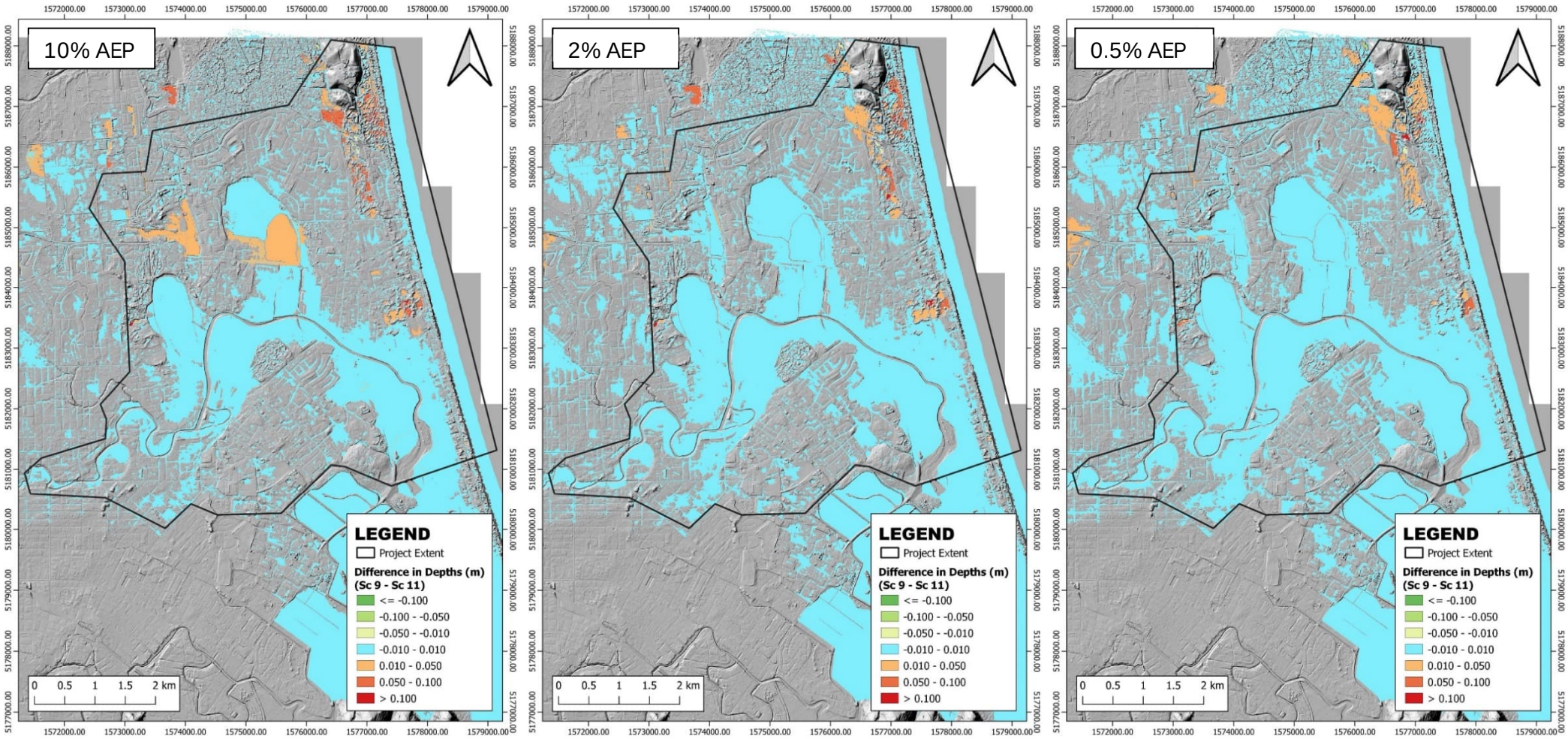

Figure 15. Difference in flood depth between Scenario 9 and Scenario 11 (85th percentile groundwater levels – 50th percentile) for 10% AEP, 2% AEP and 0.5% AEP.

The reason for the small differences in modelled flood depths appears to be due to the relatively low infiltration rates in the catchment – around 2 mm/hr on average in the model. This means that the that the total potential depth of water infiltrating to the soil over the model simulation period is also small (e.g., up to around 50 mm over a 24-hour simulation period). Therefore, in areas where the available storage depth in the soil (depth from the ground level to the groundwater level) is more than around 50 mm, rainfall losses are likely to be limited by the infiltration rate rather than the available storage depth from ground level to groundwater level. As a result, the choice of groundwater statistical surface (e.g., 50th percentile vs 85th percentile surfaces) is only likely to influence the modelled surface flooding in areas where the depth to the groundwater surface is very shallow (e.g., around 50 mm or less), and in areas which are not flooded directly from either the river or sea. As shown in Figure 16, there are few such locations within the project area and there are generally no buildings at these locations.

These results justify use of a single groundwater surface frequency for simulating flooding in the project and indicate that the 50th percentile simulations could be excluded from the simulations of flooding with the OARC Scheme.

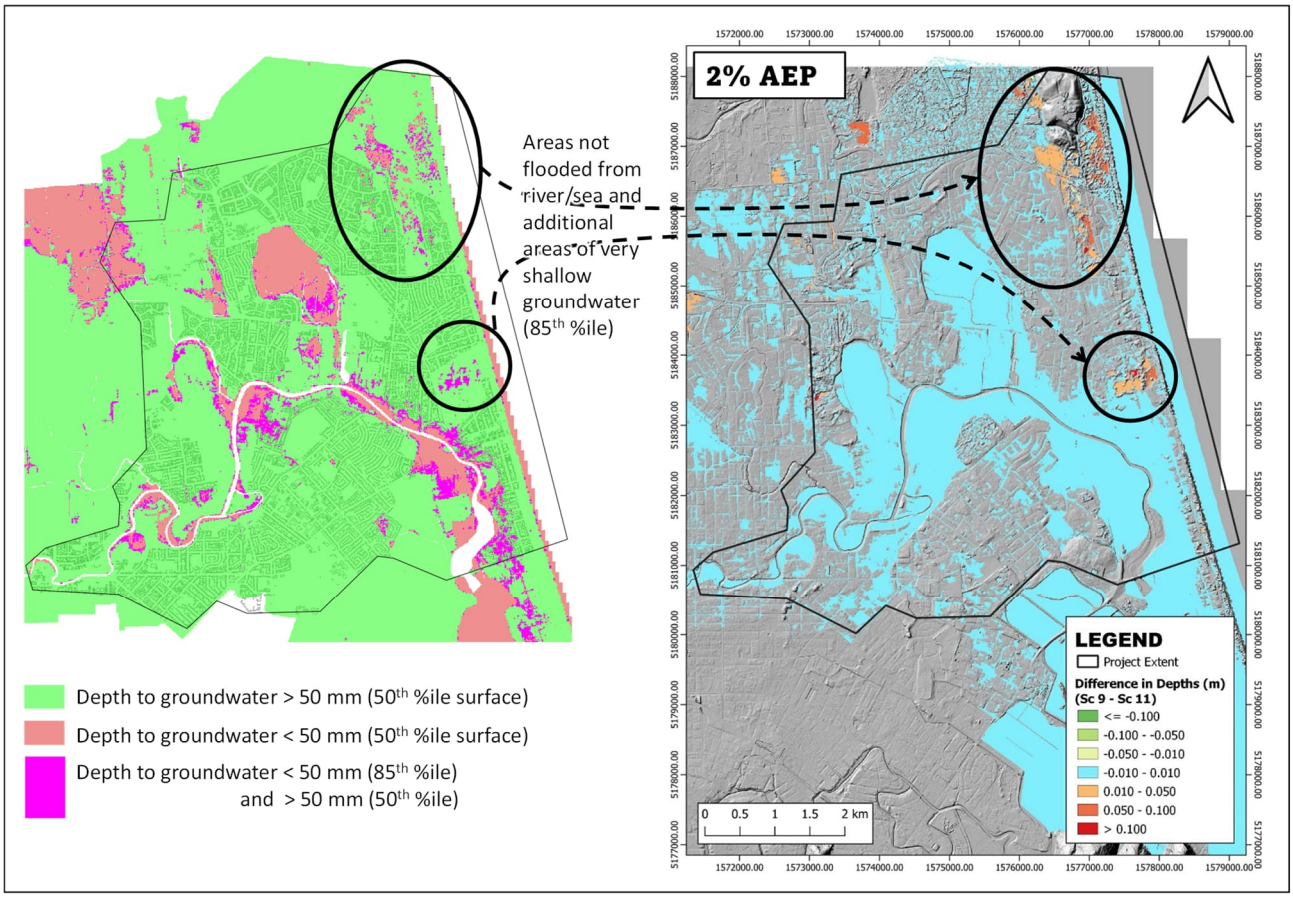

Figure 16. (Left) Areas of shallow groundwater for the 85th and 50th percentile groundwater surfaces in Scenarios 9 and 11. (Right) Difference in flood depth between Scenario 9 and Scenario 11 (85th percentile groundwater levels – 50th percentile) for 2% AEP. In the circled areas the 85th percentile groundwater levels are very shallow and flooding arises from local rainfall.

5. Conclusions and recommendations

1. Our assessment finds that the indicative magnitudes of modelled flood velocity in the Ōtākaro Avon catchment are less than 0.5 m/s over the majority of the flooded area (between 98.4% and 99.8% of the area for events reviewed).

2. Given that the indicative values are conservative, for the purpose of this stage of the Multi Hazards project, flood hazard in the types of flood event simulated in the project can be adequately quantified in terms of water depth alone, using the available processed model results.

3. Our inspection of the baseline model results for a selection of scenarios finds that the simulated water levels generally encompass the highest water levels resulting from the storm tide sequence developed for the model boundary condition. At a few locations water levels do not reach maximum values within the period simulated but we expect that any further increase in level due to continued ponding of water or additional tidal contributions would be small. Worst case water levels at these locations are likely to arise from rainfall dominated events in which effect of tides is less significant. Therefore, we consider the results appropriate for assessment of baseline flooding effects.

4. For the simulations of longer duration rainfall events (as in the tidally dominated events) a longer simulation time could be considered.

5. We have used the FloodFX tool to calculate the number of properties affected by flooding and the AADs for each baseline model scenario. We have used the AAD values to calculate Present Value damages for six future scenarios. The data are intended to be used within the Multi Hazards project and to compare the relative performance – e.g., 'better' or 'worse' – of the existing flood protection measures and the agreed new measures in the future scenarios simulated with the flood model.

6. The results show that in the early years of the future scenarios, around 50% of the total damages is due to underfloor flooding, both in terms of direct damages and through its contribution to intangible damages. Underfloor damages also contribute to indirect damages, but this forms only a small proportion of the total damages.

7. Intangible damage values represent a large proportion of the total damages – approximately 50%. There is considerable uncertainty in the valuation of this component of damage. Since these damage values are calculated as a proportion of the direct damages, uncertainty in the underfloor damages is further escalated through the intangible damage calculation.

8. As agreed with Council, we have not capped Present Value damages to properties. This allows for buildings to be repeatedly repaired or re-built after multiple flood events which might be unrealistic. We have not assessed the effect of capping present value damages of individual properties, but an initial review of average property damages suggests the extent to which damages would be capped may be limited, reflecting the generally shallow, though extensive, nature of flooding in the near future.

9. Given the significance of these factors (underfloor damages, intangible damages), we recommend that the sensitivity of the results to these factors, and the corresponding outcomes, are considered further if the data or method are to be used for any other purposes.

6. Limitations

The sole purpose of this report and the associated services performed by Jacobs is to further the understanding of the effects of multiple hazards in flood risk in the lower Ōtākaro Avon catchment in accordance with the scope of services set out in the contract between Jacobs and Christchurch City Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from information sourced from the Client and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full, and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context. The baseline flood model and simulations analysed in this assessment were developed by GHD for Christchurch City Council and this information has been used as provided with no review of the accuracy of that information or its method of development.

This report has been prepared on behalf of, and for the exclusive use of, the Client, and is subject to, and issued in accordance with, the provisions of the contract between Jacobs and the Client. Jacobs accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

Annexure A Alternative method check of property counts

An alternative analysis was conducted to verify the validity of the FloodFX outputs. An ArcMap file was created using the FloodFX building database spatial data and a polygon layer of the flood extent for all AEPs simulated in the flood model (10%, 2% and 0.5%). The purpose was to manually determine the number of building footprints that overlap the flood extent, in order to verify the automated output from FloodFX. The results of this analysis are shown below in Table 10 and an example map from the ArcMap analysis is shown in Figure 14. This analysis is only useful for verifying the number of buildings exposed to underfloor flooding as overfloor flooding is based on the relationship between building floor level and flood level at that point. There is a total of 20,329 buildings in the FloodFX database within the Stage 3 project area of the lower Ōtākaro Avon catchment.

Table 10. Analysis of the validity of the FloodFX outputs.

AEP	FloodFX Building Count	ArcMap Building Count	Additional buildings FloodFX count
10%	3018	3013	5
2%	4375	4367	8
0.5%	5528	5522	6

The properties included in the FloodFX analysis and not the ArcMap analysis are as follows:

- 126K North Parade, included for all three AEPs
- 144A Stanmore Road, included for all three AEPs
- 9 Netherby Lane, included for all three AEPs
- 29 Horseshoe Lake Road, included for the 2% and 0.5% AEP
- 16 Wilmington Place, included for all three AEPs
- 43 Waitakiri Drive, included for all three AEPs
- 151 Linwood Avenue, included for the 2% AEP
- 1/149 Linwood Avenue, included for the 2% AEP

These properties are all located along the western boundary of the study area and the building footprints extend both inside and outside of the study area boundary polygon. The model water level and depth result grids were not clipped to the study area, meaning these buildings are likely included in the FloodFX tool count as intersecting flooding that lies outside of the study area.

This review confirms that the FloodFX property count is valid. We consider it reasonable to include buildings which lie at least partially within the project area polygon but are affected only by flooding from outside the project area polygon. Excluding these buildings from the FloodFX analysis would fail to fully capture the damages accrued by buildings within the study area. Although flooding affecting these buildings of interest originates from outside of the study area, excluding them from the analysis may lead to a false understanding that those buildings are unaffected by flooding.

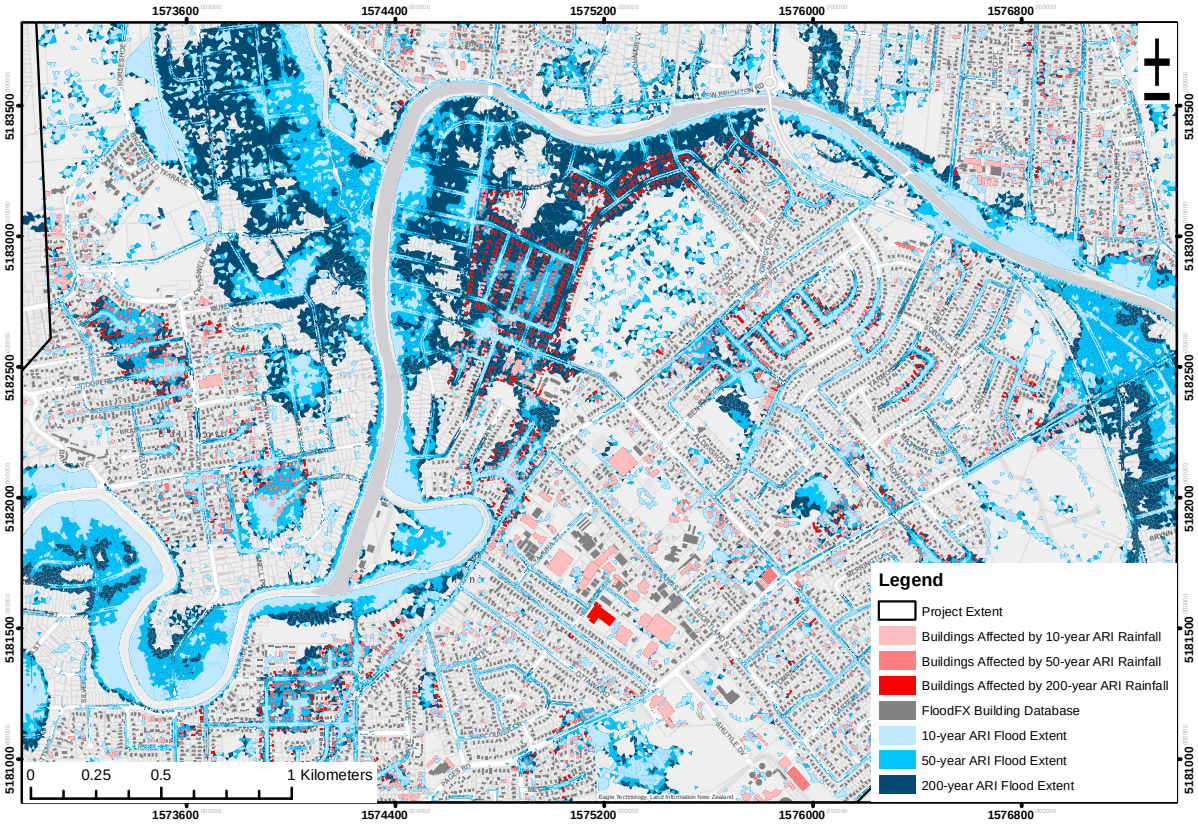

Figure 17. Example mapping of affected properties as identified using FloodFX and model flood extents

Appendix B. Task 2 Initial project response indicators for groundwater and flood hazards memo

Project Task 2: Initial Project Response Indicators for Groundwater and Flood Hazards

Date:	20 December 2023
Project name:	LDRP97 Multi Hazards Stage 3
Project no:	IZ084400
Attention:	Martin Densham, Tom Parsons
Company:	Christchurch City Council
Prepared by:	Greg Sheppard, Damian Debski, Greta Stuthridge, Ian Wiseman
Document no:	IZ084400-NW-MEM-0006 – Final
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1. Introduction

1.1 Context and purpose

Stage 3 of the Multi Hazards project will assess hazards in the lower Ōtākaro Avon catchment for a range of plausible future scenarios, combining the effects of climate change and earthquake-induced land settlement, and taking account of the new flood risk management infrastructure proposed within the Ōtākaro Avon River Corridor (OARC) Regeneration Plan. The assessment considers flood hazards, arising from storm tide, fluvial and pluvial events, and elevated groundwater.

Figure 1 shows the extent of the project area for Stage 3 of the Multi Hazards project and the OARC Regeneration Plan project area. It also presents modelled flood hazards with an Annual Exceedance Probability (AEP) of 0.5% (the chance of the hazard or greater occurring in any year). The hazards shown are with the existing flood management infrastructure in a future scenario including climate change (rise in sea level and increase in rainfall) scenario that might occur around 2060.

The infrastructure proposed as part of the OARC scheme includes realigned river stopbanks and additional stormwater pump stations. It will be designed to accommodate future raising of crest levels and increased pump capacity in response to anticipated climate change over the next 100 years. The multi-hazard assessment will provide Council with an understanding of when these future upgrades may be required. It will also identify when, and where, additional or alternative responses to flood or groundwater hazards may need to be considered.

The likely timing of future decisions in response to increasing hazards will be developed in this study by comparing the modelled flood hazard data to a set of corresponding 'project response indicators' (PRIs). Separate PRIs can be developed for the main activities and assets in the catchment (buildings, people's safety for example). This project will develop an initial list of PRIs which can be refined and added to over the study period and over the next 100 years. These PRIs are developed solely to inform the project and are not Council policy or a reflection of community risk tolerance.

The PRIs are each a quantitative measurement of flood hazard (such as probability of flooding to a particular depth or annual average damage to an asset) which can be compared to the flood model results. They will provide an indication, based on our understanding of current risk appetite, of when the magnitude of the hazard may have reached a level to require a response. Such a response could include additional investment in the planned risk management infrastructure (stopbank or pump station upgrades) or a switch to an alternative risk management approach.

The purpose of Task 2 of the project is to define these initial PRIs through the following steps:

- Review available New Zealand and global sources of information related to the level of hazard exposure that may be tolerable for different asset types and land uses. This will include flood

parameters that indicate the onset of damage to infrastructure and the level of exposure at which flood risk management responses have been triggered (where available)

- Document the information reviewed and use judgement make initial recommendations for PRIs for use with the modelled hazard data in the study area.
- Workshop with Council to agree the PRIs to be used as the basis for identifying likely future response timeframes within this project. The project Peer Review Panel also attended the workshop to understand and observe the background to developing the PRIs.

This memo records our review of the technical information and the proposed PRIs, considering the outcomes of the workshop with Council.

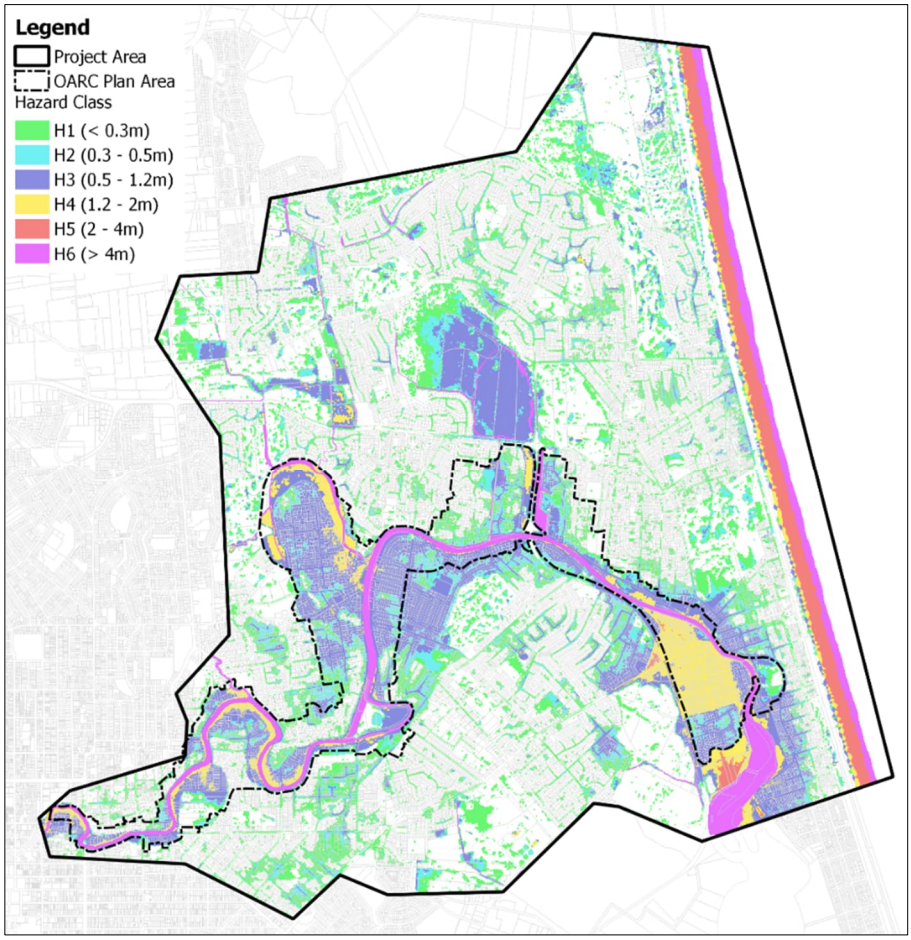


Figure 1 Location and extent of the project area for Stage 3 of the Multi Hazards project showing example modelled flood hazard for the 0.5% AEP in 2060 (approximately) with existing flood management infrastructure (flood hazard classified using the still water depth categories of the Australian Rainfall and Runoff Guidelines).

1.2 PRIs, DAPP and CHAP

The varied stage 3 scope limits the development of full Dynamic Adaptive Policy Pathways (DAPP). Our project focuses on the current preferred risk management pathway (the proposed OARC Regeneration Plan) with only very limited consideration given to alternatives for comparison purposes. The preferred pathway includes adaptive elements – raising of stopbanks, additional pump station capacity – which can be implemented on similar principles to a DAPP process in response to rising sea level and increasing rainfall intensity.

In this study we will consider when future adaptative interventions on the selected pathway may be required in response to increasing hazard exposure. We will also consider when additional responses to flood hazards may

be warranted (i.e., where the OARC does not offer the likely required level of service). These assessments will be made by comparing the initial PRIs to the modelled hazard information. The proposed PRIs are broadly in keeping with the principles of 'adaptation thresholds' commonly used in a DAPP and as set out in Stephens *et al* (2018). That is:

> *"an adaptation threshold occurs when the present pathway is no longer effective in meeting objectives and a new action or pathway is necessary. Adaptation thresholds are associated with performance of the system of concern, for example storm-tide flooding becoming too frequent for a viable community to function or, when beach nourishment or a sea wall is no longer effective due to technical, economic or social limitations."*

We use the term 'project response indicator' as an alternative to 'adaptation threshold' to reflect the fact that whilst the technical principles are similar, the purpose of application differs and the particular use of the indicators in this project and to the modelled hazard data needs to be distinguished from that of a detailed DAPP process.

In the project we will use the PRIs to assess under which future conditions on the current pathway an additional adaptive intervention or switch to an alternative pathway should be considered. We do not consider the full range of physical and social elements that may lead to implementing alternative adaptation pathways. At this stage, we have not sought or taken account of community values and objectives as this is outside of the project scope and subject to other projects and processes in Council.

Council's Coastal Hazards Adaptation Planning Programme (CHAPP) is developing community-led adaptation plans in areas at risk from coastal hazards through a DAPP process. The adaptation areas include part of the Multi Hazards Stage 3 project area but adaptation planning under the CHAPP in that area is unlikely to commence prior to completion of the Multi Hazards project. The adaptation thresholds, triggers, and signals that are established through local adaptation planning as part of a future adaptation plan for this area will likely differ in nature and values to the Multi Hazards PRIs. However, the assessment of flood hazard in the project area under the current pathway in terms of the Multi Hazards PRIs could provide part of the supporting information to the CHAPP programme.

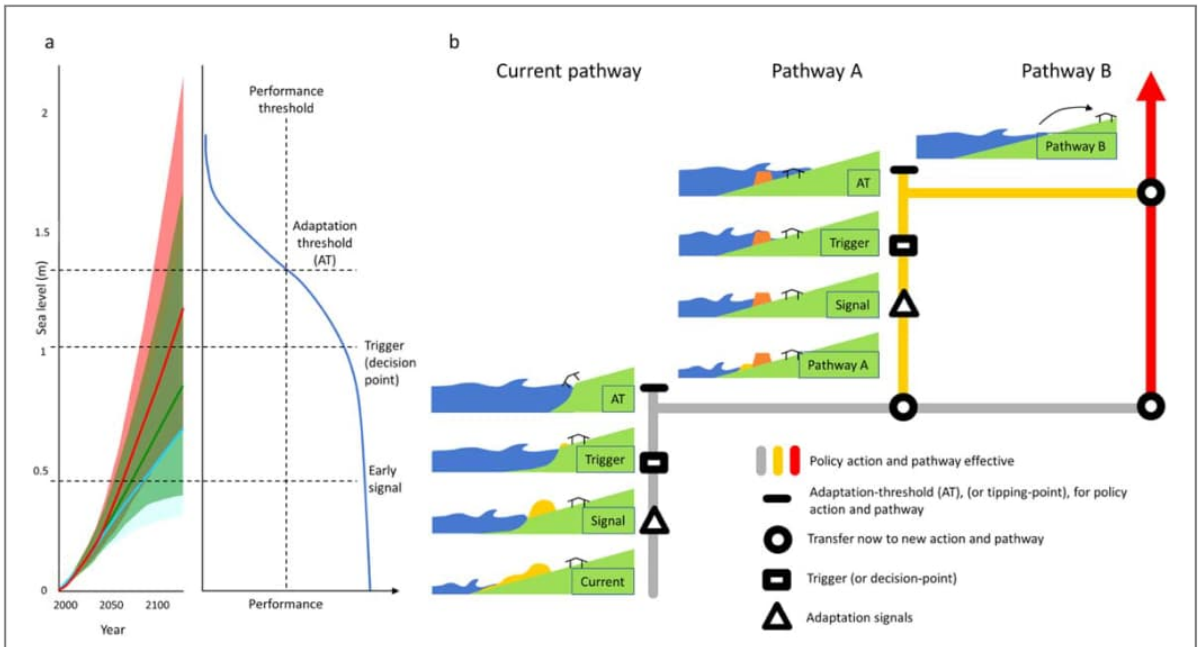


Figure 1. Key concepts for adaptive actions to SLR. (a) Probabilistic SLR projections for RCP2.6, RCP4.5 and RCP8.5 scenarios from Kopp *et al* [33] showing median projection (line) and 95% confidence intervals (shaded), along with a schematic illustrating adaptation-threshold, trigger (decision-point) and early signal in relation to SLR and pathway performance. (b), illustrated dynamic adaptive policy pathways example where pathway A shows a sea wall whereas pathway B shows managed retreat (after [16]).

Figure 2 Principles of adaptive planning as applied to an example of adaptation to sea level rise – Figure from Stephens, S A; Bell, R.G. and Lawrence, J (2018) Developing signals to trigger adaptation to sea-level rise. Environ. Res. Lett. 13 104004

'Signals' are used in a DAPP to provide an early warning of the need for a change in a pathway to be considered and 'triggers' define the point in time at which a decision on any change in pathway needs to be made if the adaptation threshold is to be avoided (Figure 2). The selection of these levels depends on the expected rate of change in hazard and the lead time need to implement a change in pathway. The levels may also depend, to some degree, on the nature of the alternative pathway or pathways planned. For example, it may take longer to implement a process of managed retreat than to construct a stopbank and therefore an earlier signal or trigger condition may be needed. If multiple alternative pathways are available, then these levels may need to provide for the longest lead time across the possible pathways.

In Stage 3 of the Multi Hazards project we will estimate when the adaptive enhancements to the proposed OARC Regeneration Plan infrastructure need to commence in relation to the future scenarios which have been modelled. The timing of the adaptation response will be estimated by comparing the modelled flood hazards to the PRIs and will take account of the lead time needed to raise stopbanks and increase pump capacities. In this way the timing of the adaptation response is analogous to the 'trigger' in a DAPP.

Where our assessment of flood hazards against PRIs shows that other response measures may be needed, we will not define specific 'triggers' – as the project will not define any other specific adaption options – but will provide high level discussion of possible signals and triggers for other measures.

2. Development of Project Response Indicators (PRIs)

2.1 Literature review

The starting point for our review of studies and reports relevant to selecting measures of flood hazard for PRIs are the recent and current Council projects which have assessed these hazards in the project area, and more widely, in some detail.

- For groundwater hazards we started from the literature review undertaken by Aqualinc for the Council Land Drainage Recovery Project 45 (LDRP45) (Rutter, 2020) and expanded our review to consider national and international practices since that time.
- For pluvial, fluvial and tidal flood hazards we have started from the literature review used to underpin the technical analysis of coastal hazards for land use planning undertaken by Jacobs for Council in 2022 as reported in 'Coastal Hazards Plan Change - Analysis/Technical Advice, Risk Based Coastal Hazard Analysis for Land-use Planning (Draft)' (Jacobs, 2022).

We have also considered other work in New Zealand that may be considering or generating data relevant to the selection of PRIs and have sought information that may inform the choices within this project. These included the 'Future Coasts Aotearoa' project led by NIWA and the 'Natural and Climate Hazard Risk and Vulnerability Assessment' currently being undertaken for Council by Urban Intelligence.

Within this literature review we have sought evidence to support the selection of quantitative measures of flood hazard which indicate that specific elements or types of land use may start to be impacted by the hazards.

In our review we have considered the following elements and types of land use within the project area, informed by those identified in Council's Natural and Climate Hazard Risk and Vulnerability Assessment.

- People – risk to life or health or of injury
- Residential land use – houses
- Roads and related infrastructure
- Commercial and industrial buildings
- School and other community infrastructure
- Wastewater infrastructure (pipes and pump stations)
- Water supply infrastructure (pipes and pump stations)
- Stormwater network infrastructure
- Utilities (power, telecoms)
- Greenspace land uses (parks, playgrounds, cemeteries).

Further details of the literature reviewed and our assessment of the information for use in developing PRIs is provided in Annexure A and Annexure B to this memo. PRI's have not been developed for sites of cultural significance as no consultation has been undertaken within the project for this purpose.

2.2 Selection of initial PRIs

In Stage 2 of the Multi Hazards project, we developed a Decision Support Framework (DSF) with Council for appraising and comparing measures to reduce flood risk in the study area. In that context, the objective of flood risk reduction measures was defined for the purposes of this project as to 'reduce overall future flood risk – including allowances for climate change – so that the risk does not increase in each study area catchment within approximately 100 years from now'. A more detailed definition of this objective is given in Figure 3.

Reduce overall future flood risk within each study area catchment, for residential buildings, strategic Council assets and - where economically viable - other buildings. Flood risk is measured by above floor (within 100mm of habitable floor level), underfloor (flood extent touching building footprint) and access flooding (flood depth in the street). Future flood risk will be reduced back to current levels until sea level rises by +1.06m above current levels, which is anticipated to occur within approximately 100 years from now. Flood risk is defined in stormwater and tidal events with Annual Exceedance Probabilities of 1/10, 1/50 and 1/200, where these include allowances for climate change. Where feasible, high groundwater levels will also be managed in areas at risk of flooding. Flood risk measures will be analysed at the overall study area catchment scale and so there may be situations where the objective is achieved at the catchment scale through a combination of option pathways decreasing risk in some areas, whilst having to accept the natural increase in risk in other areas.

Figure 3 Flood Risk Reduction Objective defined within the Decision Support Framework of the Multi Hazards project.

This objective was established for the purposes of the project envisaged at the time – to compare different options and pathways – rather than for the more detailed evaluation of the performance of a specific pathway or option. Given the proposal to implement the specific flood management measures within the OARC Regeneration Plan, it is more relevant to consider the hazards due to flooding and the effects of high groundwater under this pathway in absolute terms, rather than relative to the current level of risk, when considering when or where other measures may be needed.

In selecting the initial PRIs we have considered the hazard data available for the project area in relation to the findings of our literature review regarding the impacts of the hazards for the different types of element. The PRIs are not Council policy and are developed solely for the purposes of the study.

2.2.1 Available hazard data

Flood and groundwater hazards in the project area are available for the eight future scenarios in Table 1. The scenarios are defined primarily by an amount of sea level rise and corresponding increase in temperature from the present day, from which the changes in rainfall depth are calculated based on current guidance. The increase in rainfall depth varies with the probability and duration of individual flood events considered in each scenario.

Table 1. Future scenarios for assessment of hazards with OARC Regeneration Plan infrastructure

Future scenario	Rise in mean sea level (m)	Increase in mean temperature (degC)	Example increase in rainfall depth (% increase in 2% AEP 24-hour event)	Land settlement due to earthquake-induced liquefcation	Indicative date
1	0.00	0.0	0.0	no	2020
2	0.19	0.3	2.7	no	2030
3a	0.45	1.4	11.8	no	2060
3b				yes	
4a	1.06	2.8	23.9	no	2100
4b				yes	
5	1.88	4.6	39.0	no	2150

Future scenario	Rise in mean sea level (m)	Increase in mean temperature (degC)	Example increase in rainfall depth (% increase in 2% AEP 24-hour event)	Land settlement due to earthquake-induced liquefcation	Indicative date
6	2.40	5.0	42.0	no	2150+

Groundwater hazard data consist of surfaces of the projected median and 85th percentile groundwater levels taking account of the mean sea level rise in each future scenario.

Flood hazard data consist of grids of modelled water depths and water levels for three AEPs (10%, 2% and 0.5%), taking account of the rise in mean sea level and increase in rainfall depths in each future scenario together with the corresponding groundwater surface. In addition, the depths of flooding above or below floor level[1] and the annual average damage due to flooding at each building in the project area are also available.

2.2.2 Impacts of hazards

Our literature review finds that the impacts of flood and groundwater hazards are most commonly measured by the depth of flooding or depth of groundwater below ground level. The severity of the hazard and associated impacts are then defined by values of depth. These values can be derived through scientific analysis of the hazard or from practical experience of the hazard. The frequency of flooding (often the annual exceedance probability or average recurrence interval) is also used in some cases to categorise the hazard.

Annexure A and Annexure B provide a detailed description of the information reviewed and the consequent selection of initial PRIs.

In selecting the PRIs, we recognise that there is often a gradation in impacts rather than a single 'tipping point' in the severity of the hazard. The impacts of flooding can increase with the extent of the element affected by the hazard or the chance of it occurring. For example, underfloor flooding of a building may result in a small amount of damage, shallow flooding above the floor of a building will result in more extensive damage and deeper flooding could result in complete loss of the building. This means that a depth-impact or probability-impact relationship may be appropriate for a PRI for some elements. We have examined potential risk-based indicators for flood hazards further, as discussed in Annexure B.

2.3 Workshop of proposed PRIs

An earlier draft (Rev B issued 31/08/23) of this memo informed a workshop on the proposed PRIs. The workshop was held on the 12 September 2023 with Council and the Peer Review Panel for the project. The intent was for Council and Jacobs to discuss the proposed PRIs and for the Peer Reviewers to understand the rationale for that choice. Subsequently, Jacobs have updated this memo (Rev C) to take account of the outcomes of the workshop in confirming the initial PRIs to be used on the project.

Note that the terminology for PRI was developed after that workshop.

2.4 Application and testing of proposed PRIs

Given the uncertainties in selecting the types and values of PRIs for use in this project, we recommend that the sensitivity of the outcome of the hazard assessment to the values of the PRIs is considered. This could be done through inspection of initial assessment results and testing alternative values once the model data is available. This may result in revisions to the PRIs adopted for the project.

[1] The CCC building dataset that is used within the FloodFX tool contains information on building floor height above ground. In most cases this is an assumed level based on building type rather than a surveyed level.

3. Proposed Project Response Indicators

Table 2 presents the initial PRIs we are proposing for hazard assessment in the project. Further details of supporting literature and our selection of the PRIs is presented in Annexures 1 and 2. While it is noted that the proposed PRIs cannot be representative of all individual elements, the selected PRIs are considered to allow for a broad scale assessment of when a response may be needed to groundwater and flood hazards.

Table 2. Initial Project Response Indicators

Project Response Indicators for Groundwater Hazards ***Indicators refer to the 85th percentile groundwater level in metres below ground level (mbgl)***	
Element	***Proposed PRI value***
Local ponding/flooding	Emergent groundwater (<0 mbgl)
Buildings	New builds 0.3 m, older buildings 0.3 m (sandy soils) and 0.7 m (silty soils)
Contaminated Sites	0 mbgl - surface exposure at site 0.5 mbgl - services within 50 m of contaminated site
Parks and Reserves / Sports Fields	0.3 mbgl sandy soils 0.5 mbgl silty soils
Roads	0.1 mbgl for local roads, 0.3 mbgl main arterial routes
Service Stations	0.5 mbgl – buoyancy of underground storage tanks
Stormwater / Wastewater Laterals	Dependent on pipe depth – groundwater at mid-level of pipe
Stormwater / Wastewater Mains	Dependent on pipe depth – groundwater 1 m above top of pipe for buoyancy
Project Response Indicators for Flood Hazards ***Indicators refer to the depth of water in metres (m) above ground level or Damage Ratio[2] (DR) for a specified likelihood of flooding in terms of Annual Exceedance Probability (AEP)***	
Element	***Proposed Indicators***
People's safety (roads and properties)	0.4 m at 0.5% AEP
Buildings	No underfloor damages at 10% AEP, No above floor damage at 2% AEP, DR<0.1 at 0.5% AEP
Contaminated Sites	0 m at 0.5% AEP (i.e., no flooding for all AEPs considered)
Roads	Use people's safety threshold (lower than hazard to roads themselves)
Service stations	As for buildings
Stormwater Laterals / Mains	None
Wastewater Laterals / Mains	None
Water Supply Laterals / Mains	None
Stormwater Pump Station	0.3 m at 0.5% AEP
Wastewater Pump Station	0.3 m at 0.5% AEP
Wastewater Monitors	None
Water Supply Station	None
Parks and Reserves / Sports Fields	0.2 m at 10% AEP

[2] As defined in Table 3 of RiskScape: Flood fragility methodology, NIWA Client Report: WLG2010-45, August 2010

Annexure A. Groundwater Hazard Impact Thresholds

For the LDRP45: Impacts of Earthquakes and Sea Level Rise on Shallow Groundwater Levels study, Rutter (2020) adopted a groundwater threshold value of 0.35m 85th percentile depth to groundwater as an indicative level at which groundwater was considered to become a problem. The 0.35 m 85th percentile groundwater level has a 15% probability of exceedance in any given year.

Modelled groundwater change in median water levels were simulated for a number of sea level rise scenarios and applied to a statistically derived present day 85th percentile baseline water level surface to produce the future 85th percentile water surfaces.

The study cited a lack of previous examples of defining threshold values in literature and drew on a single study (SBR, 2007) from Rotterdam in the Netherlands.

As part of the current assessment, a further literature review for existing examples of groundwater adaptation thresholds or trigger levels has been undertaken to determine if there were any significant advances since the LDRP45 study (Rutter, 2008).

While the review may not be exhaustive, a comprehensive search was undertaken using keywords and combinations of key words including: groundwater, groundwater level rise, groundwater flooding, sea level rise, climate change, response, trigger level, threshold, adaptation, inundation, and emergent, amongst others. Not all of the literature reviewed are referenced in this report, only those that were considered to be of relevance to the current study are included.

As a general note, there seems to be a substantial increase in studies on the potential impacts on sea level rise, the definition of potential sea level rise impacts, and the various methodologies for assessing groundwater response to sea level rise since 2020. However, with the exception of previously mentioned studies (Rutter, 2020, and SBR, 2007) no examples of quantifying or setting groundwater level rise-specific adaptation thresholds or trigger levels were encountered.

A summary of some of the key examples are provided as follows.

A.1 New Zealand Examples

Natural and Climate Hazard Risk & Vulnerability Assessment Methodology (Urban Intelligence, 2023)

- Refer Section A.5 for full discussion.
- Risk and vulnerability (low, medium, high) assigned based on forecast depth to groundwater under future climate change and sea level rise scenarios across twenty-eight sub-domains including Human, Built, and Natural environments.

Groundwater Rise and Associated Flooding in Coastal Settlements Due to Sea-Level Rise: A Review of Processes and Methods (Bosserelle *et al.* 2022)

- Paper focussed on the methods, tools and approaches available to assess groundwater response to sea level rise to inform resilience and adaptation initiatives (analytical methods, geospatial modelling and numerical modelling).
- Does not define adaptation thresholds.

Preparing for Sea-Level Rise through Adaptive Managed Retreat of a New Zealand Stormwater and Wastewater Network (Kool *et al.* 2020)

- Study Area in Hutt City, Wellington
- Although rising groundwater levels are noted as a consideration, these are not defined or used in the study. The study recommends adaptation thresholds linked to incremental sea level rise and coastal inundation as opposed to specific groundwater levels.

  "…we here use a dynamic adaptive pathway planning approach to identify thresholds for stormwater and wastewater services and retreat options, and for developing a comprehensive and area-specific retreat strategy comprising pathway portfolios, retreat phases, potential land use changes, and for exploring pathway conflicts and synergies. The result is a prototype for an area near Wellington, New Zealand, where a managed retreat of water infrastructure is being considered at some future juncture."

- SLR increment overlays were mapped onto asset layers for exposure up to +1.2 m SLR using RiskScape.

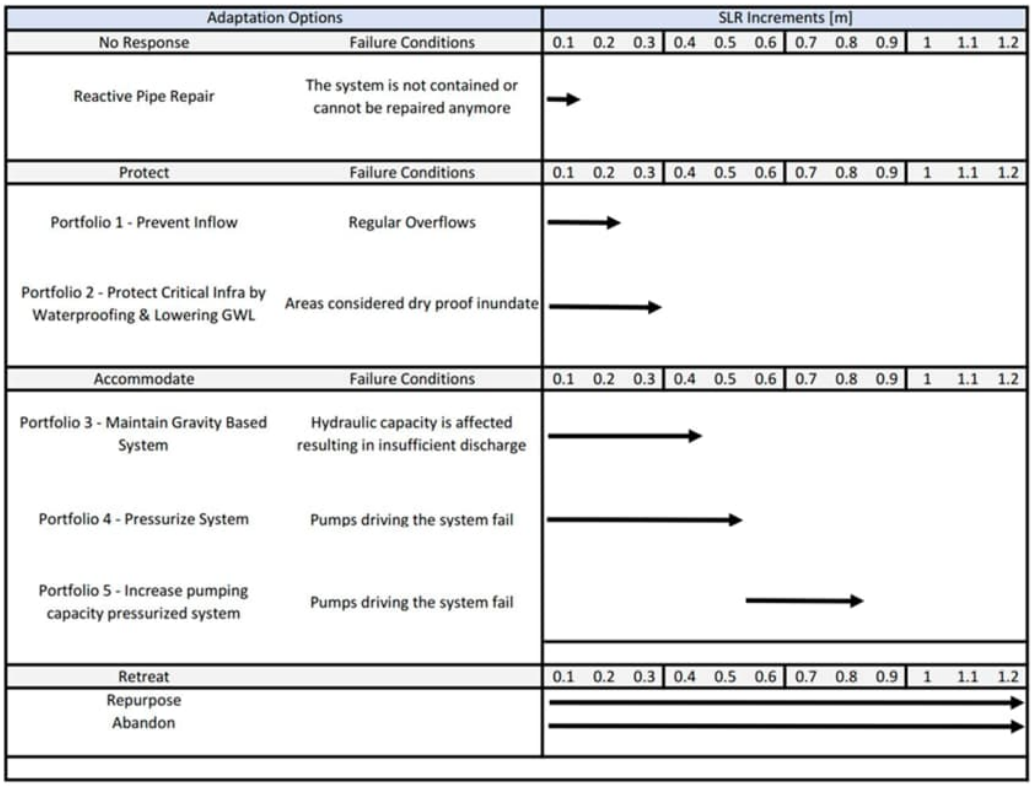


Figure 4 Adaptation portfolios – stormwater and wastewater network, Hutt City – Figure 5 from Kool *et al.* 2020.

LDRP45: Impacts of Earthquakes and Sea Level Rise on Shallow Groundwater Levels (Rutter, 2020)

- Undertook a high-level study to investigate the scale of the potential issues for residential areas in Christchurch.
- Using the adopted trigger level (groundwater 0.35 m below ground surface), a number of properties were identified as potentially above this trigger level. With sea level rise, and with land subsidence from future earthquakes, the area and number of properties affected is likely to increase significantly. The effects were assessed as being greatest in areas close to the coast or tidal reaches of river, with a reduced effect further away.
- The 0.35 m depth to groundwater trigger level was derived from previous work by SBR (2007) and through workshopping with Christchurch City Council.

Table 3. Minimum drainage depths associated with various urban functions – Table 11 from Rutter, 2020 and SBR, 2007.

Land use type	Drainage depth (depth to groundwater in m below surface level)	CCC guidelines
Houses, buildings, structures	0.70	
Primary roads	1.00	0.65 (NZTA – 1.5m)
Secondary roads	0.70	0.65 (NZTA – 1.5m)
Cables and pipes	0.60 – 1.20	0.4 (UFB 0.3m)
Gardens and parks	0.50	1.0 (trees)
Sports fields	0.50	
Graveyards	0.30 below coffin	
Footpaths		0.4 (NZTA – 1m)

- Rutter (2020) found that using the 0.7 m median depth to water as a trigger level was equivalent to a trigger level of 0.35 m 85th percentile groundwater depth, in terms of the numbers of properties affected and the 0.35 m trigger level was adopted.
- Groundwater level rise was assessed based on the forecast 0.19 m, 0.4 m, 1 m, 1.88 m and 2.40 m SLR scenarios.

A.2 Other Examples

Other studies reviewed, primarily in the United States, include assessment of sea level rise impacts and associated issues in California[3], Honolulu[4], New Orleans[5], Florida[6], and Alabama[7]. A Danish study (Rasmussen et al. 2022) assessed several adaptation (mitigating) measures to counter rising groundwater in urban areas. The measures assessed included the use of drainage pipes, shallow wells, open drainage ditches and afforestation to increase evapotranspiration. While these studies generally modelled and mapped shallow and emergent groundwater, no trigger levels or adaptation thresholds were defined.

Some other useful studies, not specifically related to climate change, included a Swedish assessment of groundwater level influence on pavement strength (Salour & Erlingsson, 2014), an assessment of effects of rising groundwater on the service life of pavements (Knott et. al. 2017), and a study of the effect of the water table depth on the bearing capacity of shallow foundations (Chen et al., 2022).

The studies in California and Honolulu were generally concerned with mapping areas of emergent groundwater and groundwater flooding, as well as depths to groundwater resulting from sea level rise. While areas predicted to be impacted by groundwater flooding and shallower groundwater were predicted for various sea level rise scenarios, no triggers or adaptation thresholds were developed.

The studies in Florida and Alabama were concerned with the impacts of saltwater intrusion to shallow aquifers and impacts to infrastructure through accelerated corrosion and impacts to water resources.

A.2.1 Potential Saline Intrusion

While it is noted that for the current assessment, potential impacts related to salinisation are excluded, the Florida study highlights how salinity impacts can potentially be exacerbated by implementing groundwater level controls, and serves as a reminder for subsequent studies when considering potential remedial options for controlling shallow groundwater.

The Florida study highlighted the potential for exacerbated saline intrusion if groundwater level rise did not keep pace with sea level rise, or if groundwater level control measures were implemented that maintained groundwater level close to current levels to reduce risks of groundwater flooding. If shallow groundwater levels rise equally with sea level rise the the saline interface (assuming a sharp interface) then the depth of the saline interface will also rise by approximately the same amount. However, given the density differential between fresh groundwater and saline seawater, if shallow groundwater levels are not allowed to rise, then for every metre of sea level rise, the saline interface would rise by approximately 41 m. This effect is depicted on Figure 5.

[3] May et al. 2020.

[4] Habel et al. 2020.

[5] Fischetti, 2001.

[6] Heimlich et al. 2016.

[7] Mohamed et al. 2022.

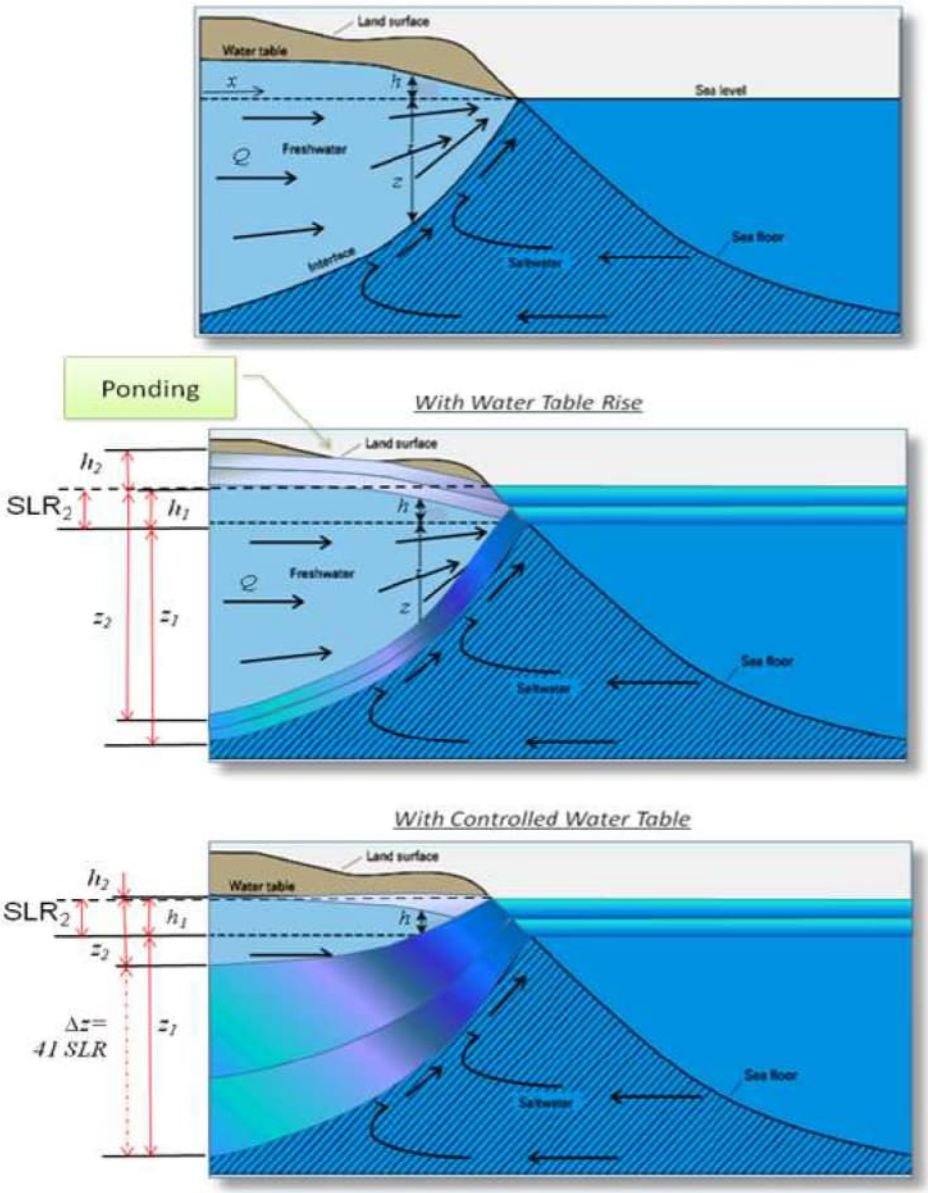


Figure 5 Influence of sea level rise on water table and saline interface – Figure 32 from Heimlich *et al.* 2016.

A.2.2 Assessment of mitigating measures

In the case of the Danish study, assessing various adaptation (mitigating) measures to counter rising groundwater in urban areas, the rising groundwater levels were in response to elevated winter groundwater levels driven by large seasonal variations in recharge. The area assessed was inland and not associated with sea level rise. Four mitigation methods were assessed, these being: installation of sub-soil drainage pipe (parallel to exiting sewer pipe that had been upgraded and no longer acted as groundwater drains themselves), pumping from a network of shallow bores, establishing a plantation forest to increase evapotranspiration, and establishment of an open drainage channel. While the sub-soil drainage pipe was identified as the most effective option, management of produced water was identified as an issue. It is noted that due to the inland location of the investigation area, the potential for saline intrusion was not an issue. The study highlights the role that older sewage and stormwater systems play in maintaining groundwater levels by acting as passive drains. It is noted that this is likely to be occurring in many areas in Christchurch. Rutter (2020) includes an assessment of rising groundwater levels in response to decommissioning of a gravity wastewater drain in Woolston.

A.2.3 Effects on Pavement

The Swedish study on pavement bearing capacity (Salour and Erlingsson, 2014) showed that by raising groundwater level from approximately 2.5 mbgl to 1 mbgl increased moisture content in the sub-grade and sub-base layers (at 0.9 mbgl and 0.5 mbgl, respectively) resulting in reduced stiffness and bearing capacity.

Deflection at the road surface was increased by approximately 50%, and the strength of the sub-base and sub-grade layers were reduced by approximately 30% and 37% respectively. The increased groundwater levels are shown on Figure 6, and the resulting increase in soil moisture and deflection are shown on Figure 7.

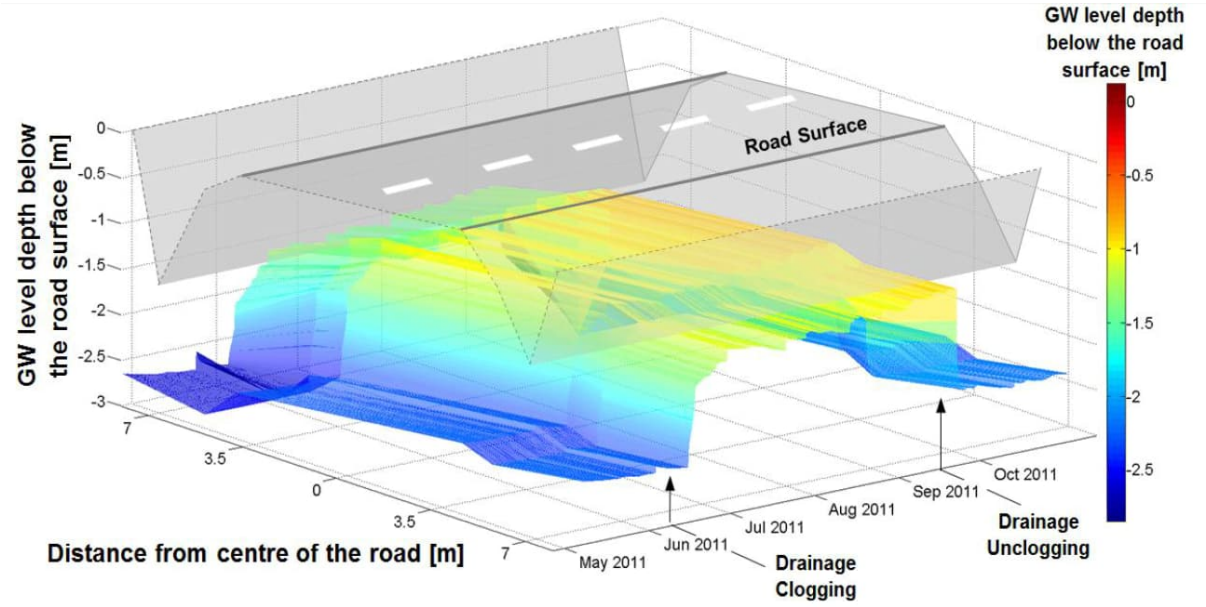


Figure 6 Variation in groundwater levels to assess influence on pavement strength – Figure 8 from Salour and Erlingsson, 2014.

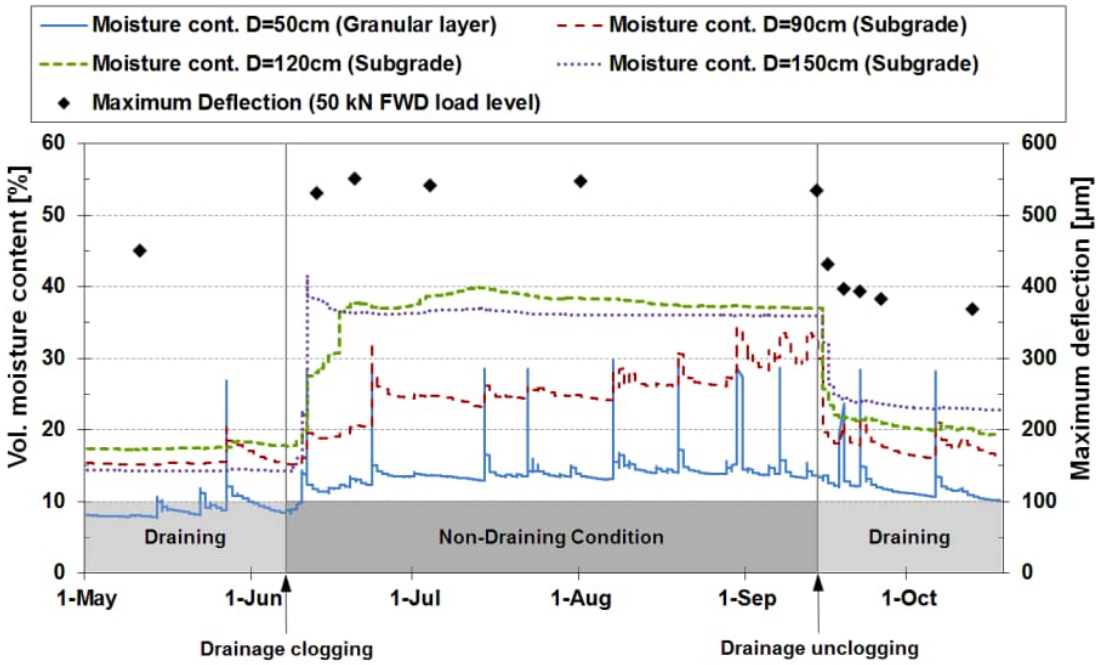


Figure 7 Influence of moisture content on pavement deflection – Figure 13 from Salour and Erlingsson, 2014.

Knott et al. (2017) studied the effects of rising groundwater levels due to sea level rise on coastal roads in New Hampshire (New England, U.S.). The study included roads ranging from local to interstate highways. Groundwater levels were modelled for a range of sea level rise scenarios. The models were run in steady state and did not consider seasonal or annual variation in recharge rates caused by climate change.

Typical pavement profiles were developed for five investigation sites, including thickness of asphalt and base layers, and nature and thickness of subgrade layers. Numerical modelling was undertaken to determine pavement response to loading with elevated groundwater levels induced by the sea level rise scenarios.

Key findings were as follows, for roads that are vulnerable:

- reductions of 5% to 17% in fatigue life are predicted as groundwater rises in the subgrade and increasing to 50% as groundwater moves into the base layers of the pavement.
- reductions in rutting life from 38% to 92% are predicted when groundwater moves from the subgrade into the base layers.

A.3 Potential Groundwater Related Issues

The following provides an overview of potential groundwater related issues that may need to be considered. The list is not exhaustive but provides an overview of the range of issues that have potential to arise.

Shallow/rising groundwater

- Services / infrastructure
  - Groundwater ingress / subsurface inundation
  - Reduced functionality of gravity drains and sewers
  - Increased pumping demand in pumped catchments
  - Reduced stormwater infiltration
  - Potential buoyant forces – underground storage tanks / underground pump housings etc
  - Increased corrosion due to salinification
  - Elevated groundwater levels requiring dewatering to undertaken work and repairs
  - Reduced service life of wooden power poles
- Roads
  - Increased flooding due to reduced drainage performance
  - Increased soil moisture resulting in reduced bearing capacity, resulting in reduced service life and increased maintenance costs.
  - Will impact state and local roads differently due to both age and drainage specifications
- Buildings
  - Increased soil moisture resulting in reducing bearing capacity causing settlement
    - (potentially an issue for larger buildings > 2 stories)
  - Water ingress to underground structures / basements
  - Rising damp
    - unlikely to be an issue for modern buildings with damp course / vapour barriers.
    - older and historic buildings.
- Wetlands / Stormwater basins
  - Reduced functionality in sediment retention and flood detention if flooded by groundwater prior to storm events.
  - Potential for salinification altering vegetation and treatment outcomes.
- Seismic
  - Increased liquefaction hazard
- Vegetation
  - Vegetation stress / die-off or change in vegetation type.

  - Too much water is as damaging to plants as too little, especially if the flooding persists for more than 2 or 3 days. Roots require abundant oxygen to live and grow, and waterlogged soils become anaerobic quickly.
  - Transition from previous grassed area to wetlands – e.g. Prestwick Street wetland at Kerrs Reach.

- Parks / sports fields / green areas
  - increased soil moisture and reduced infiltration
  - reduced trafficability - water logged muddy surface
  - loss of recreational / aesthetic amenity
  - also applicable to private lawns / bowling greens etc
- Cemeteries
  - Reduced functionality – limitation on depth of excavation/internment
- Saline intrusion
  - Biggest risk of substantial change is in areas of shallow groundwater management due to drains pumping etc pumping and discharge of saline groundwater
  - Risk to shallow groundwater users, vegetation, soil salinification

Emergent Groundwater

- Direct inundation/flooding
  - Contaminant migration and exposure (contaminated sites / landfill / cemeteries / sewage / septics etc)
  - Restricted movement (traffic, pedestrians)
  - Filling of stormwater retention ponds – reducing effectiveness
  - Reversal of stormwater flows – storm drain backflow produced flooding in underground parking garages etc.
  - Impact on access and public services like mail delivery
  - Change in vegetation growth
  - Nuisance insect growth/breeding

Note- Many of the impacts to buildings listed above for shallow/rising groundwater are worse for emergent groundwater.

Soil Type

A number of potential groundwater related issues are dependent on soil type which influences both the potential for capillary rise and the degree of drainage. Begg et al. (2015) have mapped the geomorphology of the Christchurch area, within the study area there are two dominant landforms, these being: swamp basin deposits, characterised by predominantly silty soils with impeded drainage; and coastal dune deposits, characterised by relatively free draining sand soils.

The coastal dune areas are typically elevated compared to the swamp basin deposits and therefore usually have a greater depth to groundwater. Areas of current and future issues related to shallow groundwater are, for the most part, most closely associated with areas dominated by swamp basin type deposits. Key exceptions to this are the lower lying landward coastal areas between Waimairi and South Brighton.

A.4 Future Coasts Aotearoa Project

Jacobs have engaged with the team running the Future Coasts Aotearoa project Future Coasts Aotearoa | NIWA. This multi-year research project is investigating, understanding, and adapting to changes in coastlines with climate change. The project focuses on rural landscapes and includes understanding social science impacts of changing hazards, as well as the physical aspects of groundwater rise and associated effects. The project also has a focus on ecosystems such as wetlands in coastal areas. The aim is to develop evidence-based information to understand impacts on coasts to lead adaptation.

The project started last year, and is currently focusing on economic and social sciences, as well as physical modelling of sea level rise scenarios. The project aims to develop various case studies to explore adaptation and policy testing by modelling. The project will include adaptation thresholds; however, at the time of writing this memo, it is understood that this work is not yet underway.

The team noted that they have also completed a global review of numeric thresholds for assets which did not return any guidance related to numeric values for these either.

A.5 CCC Risk and Vulnerability viewer

The CCC Risk and Vulnerability Viewer assesses risk based on the exposure and vulnerability of elements and indicators to hazards. Risk is assessed where:

- exposure occurs when an asset is in an area susceptible to a hazard, and
- vulnerability is a combination of the severity of exposure and the asset's ability to withstand that level of exposure.

Vulnerability is assessed through development of a fragility curve for each asset, with the vulnerability curve plotting hazard severity against asset damage. In some cases, where an assets fragility to certain hazards was unknown or could not be quantified, then the degree of exposure was applied. In other cases, a qualitative assessment of the asset's vulnerability was undertaken based on information available via literature review or consultation with subject-experts and mana whenua (Urban Intelligence, 2023).

Vulnerability in the viewer is rated as either low, medium, or high, and relate to the 'asset' as opposed to the 'service'. For example, while it would be unsafe to drive over a road with 2m of flood depththe road itself might be Ok and thus the vulnerability level relates to the asset impact not the impact on users. in the context of adaptation. A summary of key vulnerability rankings with respect to groundwater is provided on Table 4 along with commentary from the current study. A full overview of vulnerability rankings with respect to groundwater is provided in Appendix B2.

Table 4. Risk and Vulnerability Viewer Groundwater Vulnerability Categories

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Cemeteries	Below depth of double internment Below 1.8 mbgl	Between depth of single and double internment 1.4 to 1.8 mbgl	Above depth of single internment above 1.4 mbgl	Any groundwater encountered in internment excavation would require adaptation. Lowering casket into flooded grave would be intolerable. As no consideration of wider societal and cultural values have been made no project response indicator is therefore proposed..
Commercial Buildings and Facilities / Council Housing / Industrial Buildings and Facilities / Residential Buildings / Schools	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Contaminated Sites	tbd[1]	tbd	tbd	Risk of exposure and or mobilisation
Parks and Reserves / Sports Fields	Below 0.7 mbgl	0.3 to 0.7mbgl	Above 0.3 mbgl	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Roads / State Highways	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Service Stations	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Older service stations and Underground Storage Tanks (USTs) likely less tolerant than new builds.
Stormwater Laterals / Mains	At or above a pipe including allowance for seasonal fluctuation	At or above a pipe that is not metal or concrete	At or above a concrete or metal pipe	Low should be below pipe? Does not state at or above top or invert of pipe – assume invert?
Stormwater Pump Station	Below 0.5 mbgl	0 to 0.5mbgl	At or above ground surface	Dependant on depth of service
Wastewater Monitors	tbd	tbd	tbd	Not specifically assessed
Wastewater Laterals / Mains	Not stated	Not stated	Not stated	Dependant on pressure/suction or gravity and depth
Wastewater Pump Station	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Dependant on depth of service
Water Supply Laterals / Mains	At or above a pipe including allowance for seasonal fluctuation	At or above a pipe that is not metal or concrete	At or above a concrete or metal pipe	Low should be below pipe? Groundwater low risk to water supply pipes? Could hinder repairs or replacement?
Water Supply Station	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Dependant on depth of service

Note: tbd - to be determined still by the Urban Intelligence team, current timeline unknown. Where vulnerability data is still to be developed we will use alternative information to inform our PRI's.

A.6 Proposed Project Response Indicators for Groundwater Hazards

Proposed project groundwater level indicator values are provided on Table 5. The indicators are proposed for when groundwater level rise is considered likely to become an issue for a particular service or asset. It is noted that not all of the issues discussed on Table 5 have been adopted for the final assessment. Adopted indicators and indicator values are provided in Table 5.

The data available to apply to the project indicators comprise median and 85th percentile water levels for present day and under future sea level rise scenarios as developed by Rutter (2020).

Rutter (2020) adopted a 0.35 mbgl 85th percentile groundwater level as the trigger level at which groundwater was considered to become a problem. As a broad regional scale triage approach to identify problem areas this is reasonable. However, the indicator values proposed in Table 5 below for specific elements of land use are generally deeper below ground level than the broad-brush trigger of 0.35 mbgl and individual elements will require their own specific triggers or indicators.

The 85th percentile water level is considered to be a suitable value for defining indicator values. If an indicator has a 15% probability of exceedance, that is equivalent to approximately 55 days of the year. Whether this is likely to result in impact or not depends on the susceptibility of the subject to groundwater and whether the occurrence is intermittent of consecutive. However, a conservative approach would be to assume that any significant exceedance of a defined indicator (notionally 15% exceedance) could be of concern.

It is noted that Jacobs have not verified the accuracy of modelled 85th percentile depth to water and it is recognised that given the original intent of the modelling, and the subsequent availability of more detailed shallow groundwater datasets that were not included in the model calibration, the model may not accurately represent detailed water level at the local scale. However, as these are the datasets that the adaptation indicators will be assessed against they are taken as being appropriate for the purposes of this study and are considered suitable for a broad scale screening for potential groundwater related issues.

Initial indicator levels were estimated based on available literature and discussion with Zeb Etheridge (pers.com. 2023) regarding indicative indicator values adopted for the Future Coasts work for NIWA, and have been refined as an outcome following the indicators workshop.

Table 5. Proposed Project Groundwater Response Indicators

Cause	Issue	Discussion	Proposed indicator	Proposed indicator value
Emergent Groundwater	Contaminant exposure	Direct exposure to contaminants due to emergent groundwater or migration of contaminant to shallow services stormwater etc. Mapped/ known contaminated sites / Hail sites	Groundwater level at surface or near surface or at level of service when in proximity to site	0 mbgl for surface exposure at contaminated site. Nominal 0.5 mbgl for services where services within 50 m of contaminated site (dependant on depth of services).
	Surface Inundation / flooding	Groundwater flooding, exacerbated surface flooding Note – modelled groundwater elevations above ground level are not indicative of potential depth of inundation	Groundwater level at surface for surface flooding	0 mbgl
	Wetlands / Stormwater basins	Groundwater flooding of basins leading to reduced functionality and attenuation.. Continual or increased pumping of groundwater to maintain attenuation capacity.	Groundwater level above invert of basin	Nil – not included for current assessment. Most OARC basins still to be developed hence invert levels unlikely to be known for comparison.
Shallow Groundwater	Service Inundation / flooding	Dependent on depth of services e.g. gravity drains and sewers will be shallower in collection areas and deepening towards outlets / pump stations. Also dependent on vulnerability of service to groundwater.	Groundwater level at or above top of service	Nil – not included for current assessment. Generally captured under Emergent Groundwater and flooding triggers.
	Groundwater ingress to services	Dependant on depth and type of service. Notionally groundwater at invert will not disrupt service. Groundwater at top of service potential for complete disruption – assumes leaky service. As a workshop outcome it was identified that gravity wastewater and stormwater laterals were most vulnerable.	Groundwater level at mid-level of service depth resulting in disruption or reduced capacity of service	Variable dependant on depth to service Nominal mid-section elevation of pipework.
	Reduced life expectancy of services	Accelerated corrosion. Reduced life of wooden power poles.	Groundwater level at invert of service	Nil – not included for current assessment. Depth to services too variable across wide study area to consider at this stage and in many cases likely unknown plus significant volumes of services. Would be better considered on small scale site specific basis.

Cause	Issue	Discussion	Proposed indicator	Proposed indicator value
	Buoyancy – tanked underground structures, underground storage tanks, pipes	Highly variable and dependant on size, depth and design of structure. USTs should be anchored in shallow groundwater areas but could still be susceptible to damage	Groundwater level above invert of structure/tank	Tanked underground structures not included for current assessment. Nominal **0.5 mbgl** for USTs.
	Roads / pavement	Will vary depending on state or local roads. New roads should have sub-soil drains and drainage layers installed in shallow groundwater areas. Older roads may have been resurfaced rather than rebuilt, so may not include drainage layers.	Groundwater rise becomes an issue when groundwater levels come close to the top of drainage layer resulting increased moisture content in sub-base layer. Significance will also vary with road hierarchy and construction – main arterial roads vs local roads Some low lying roads are likely already within indicator values e.g. ANZAC Drive, New Brighton Road	Variable dependent on depth of road base. Nominally **0.1 mbgl** for local roads and **0.3 mbgl** form main arterial routes.
	Buildings – rising damp	Capillary rise / rising damp probably not an issue for recent builds that incorporate vapour barriers, damp course and elevated floor levels. Issue is groundwater at level of slab/beams. Applicable to wooden piled buildings and older houses. Will also vary depending on dominant soil types with potential capillary rise proportional to fine grained portion of soils.	For older buildings, based on soil mapping or predominantly sandy soils and predominantly silty soils For modern buildings indicators would be shallower and associated with shallow excavations for soil improvemnt.	For new builds, notionally **0.3 mbgl** For older susceptible buildings Sandy soils - Notionally **0.3 mbgl** Silty soils - Notionally **0.7 mbgl**
	Water ingress to underground structures	Dependant on depth and type of structures Tanked or un-tanked Unsure of applicability in study area	Groundwater level above invert level	Nil – not included for current assessment. Likely too dependant on depth and type of structures which cannot be feasibly assessed at the wide project scale. Best considered for local scale assessment of specific assets.
	Seismic	Increased risk of liquefaction with increasing groundwater levels and increased saturation of fine-grained sediments Already covered by Liquefaction Lab that allows assessment of potential damage with increasing groundwater level above average water level	n/a	Nil – not included for current assessment. As already covered as discussed.

Cause	Issue	Discussion	Proposed indicator	Proposed indicator value
		https://apps.canterburymaps.govt.nz/ChristchurchLiquefactionViewer/		
	Vegetation	Increase in water logging and anaerobic conditions resulting in vegetation stress and die off Highly dependent on vegetation type and rooting depths Changing climate conditions and rising groundwater levels are already a consideration of the Ōtautahi Christchurch Urban Forest Plan.	Variable – dependant on vegetation and soil type. Ecologist may be able to advise more applicable indicators.	Nil – not included for current assessment. Too highly dependant on vegetation type and rooting depth. Generally cover by parks and sports fields.
	Parks / sports fields / green areas / golf clubs	Elevated moisture content resulting in reduced infiltration, sustained water logging and loss of amenity.	Variable – dependant on soil type.	Sandy Solis - Notionally **0.3 mbgl** Silty soils - Notionally **0.5 mbgl**
	Cemeteries (new burials)	Dependent on depth of internment. Typical internment depths are 1.4 m single and 1.8 m double. Water table above depth of internment would prevent excavation. Relevance to study area • Barbadoes Street Cemetery – closed. • Linwood Cemetery - open for ashes internment, second internments, and Hebrew Congregational burials. It is noted that the Jewish internment blocks (16, 19) are outside of the project area. • Memorial Park Cemetery - open for casket and ash internment. Memorial Park Cemetery is noted to currently have shallow depth to groundwater (<1.5mbgl) under part of the grounds, however, vacant plots are generally on elevated ground. No consideration of wider cultural and societal values has been made hence a PRI for all possible scenarios has not been developed.	Groundwater level approaching internment level SBR (2007) – 0.3 m below coffin	Nil – not included for current assessment. As no consideration of wider cultural and societal values has been made hence a PRI for all possible scenarios has not been developed.

Annexure B. Flood Hazard Project Impact Indicators

We have reviewed the current range of approaches to assessing and categorising the risk of direct flooding impact. The review considered relevant New Zealand local government plans (e.g., District and Regional Plans), relevant New Zealand guidance (e.g., central government guidance and legislation) together with risk classification approaches from selected international hazard management guidelines. This section provides a summary of the findings of our review. The detail of the review is provided in Appendix B1. Our proposed indicators are presented in Section B.6.

Land use planning indicators for flooding generally consider either the likelihood of exposure to flooding or the flooding hazard (i.e., the severity or consequences of the flooding) or a combination of likelihood and hazard, i.e., the risk. Likelihood of flooding is usually described by the Annual Exceedance Probability (AEP) and flood hazard is usually defined by categories of danger from flooding or the financial damages resulting from the flooding. Flood hazard can be considered in terms of the hazard to people, buildings, infrastructure or other elements of land use.

B.1 New Zealand examples

New Zealand Building Code Clause E1 – Surface Water (NZBC E1)

Performance Objective E1.3.2 of NZBC E1 requires that 'surface water, resulting from an event having a 2% probability of occurring annually, shall not enter buildings'. The requirement applies to 'to housing, communal residential and communal non-residential buildings'. A freeboard of 150 mm (500 mm where deeper water extends from roads to the building) is also required such that the adaptation indicator could be set as when the flood level is less than, e.g., 150 mm below floor level in the 2% AEP.

New Zealand Standard NZS4404:2010 Land Development and Subdivision Infrastructure

Stormwater systems in new subdivisions are expected to ensure that ponding or secondary flow on local roads is less than 100 mm deep on the center line and the velocity limited such that the carriageway is considered passable in a 5% AEP design storm. This threshold therefore takes account of both likelihood and hazard.

Christchurch District Plan

The District Plan, which gives effect to the Canterbury Regional Policy Statement (CRPS) policies, uses a combination of flood likelihood, velocity and depth to define hazard categories and thresholds. The Plan defines the Flood Management Area as the 0.5% AEP flood extent and requires that minimum floor levels are set at least 400 mm above the flood level. The High Flood Hazard Management area is defined as where the depth (m) x velocity (m/s) of flooding in a 0.2% AEP flood is equal or greater than one. Much of the project area lies within the Flood Management Area

Hamilton City District Plan

The District Plan uses depth as the only parameter for categorising flood hazard within the Waikato River Corridor and depth and velocity for the hazard outside the River Corridor. In both cases hazard is defined by a single likelihood of flooding (1% AEP).

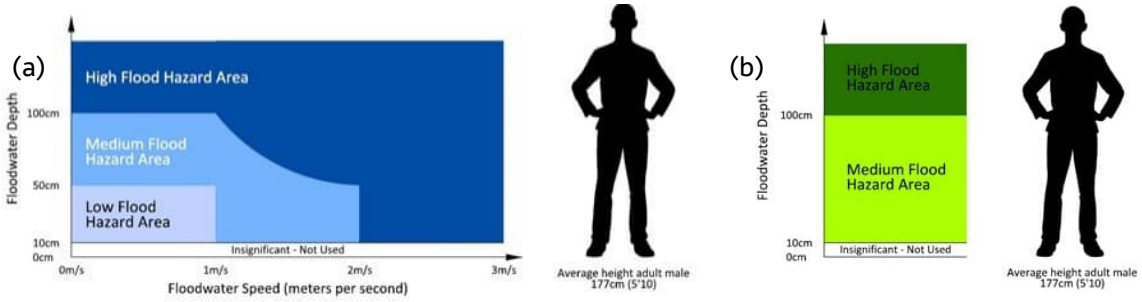


Figure 8. Definition of flood hazards in the Hamilton City District Plan (a) outside the Waikato River Corridor and (b) inside the Waikato River Corridor.

In this case adaptation indicators could be defined by the limits of a selected hazard category, for example the indicator could be defined as the hazard being no more than low.

Auckland Council – Recovery from extreme weather and natural disasters – Property Risk Categories

Auckland Council has been responding to the extreme weather events of early 2023 which caused a lot of flood damage. As part of that there was a categorisation of properties in storm affected areas using a government property risk assessment framework. The guidance note entitled "How we decide property risk categories (Dated Dec 23)[8]" gives a concise summary of the method applied for categorising risk and is a useful reference to consider. The emphasis is very much on the risk to people rather than buildings themselves. Category 3 is where the risks are most severe, defined as "meeting the threshold for intolerable risk to life…".

In terms of what "intolerable" means for flooding hazards, that is defined as "a high risk to life for vulnerable people in a flood event that has a one per cent chance of happening or being exceeded in any one-year (an existing 1% Annual Exceedance Probability (AEP) flood event)."

Using the Australian Rainfall & Runoff Guidelines method for hazard categories (discussed in Section B2 below), still water depth > 0.5 m is "unsafe for children and the elderly" so that could be taken as "high risk to life for vulnerable people". Therefore a plausible threshold for intolerable risk could be 0.5 m depth of water in a 1% AEP event.

RiskScape: Flood fragility methodology, NIWA Client Report: WLG2010-45, August 2010

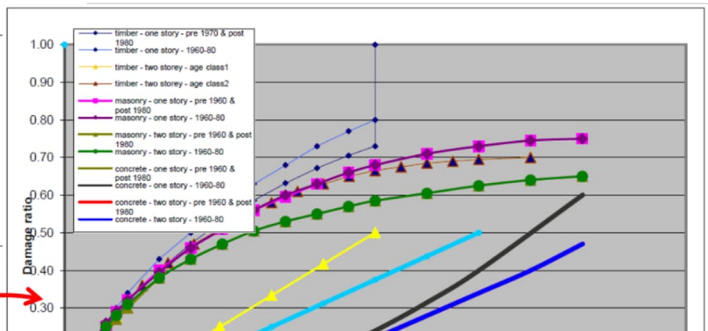
This report summarises the development of the methodology within the NIWA RiskScape model to define the damage to property, infrastructure and people from flooding. Depth-damage functions, or fragility curves, are commonly used to estimate potential direct damage costs and typically relate the percentage damage (relative to replacement cost) for a variety of elements such as buildings, cars, household goods, relative to flood characteristics such as inundation depth, velocity or duration.

The study developed fragility curves for a variety of building types, which have been adopted in Council's FloodFX tool used to quantify flood damages in the Multi-Hazards project. The direct building damage is expressed in terms of damage ratio, i.e., repair cost relative to replacement cost or as a damage state. As shown in Figure 9 (A), five 'damage states' are defined, and for each, different repair actions would be required to restore the structure to its pre-flood condition. For example, Damage State 1 (DS1) represents non-structural damage, referring to repairs such as, 'repair of interior walls that have been saturated, and possible superficial external damage (e.g. broken windows)'. In comparison, DS4 represents severe damage to the structural system itself, thus requiring partial or complete demolition and rebuild of the structure. For each of these damage states a threshold damage ratio is defined.

The fragility curves define the relationship between flood depth above floor level at the building and the damage ratio for each type of building considered, as shown in in Figure 9 (B).

(A)

Damage state	Description	Damage ratio
DS0	Insignificant	0–0.02
DS1	Light—Non-structural damage, or minor non-structural damage	0.02–0.1
DS2	Moderate—Reparable structural damage	0.1–0.5
DS3	Severe—Irreparable structural damage	0.5–0.95
DS4	Collapse—Structural integrity fails	> 0.95



(B)

Figure 9. (A) Definition of Damage States, damage description, and damage ratio used within Riskscape. (B) Flood fragility curves for various building types, relating inundation depth above the floor level (m) along the horizontal axis with damage ratio along the vertical axis.

Project Response Indicators for flooding of buildings could be defined by Damage States – e.g., DS0, DS1, DS2 etc. – and the corresponding indicators of damage ratio values. The fragility curves could then be used to calculate the damage ratio from flood depth for comparison with the indicators as shown in Figure 10.

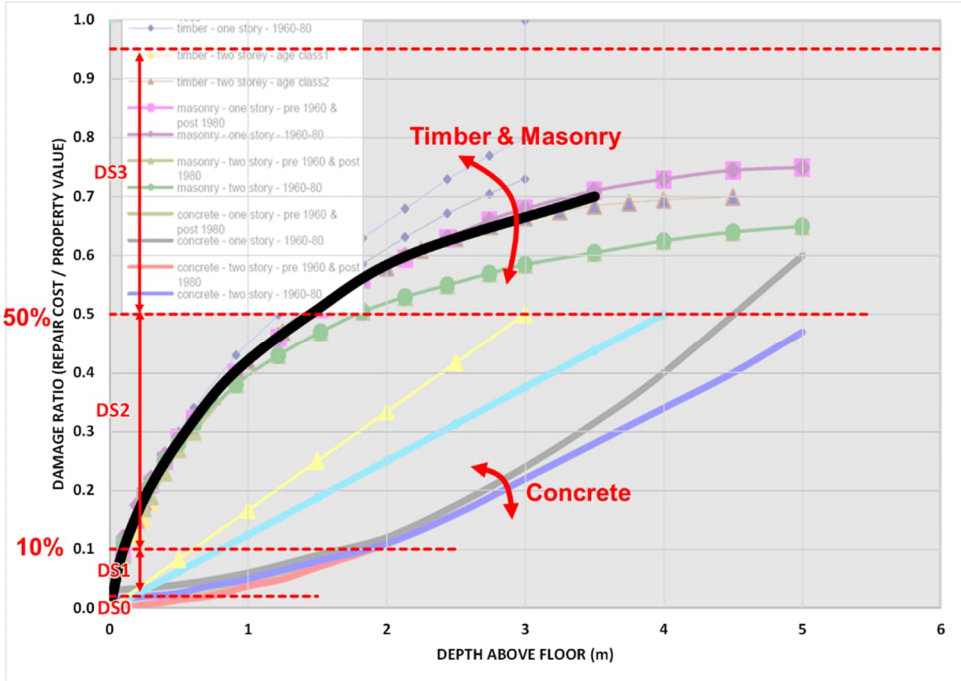


Figure 10. Flood fragility curves adapted from Riskscape for potential implementation into our project indicators framework. Fragility curves for Timber and Masonry versus Concrete building types, with inundation depth above the floor level (m) along the horizontal axis and average damage ratio and damage states along the vertical axis.

B.2 Other examples

Australian Rainfall and Runoff Guidelines Combined Flood Hazard Curves[9]

The Australian Rainfall and Runoff (AR&R) Combined Flood Hazard Curves define categories of severity of flood hazard for people, vehicles and building according to the combination of flood depth and velocity (Figure 11). The thresholds for hazard to people are lower than for buildings, and the thresholds for hazard to vehicles are lower than for people. For lower velocities, less than 0.5 m/s, the hazard thresholds are independent of velocity and are defined by water depth only. The AR&R guidelines are widely used to categorise flood hazard in Australia and elsewhere. In New Zealand the guidelines are specified by Greater Wellington Regional Council for mapping flood hazard in their Flood Hazard Modelling Standard (May 2021).

Review of the baseline model results for the project area shows that flood water velocities over almost all the project area are less than 0.5 m/s and therefore adaptation indicators could be defined simply by the limiting still water depths for an appropriate hazard category and applied to model results for maximum flood depths.

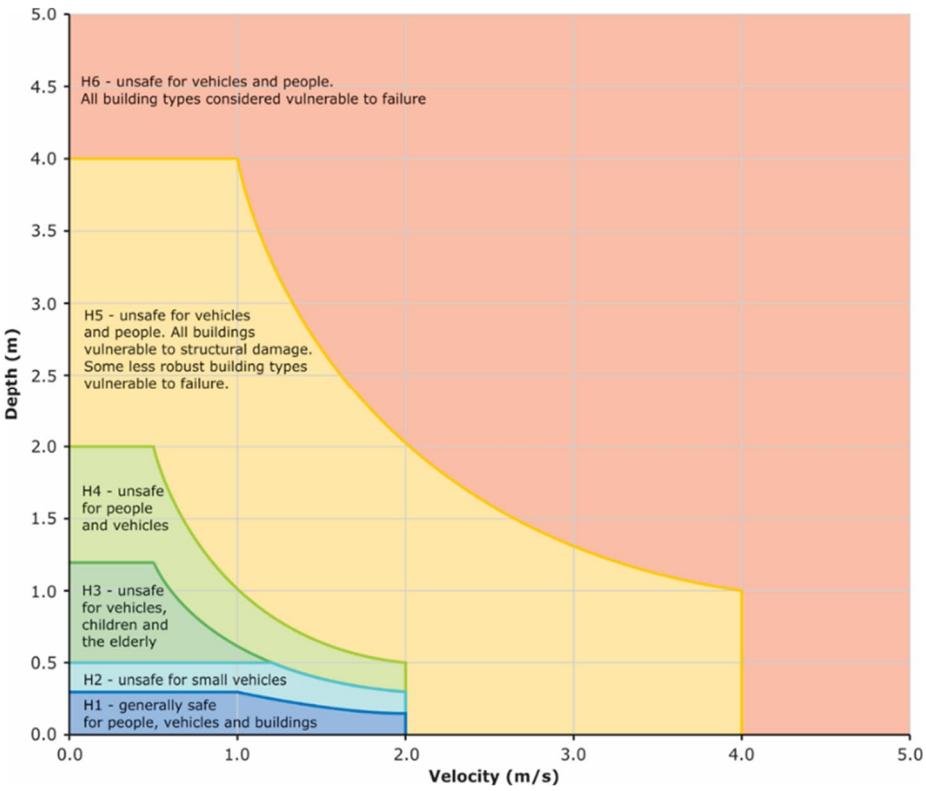


Figure 11. Combined Flood Hazard Curves of the Australian Rainfall and Runoff Guidelines.

UK DEFRA/Environment Agency Framework and Guidance for Assessing and Managing Flood Risk for New Development

[9] Australian Government (2017) Supporting document for the implementation of Australian Disaster Resilience Handbook 7 Managing the Floodplain: A Guide to Best Practice in Flood Risk Management in Australia (AIDR 2017), The Technical flood risk management guideline: Flood hazard Australian Disaster Resilience Handbook Collection 2017

This guidance defines four classes of flood hazard to people according to a Flood Hazard Rating calculated from the flood depth and velocity and an allowance for the additional hazard of debris (Figure 12). The hazard class thresholds for are generally lower than in the AR&R guidelines for similar severities of hazard and more dependent on flood water velocity, even at lower values.

Adaptation indicators could be defined by the thresholds of hazard class and would need to be applied to the Flood Hazard Rating as calculated from modelled water depths and velocities.

HR	Depth of flooding - d (m)												
	DF = 0.5				DF = 1								
Velocity v (m/s)	0.05	0.10	0.20	0.25	0.30	0.40	0.50	0.60	0.80	1.00	1.50	2.00	2.50
0.0	0.03 + 0.5 = 0.53	0.05 + 0.5 = 0.55	0.10 + 0.5 = 0.60	0.13 + 0.5 = 0.63	0.15 + 1.0 = 1.15	0.20 + 1.0 = 1.20	0.25 + 1.0 = 1.25	0.30 + 1.0 = 1.30	0.40 + 1.0 = 1.40	0.50 + 1.0 = 1.50	0.75 + 1.0 = 1.75	1.00 + 1.0 = 2.00	1.25 + 1.0 = 2.25
0.1	0.03 + 0.5 = 0.53	0.06 + 0.5 = 0.56	0.12 + 0.5 = 0.62	0.15 + 0.5 = 0.65	0.18 + 1.0 = 1.18	0.24 + 1.0 = 1.24	0.30 + 1.0 = 1.30	0.36 + 1.0 = 1.36	0.48 + 1.0 = 1.48	0.60 + 1.0 = 1.60	0.90 + 1.0 = 1.90	1.20 + 1.0 = 2.20	1.50 + 1.0 = 2.55
0.3	0.04 + 0.5 = 0.54	0.08 + 0.5 = 0.58	0.15 + 0.5 = 0.65	0.19 + 0.5 = 0.69	0.23 + 1.0 = 1.23	0.30 + 1.0 = 1.30	0.38 + 1.0 = 1.38	0.45 + 1.0 = 1.45	0.60 + 1.0 = 1.60	0.75 + 1.0 = 1.75	1.13 + 1.0 = 2.13	1.50 + 1.0 = 2.50	1.88 + 1.0 = 2.88
0.5	0.05 + 0.5 = 0.55	0.10 + 0.5 = 0.60	0.20 + 0.5 = 0.70	0.25 + 0.5 = 0.75	0.30 + 1.0 = 1.30	0.40 + 1.0 = 1.40	0.50 + 1.0 = 1.50	0.60 + 1.0 = 1.60	0.80 + 1.0 = 1.80	1.00 + 1.0 = 2.00	1.50 + 1.0 = 2.50	2.00 + 1.0 = 3.00	2.50 + 1.0 = 3.50
1.0	0.08 + 0.5 = 0.58	0.15 + 0.5 = 0.65	0.30 + 0.5 = 0.80	0.38 + 0.5 = 0.88	0.45 + 1.0 = 1.45	0.60 + 1.0 = 1.60	0.75 + 1.0 = 1.75	0.90 + 1.0 = 1.90	1.20 + 1.0 = 2.20	1.50 + 1.0 = 2.50	2.25 + 1.0 = 3.25	3.00 + 1.0 = 4.00	3.75 + 1.0 = 4.75
1.5	0.10 + 0.5 = 0.60	0.20 + 0.5 = 0.70	0.40 + 0.5 = 0.90	0.50 + 0.5 = 1.00	0.60 + 1.0 = 1.60	0.80 + 1.0 = 1.80	1.00 + 1.0 = 2.00	1.20 + 1.0 = 2.20	1.60 + 1.0 = 2.60	2.00 + 1.0 = 3.00	3.00 + 1.0 = 4.00	4.00 + 1.0 = 5.00	5.00 + 1.0 = 6.00
2.0	0.13 + 0.5 = 0.63	0.25 + 0.5 = 0.75	0.50 + 0.5 = 1.00	0.63 + 0.5 = 1.13	0.75 + 1.0 = 1.75	1.00 + 1.0 = 2.00	1.25 + 1.0 = 2.25	1.50 + 1.0 = 2.50	2.00 + 1.0 = 3.00	3.50	4.75	6.00	7.25
2.5	0.15 + 0.5 = 0.65	0.30 + 0.5 = 0.80	0.60 + 0.5 = 1.10	0.75 + 0.5 = 1.25	0.90 + 1.0 = 1.90	1.20 + 1.0 = 2.20	1.50 + 1.0 = 2.50	1.80 + 1.0 = 2.80	3.40	4.00	5.50	7.00	8.50
3.0	0.18 + 0.5 = 0.68	0.35 + 0.5 = 0.85	0.70 + 0.5 = 1.20	0.88 + 0.5 = 1.38	1.05 + 1.0 = 2.05	1.40 + 1.0 = 2.40	1.75 + 1.0 = 2.75	3.10	3.80	4.50	6.25	8.00	9.75
3.5	0.20 + 0.5 = 0.70	0.40 + 0.5 = 0.90	0.80 + 0.5 = 1.30	1.00 + 0.5 = 1.50	1.20 + 1.0 = 2.20	1.60 + 1.0 = 2.60	3.00	3.40	4.20	5.00	7.00	9.00	11.00
4.0	0.23 + 0.5 = 0.73	0.45 + 0.5 = 0.95	0.90 + 0.5 = 1.40	1.13 + 0.5 = 1.63	1.35 + 1.0 = 2.35	1.80 + 1.0 = 2.80	3.25	3.70	4.60	5.50	7.75	10.00	12.25
4.5	0.25 + 0.5 = 0.75	0.50 + 0.5 = 1.00	1.00 + 0.5 = 1.50	1.25 + 0.5 = 1.75	1.50 + 1.0 = 2.50	2.00 + 1.0 = 3.00	3.50	4.00	5.00	6.00	8.50	11.00	13.50
5.0	0.28 + 0.5 = 0.78	0.60 + 0.5 = 1.10	1.10 + 0.5 = 1.60	1.38 + 0.5 = 1.88	1.65 + 1.0 = 2.65	3.20	3.75	4.30	5.40	6.50	9.25	12.00	14.75

Flood Hazard Rating (HR)	Colour Code	Hazard to People Classification
Less than 0.75		Very low hazard - Caution
0.75 to 1.25		Danger for some – includes children, the elderly and the infirm
1.25 to 2.0		Danger for most – includes the general public
More than 2.0		Danger for all – includes the emergency services

Figure 12. Flood Hazard Rating and Hazard to People Classification of the UK DEFRA/Environment Agency Framework and Guidance for Assessing and Managing Flood Risk for New Development. [DF = 'Debris factor', Flood Hazard Rating (HR) is calculated as HR= d x (v + 0.5) + DF]

UK Environment Agency Flood Map for Planning

The UK Environment Agency Flood Map for Planning (Rivers and Sea) defines four Flood Zones according to three likelihoods of flooding (from any source or combination of sources) as shown in Figure 13.

Flood Zone	Definition
Zone 1 Low Probability	Land having a less than 1 in 1,000 annual probability of river or sea flooding. (Shown as 'clear' on the Flood Map – all land outside Zones 2 and 3)
Zone 2 Medium Probability	Land having between a 1 in 100 and 1 in 1,000 annual probability of river flooding; or land having between a 1 in 200 and 1 in 1,000 annual probability of sea flooding. (Land shown in light blue on the Flood Map)
Zone 3a High Probability	Land having a 1 in 100 or greater annual probability of river flooding; or Land having a 1 in 200 or greater annual probability of sea flooding.(Land shown in dark blue on the Flood Map)
Zone 3b The Functional Floodplain	This zone comprises land where water has to flow or be stored in times of flood. Local planning authorities should identify in their Strategic Flood Risk Assessments areas of functional floodplain and its boundaries accordingly, in agreement with the Environment Agency. (Not separately distinguished from Zone 3a on the Flood Map)

Figure 13. Definition of Flood Zones in the UK Flood Map for Planning (Rivers and Sea)

In this approach, adaptation indicators could be defined by the likelihood of flooding alone, regardless of the consequences. However, such an approach does not allow variations in consequence and hence level of tolerance across an inundated area to be captured in defining when an indicator is exceeded.

Piloting the Use of Network Analysis and Decision-Making under Uncertainty in Transport Operations, X Espinet et al, 2018

This paper presents a methodology using network analysis and decision-making under uncertainty, such as changing flood risk, in transport operations. During the prioritisation process, the authors classify risk to be expressed in terms of damage to the infrastructure, with potential risk to users not incorporated.

The damage to the infrastructure is quantified as the Expected Annual Damage to the infrastructure based on the calculated damages to the road surface at three thresholds: 0.2 m, 0.5 m and 1.5 m of water depth above the road surface. It is assumed that roads are built at ground level (no embankments). For each of the three water depth thresholds a damage value of a percentage of the total replacement coast is adopted – 1%, 2% and 20% respectively for paved roads and 20%, 50% and 100% for unpaved roads. The Expected Annual Damage is then evaluated from flood depths for a range of AEPs. On this basis, adaptation indicators could be based on the depth thresholds for damage values and applied to model flood depths on roads.

B.3 CCC Risk and Vulnerability viewer

The Urban Intelligence (UI) Natural and Climate Hazard Risk & Vulnerability Assessment is under development for council. We have considered the approach it is taking, and the value of vulnerability classifications being used. The assessment considers three wellbeing domains: Human, Natural Environment and Built Environment. To assess the risks to these domains, the vulnerability of elements within each domain is first classified. Within the Built Environment, vulnerability is classified generally by the repair cost of the element as a percentage of the replacement cost, in a similar way to the NIWA Riskscape method for building fragilities. In the Human and Natural Environment, vulnerability is generally classified by water depth and is rated as either low, medium, or high. A summary of key vulnerability rankings with respect to surface water flooding (river or coastal flooding) is provided in Table 6 below.

The vulnerability class thresholds adopted in the CCC Risk and Vulnerability viewer are generally the same for 'coastal flooding' and 'river flooding'. However, several receptor types, particularly those in the natural, cultural, and social domains, do not yet have vulnerability rankings assigned to them for either 'coastal flooding' or 'river flooding'.

Vulnerability rankings related specifically to hazard to life or injury are not defined by the CCC Risk and Vulnerability viewer, except for the 'Social Deprivation' element which considered, 'Physical health from exposure to hazards'. However, thresholds for this element relate to Damage Ratios associated with buildings only, rather than the severity of hazards associated with surface flooding as they relate to human life (or injury). In the current study, we will evaluate the potential risk to three wellbeing domains, including a 'Life' domain

dedicated to the consequences of surface flooding on people's safety. By assigning adaptation thresholds to public safety, the ongoing health and safety of communities (particularly in high flood risk areas) is regulated through a risk-based approach.

Figure 14 compares the depth thresholds adopted by UI for classifying the level of vulnerability for selected elements of land use with those derived under other assessment methods described above.

Table 6 CCC Risk and Vulnerability Viewer Surface Flooding Vulnerability Categories

Domain / Subdomain	Surface Flooding Vulnerability		
	Low	Medium	High
Cemeteries	-	-	Any flooding over the cemetery area
Buildings *(Boat sheds, Commercial Buildings and Facilities, Community Facilities, Council Housing, Heritage Sites, Industrial Buildings and Facilities, Marae, Residential Buildings, Service Stations, Transfer Stations, Religious Facilities, Schools/early childhood education)*	The structural damage is expected to be insignificant or minor - less than 10% of the structure's cost[1]	The structural damage is expected to be repairable - less than 50% of the structure's cost[1]	The structural damage is expected to be unrepairable or structurally unsafe - more than 50% of the structure's cost[1]
Contaminated Sites	tbd	tbd	tbd
Parks and Reserves, Sports Areas, Walkways, Māori Land Claims	Below 10cm depth	Between 10cm and 20cm depth	Above 20cm depth
Road/rail infrastructure *(Carparks, Cycleways, Port Access, Public Transport Systems, Rail, Roads, State Highways)*	When the road damage is expected to be insignificant or minor - less than 10% of the road's cost	When the road damage is expected to be repairable - less than 50% of the road's cost	When the road damage is expected to be unrepairable - more than 50% of the road's cost
Coastal Barriers and Sea Walls	Below 1m depth and the Condition[2] is either "A" or "B"	- Below 1m depth and the condition[2] is "C" OR - Between 1m and 2m depth and the condition is either "A" or "B"	Either: - Condition[2] is "D" - Condition is "E" - Above 1m depth and the condition is "C" - Above 2m depth and the condition is either "A" or "B"
Stopbanks and Engineered Flood Management Schemes	-	Less than 1m depth	Above 1m depth
Mobile Towers	Greater than 2m from the top of the mobile tower	Within 0.5m to 2m of the top of the mobile tower	Within the top 0.5m of the mobile tower
Wastewater Network Laterals, Pipes, Stations, and Treatment Plants, Water Supply Network Stations, and Treatment Plants	-	-	Above 0cm depth
Stormwater Network Stations	Below 10cm depth	Between 10cm and 30cm depth	Above 30cm depth
Wastewater Monitors, Water Supply Network Laterals, pipes, and supply towers, Stormwater Network Laterals and Pipes	tbd	tbd	tbd
Electrical Structures	The probability of the substation failing due to being inundated is less than 10%	The probability of the substation failing due to being inundated is between 10% and 50%	The probability of the substation failing due to being inundated is over 50%

Key:
[1] The expected structural damage is calculated by the Damage Ratio, repair cost as a percentage of replacement (considering the age of the building and its typology - which is assumed to be a single-storey concrete building).

[2] Condition ratings of each asset were given ('A' being the best and 'E' the worst). Where assets were assigned multiple condition ratings, the worst condition rating was used for the vulnerability methodology.

Note: tbd - to be determined.

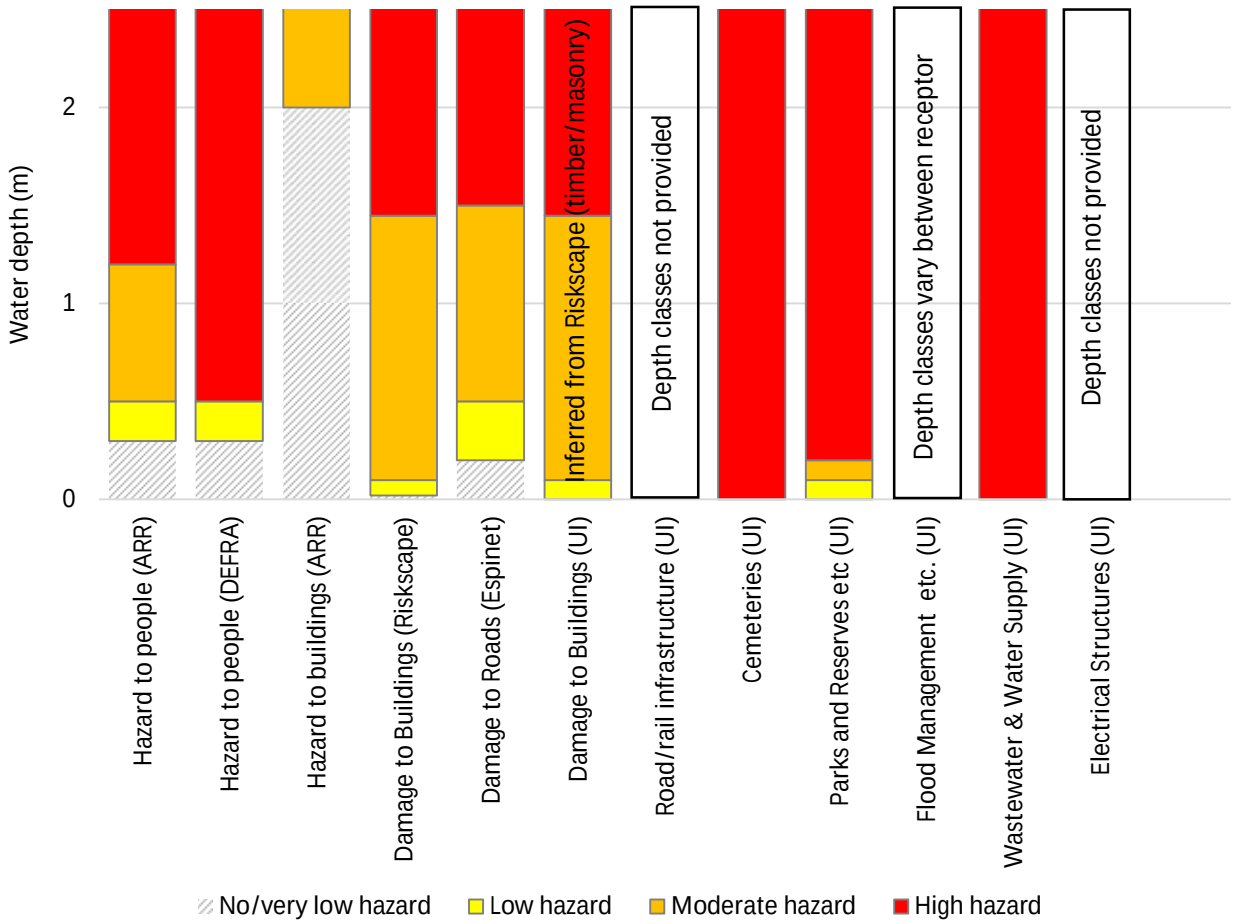


Figure 14. Comparison of flood depth thresholds adopted for varying degrees of hazard severity to elements of land use between UI Risk and Vulnerability Viewer and other methods of assessment.

B.4 The New Zealand Planning Context

This analysis considered various statutory planning documents and guidance relevant to the project area. The statutory planning framework provides guidance on the relative importance of addressing hazard impacts, the types of hazard risks or effects that should be considered, and the timeframe for projections. Decisions made under the planning framework establish a baseline for future outcomes.

1. The Resource Management Act 1991

The current NZ planning framework has been established under the Resource Management Act 1991 (RMA). The RMA provides the overarching legislation for sustainable management at the national, regional and district/city levels and provides scope, content and outcomes sought in planning documents.

Part 2 of the RMA details its purpose and principles, with the principles following a hierarchy beneath the purpose (i.e., sections 5 – 8). Part 2 sets out with the purpose of the RMA:

> *(1) The purpose of this Act is to promote the sustainable management of natural and physical resources.*
>
> *(2) In this Act, sustainable management means managing the use, development, and protection of natural and physical resources in a way, or at a rate, which enables people and communities to provide for their social, economic, and cultural well-being and for their health and safety while –*
>
> *(a) sustaining the potential of natural and physical resources (excluding minerals) to meet the reasonably foreseeable needs of future generations; and*

(b) safeguarding the life-supporting capacity of air, water, soil, and ecosystems; and

(c) avoiding, remedying, or mitigating any adverse effects of activities on the environment.

As shown above, the purpose of the RMA is focused on the sustainable management of resources, as opposed to "sustainable development" which is more widely used internationally. A key aspect of sustainable management is ensuring that community wellbeing is delivered in a manner which protects their health and safety. This is also linked to providing the reasonably foreseeable needs of future generations.

Also, Section 5 of part 2 indicates the ability of councils to take action to protect communities against hazards (i.e., protect their health and safety). When determining the risks of these hazards, councils should consider those hazards which are 'reasonably foreseeable'. This wording implies that extreme or unlikely hazard scenarios should not be employed in the decision making under the RMA. Rather the application of SLR scenarios and hazard indicators should be based on certainty and likelihood, the more certain or likely of which should then be employed to develop the content of a future plan change and/or other responses.

However, the chance that a low probability event (such as the 1% or 0.5% AEP) will occur at some point becomes relatively likely (a 40% to 50% chance) when considering a time period of 60 to 100 years. With reference to the requirements of Section 5 of the RMA, this chance of occurrence is considered to be consistent with being **'reasonably foreseeable'** and supports adopting a relatively low probability to define areas at risk of flooding and hence adaptation indicators.

2. **The Canterbury Regional Policy Statement (CRPS):**

The objectives and policies of the RPS Chapter 11 "Natural Hazards" recognises and provides for the projected increases in flood hazards. It sets out the types of risks to be considered, principally loss of life or significant damage to property. The policies are directive and set out a definition for "high hazard areas" for the Christchurch District as well as specific requirements for building in inundation areas. This direction has been incorporated into this study's identification of risk indicators. The policy framework also set out the requirement for district and city councils to investigate, map and address natural hazards, with specific regard given to the effects of sea level rise and climate change.

CRPS Chapter 11 "Natural Hazards" policies provide some direction for assessing flood hazards. The two relevant objectives of this chapter are:

11.3.1 - Avoidance of inappropriate development in high hazard areas

To avoid new subdivision, use and development (except as provided for in Policy 11.3.4) of land in high hazard areas, unless the subdivision, use or development:

1. is not likely to result in loss of life or serious injuries in the event of a natural hazard occurrence; and

2. is not likely to suffer significant damage or loss in the event of a natural hazard occurrence; and

3. is not likely to require new or upgraded hazard mitigation works to mitigate or avoid the natural hazard; and

4. is not likely to exacerbate the effects of the natural hazard; or

5. Outside of greater Christchurch, is proposed to be located in an area zoned or identified in a district plan for urban residential, industrial or commercial use, at the date of notification of the CRPS, in which case the effects of the natural hazard must be mitigated; or

6. Within greater Christchurch, is proposed to be located in an area zoned in a district plan for urban residential, industrial or commercial use, or identified as a "Greenfield Priority Area" on Map A of Chapter 6, both at the date the Land Use Recovery Plan was notified in the Gazette, in which the effect of the natural hazard must be avoided or appropriately mitigated; or

7. Within greater Christchurch, relates to the maintenance and/or upgrading of existing critical or significance infrastructure.

RPS Policy 11.3.1 (Avoidance of inappropriate development in high hazard areas) provides a definition for "high hazard areas" which for the Christchurch District includes:

1) flood hazard areas subject to inundation events where the water depth (metres) x velocity (metres per second) is greater than or equal to 1, or where depths are greater than 1 metre, in a 0.2% AEP (1 in 500 year) flood event;

3) land within greater Christchurch likely to be subject to coastal erosion including the cumulative effects of sea level rise over the next 100 This includes (but is not limited to) the land located within Hazard Zones 1 and 2 shown on Maps in Appendix 5 of this Regional Policy Statement that have been determined in accordance with Appendix 6; and

4) land subject to sea water inundation (excluding tsunami) over the next 100 years. This includes (but is not limited to) the land located within the sea water inundation zone boundary shown on Maps in Appendix 5 of this Regional Policy Statement.

11.3.2 - Avoid development in areas subject to inundation

In areas not subject to Policy 11.3.1 that are subject to inundation by a 0.5% AEP flood event; any new subdivision, use and development (excluding critical infrastructure) shall be avoided unless there is no increased risk to life, and the subdivision, use or development:

1. is of a type that is not likely to suffer material damage in an inundation event; or

2. is ancillary or incidental to the main development; or

3. meets all of the following criteria:

   a. new buildings have an appropriate floor level above the 0.5% AEP design flood level; and

   b. hazardous substances will not be inundated during a 0.5% AEP flood event;

   provided that a higher standard of management of inundation hazard events may be adopted where local catchment conditions warrant (as determined by a cost/benefit assessment). When determining areas subject to inundation, climate change projections including sea level rise are to be taken into account.

3. Christchurch City Council Flood Intervention Policy

Council will help property owners who have had frequent above-floor flooding, where their flooding has been worsened by the earthquakes, and planned flood mitigation schemes will not offer a timely reduction to their flood risk. In other high priority flood risk areas, once the Council's Land Drainage Recovery Programme has completed flood risk investigations, if there are still properties at high risk that won't benefit from timely area-wide mitigation, the Council will offer the same assistance to these property owners.

To be eligible for assistance, the property must (i) be residential, and within the Christchurch city urban area, (ii) the habitable floor (excluding garages, laundries, sleep outs and utility areas) is at risk from a **10% AEP flood event**, as confirmed by Council modelling and a survey of the floor level, or by frequent post-earthquake flooding, (iii) the earthquakes have worsened the flood risk – assessed by eligibility by Council flood modelling and/or EQC Increased Flooding Vulnerability (IFV).

A 10% AEP flood event is highly likely over the lifetime of a development and the CCC Flood Intervention Policy serves as an example or rule to justify a subsequent analogous indicator of flood likelihood for when adaptation or mitigation decisions may be required.

B.5 Christchurch City Council Coastal Hazards Planning

Under the current Draft Coastal Hazards Plan Change (PC12) and Proposed Housing and Business Choice Plan Change (PC14), Christchurch City Council has proposed a risk-based approach to managing new development in areas exposed to coastal hazards.

For coastal flooding, four different risk categories were identified - High, Medium, Low and Very Low. As shown in Figure 15, these categories are defined by:

- Likelihood of flooding (0.2% AEP).
- Consequence of flooding (depths of flooding which have the potential to cause damage, injury or harm)
- Change in likelihood and consequence in the future with sea level rise (60cm and 1.2m)

The basis for these definitions of flood risk is set out in 'Addendum Report to Risk Based Coastal Hazard Analysis for Land-use Planning Report' IS417100-NP-RPT-0003, Jacobs 2022.

Coastal flood risk category	Flood hazard with 0.6m SLR	Flood hazard with 1.2m SLR
Very low	None (dry)	Low (d < 0.4 m)
Low	Low (d < 0.4 m)	Medium (0.4 m < d < 1.0 m)
Medium	Medium (0.4 m < d < 1.0 m)	High (d > 1.0 m)
High	High (d > 1.0 m)	High (d > 1.6 m)

Figure 15. Definitions of coastal flood risk categories proposed under Draft Coastal Hazards Plan Change (PC12) and Proposed Housing and Business Choice Plan Change (PC14)

The severity of flood hazard (low, medium or high) is categorised according to water depth as informed by the Combined Flood Hazard Curves of the Australian Rainfall and Runoff Guidelines (Figure 11). The depth is that for a single probability of flooding (0.2% AEP).

The area over which these coastal flood risk categories are proposed includes a substantial portion of the Multi Hazards Stage 3 project area and this approach to defining hazard categories – e.g., low hazard (less than 0.4 m depth), or medium hazard (less than 1.0 m depth) – could also be used to define project impact indicators for assessing the viability of land use in the Multi Hazards project.

B.6 Proposed Project Response Indicators for Flood Hazards

From the literature review, the key factors considered in defining impact indicators for flood hazards to a specific element are recognised to be:

- Likelihood of flooding – which can be expressed in terms of AEP
- Consequences of flooding – which can be defined by depth or by damage state or other measure of consequence or impact

The duration of flooding can also be important in terms of the level of disruption and in some cases the amount of damage caused by flooding. However, information for this aspect of flooding is not fully included in the model scenario data because the model simulations are limited to the duration of the rainfall and tidal events considered. Given the period of time simulated, the range in duration of flooding in the model data will be matter of hours or a day at most. Any longer term flooding, more relevant to duration indicators – e.g. due to

retention of water behind stopbanks – is not captured in the model outputs. Therefore, we have not considered PRIs for duration of flooding further. The literature mainly considers indicators of flood hazard to people, buildings, and some other elements of the built environment domain. We have found little previous work to identify flooding indicators for elements in other domains. The CCC Risk and Vulnerability Viewer defines vulnerability categories for some of these other elements, developed through literature review and consultation with Council stakeholders. However, flood vulnerability definitions for around a third of the elements considered are still to be defined in that assessment.

We have considered these factors and the thresholds identified or adopted in the sources we have reviewed to propose project adaptation indicators for elements of land use as presented in Table 7. In selecting the PRIs we have taken into account the flood hazard data available for application of the PRIs. These comprise modelled water depths and water levels over the project area for three representative likelihoods of flooding (10% AEP, 2% AEP and 0.5% AEP) at six increments of sea level rise with corresponding increases in rainfall intensity and groundwater levels. Calculations of flood damages to buildings and counts of properties flooded in each of the modelled scenarios are also available.

All our proposed PRIs include reference to the 0.5% AEP flood hazard, the most extreme modelled. We consider this is appropriate given the likelihood of such events occurring over the project assessment timescale and is in keeping with the orders of likelihood of flooding which are widely considered in planning instruments, for example the Canterbury Regional Policy Statement and the Christchurch District Plan.

For some elements, any exposure to flooding, regardless of its depth, may define the indicator. For example, the Council's Natural and Climate Hazard Risk and Vulnerability Assessment has, through consultation with Council, identified cemeteries as highly vulnerable to any flooding. For this particular element, in the absence of other data, we propose a single adaptation indicator of zero depth of flooding at the lowest likelihood of flooding for which data are available (0.5% AEP).

For other elements, our review suggests that the flood hazard indicator could be varied with the likelihood of the hazard – i.e., the hazard consequence indicator may be higher (more severe) if it is very unlikely to occur than if it is more likely to occur. We have considered how PRIs could be defined using such a risk-based approach for the hazard to people and buildings.

Risk-based PRI for hazard to people

For hazard to people, we propose PRIs based on the AR&R hazard categories which are widely used by practitioners for assessing flood hazard. Baseline flood modelling for the project area shows that velocity of flood water is relatively low over almost the entire project area so that hazard can be categorised by water depth alone.

We have considered two risk-based approaches:

(a) <u>Depth and probability based on the AR&R hazard categories</u>

Figure 16 shows an approach to varying the hazard indicator with the likelihood of flooding. For the most likely flooding modelled (10% AEP), we consider that an indicator of 0.3 m water depth (corresponding to the limiting value for hazard class H1, 'generally safe for people') would be appropriate. For less likely flood events – 2% AEP and 0.5% AEP (the least likely flooding modelled) – indicators of 0.5 m and 1.2 m, corresponding to the limiting values for hazard class H2 (unsafe for small vehicles) and H3 (unsafe for vehicles, children, and the elderly) respectively may be appropriate. The overall, risk-based, hazard indicators is then defined by exceedance of any of the depth indicators at the respective likelihoods of flooding. This PRI would be applied to flooding around properties and in access routes – primarily roads – to properties. In other parts of the project area – reserves, parks, wetlands for example – where public access is not essential and can be controlled, other PRIs are more appropriate.

Figure 17 shows an example application of these PRIs within the project are using the baseline flood model results for flooding in 2060. This approach allows areas where indicators are exceeded in lower likelihood events – such as Landy Street in the 10% AEP, or Avondale in the 2% AEP – to be identified together with areas of higher hazard in less frequent events (0.5% AEP).

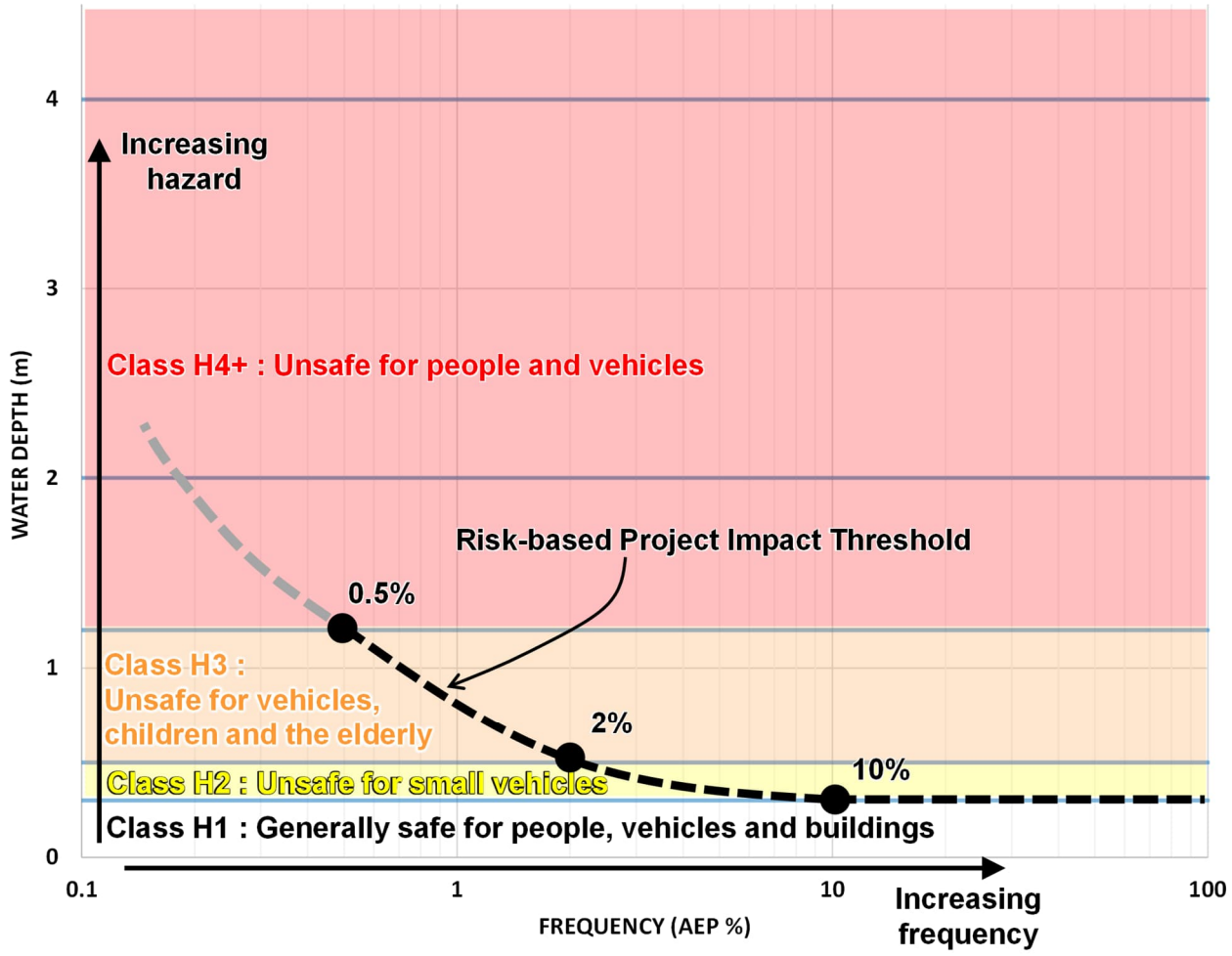


Figure 16. Example of risk-based response indicators for flood hazard to people based on the AR&R hazard classifications applied to the three likelihoods of flooding modelled for the project.

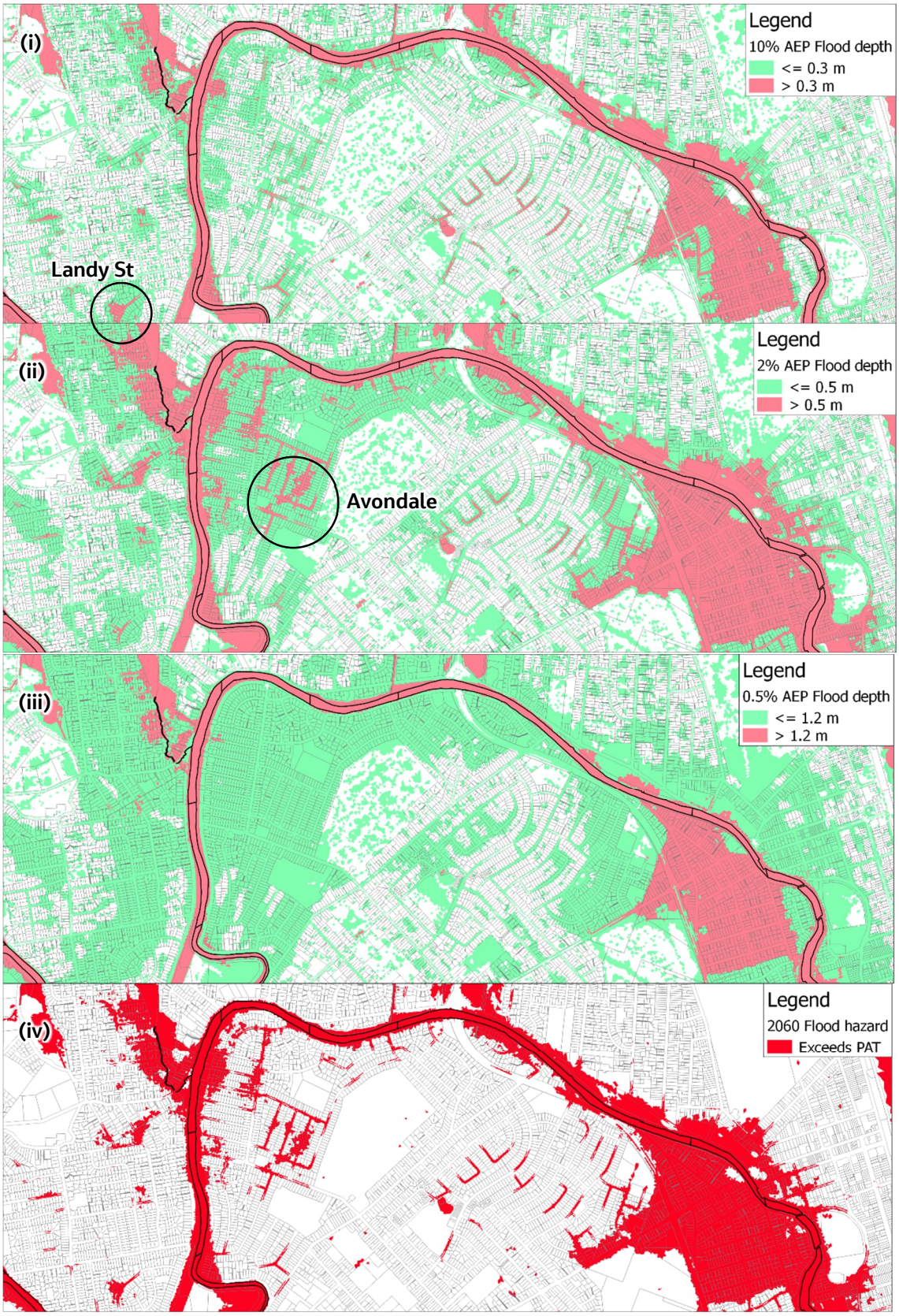


Figure 17. Application of risk-based adaptation indicator showing areas exceeding individual indicators for (i) 10% AEP, (ii) 2% AEP, (iii) 0.5% AEP and (iv) combined PRI for modelled flooding with the existing stopbanks in 2060.

(b) Depth based on the proposed coastal flood risk category definitions

As an alternative to the risk-based approach illustrated in Figure 16, which requires evaluation of flood depth at three probabilities of occurrence, we have also considered a simpler approach, based on flood depth for a single probability of occurrence, as proposed for the costal hazards plan change. In that approach, flood depth indicators of 0.4 m (limit of 'low' hazard) and 1.0 m (limit of 'medium' hazard) are applied to flood depths in the 0.2% AEP.

We have assessed the implications of applying either of these indicators to the smallest modelled probability in the Multi Hazards project (0.5% AEP) by inspecting the modelled flood depths over the project area for two of the modelled future scenarios – 2060 climate with existing stopbanks and 2100 climate without stopbanks. Figure 18 shows the distribution of model flood depths for the 10% AEP and 2% AEP at sampled locations where the 0.5% AEP flood depth is below the indicator value (0.4 m or 1.0 m) in each of these two future scenarios. This shows that where the 0.5% AEP depths are below an indicator of 0.4 m ('low' coastal flood hazard), the corresponding depths for both the 10% AEP and 2% AEP are below 0.3 m for the majority (more than 95%) of sample locations for both future scenarios considered. This depth (0.3 m) corresponds to the lowest threshold in the AR&R hazard classification system ('generally safe for people, vehicles and buildings'). For locations where the 0.5% AEP depths are below 1.0 m ('medium' coastal flood hazard), flood depths in the 10% and 2% AEP exceed a depth of 0.5 m ('unsafe for vehicles, children and the elderly') at 3%-9% and 12%-21% of locations respectively, depending on future location.

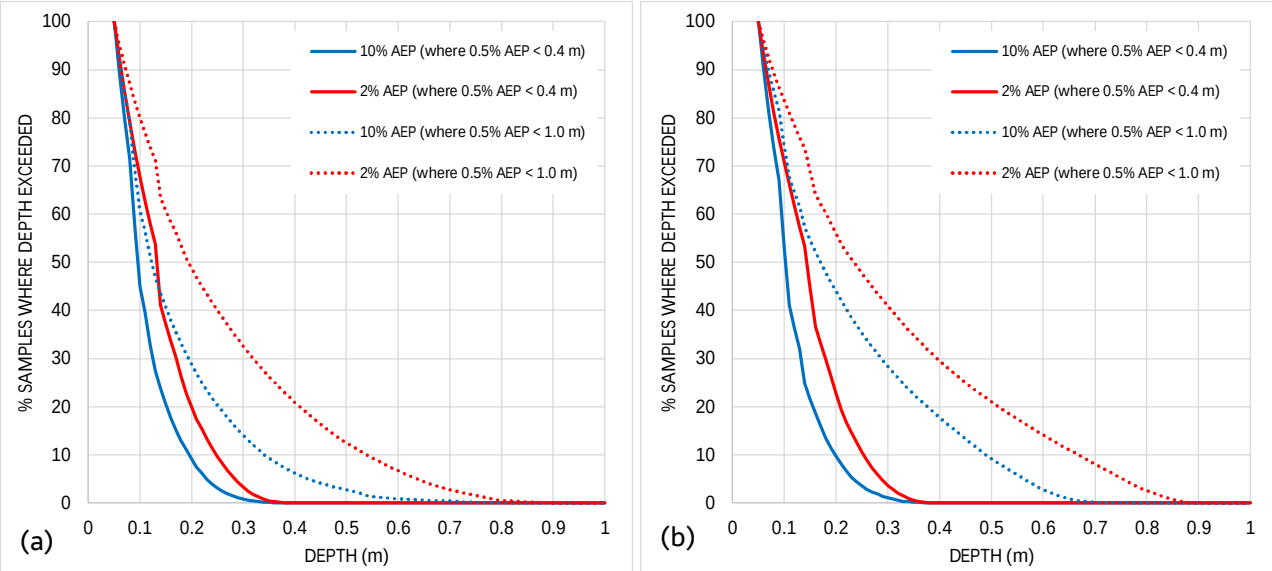


Figure 18. Distribution of 10% and 2% AEP flood depths at locations where 0.5% AEP depth is below indicators of 0.4 m and 1.0 m in (a) 2060 climate with stopbanks; and, (b) 2100 climate without stopbanks

Based on this assessment, adopting an indicator depth of 0.4 m for the 0.5% AEP will also provide a lower indicator (of the order of 0.3 m or less) for more likely events (10% AEP and 2% AEP) which is consistent with adopting lower hazard thresholds for these events in a risk-based approach. This approach is also consistent with that currently proposed for the coastal hazards plan change – which applies to a large part of the project area.

For these reasons we propose a single PRI of 0.4 m flood depth at the 0.5% AEP.

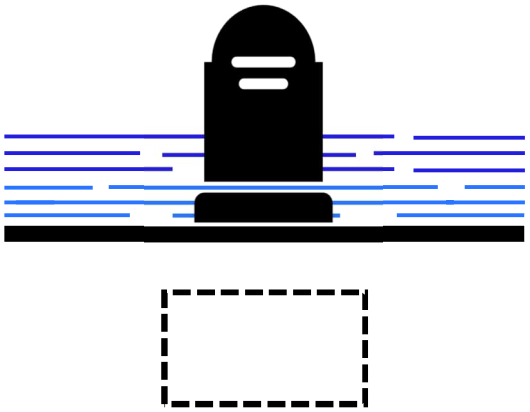
Risk-based PRI for damage to buildings

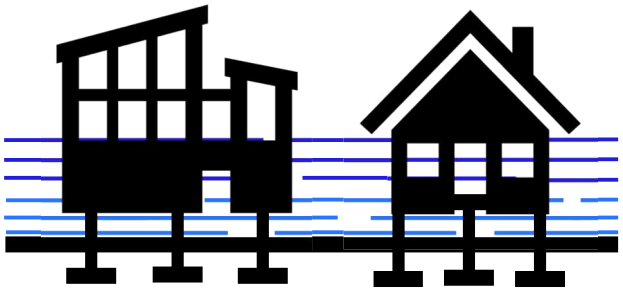
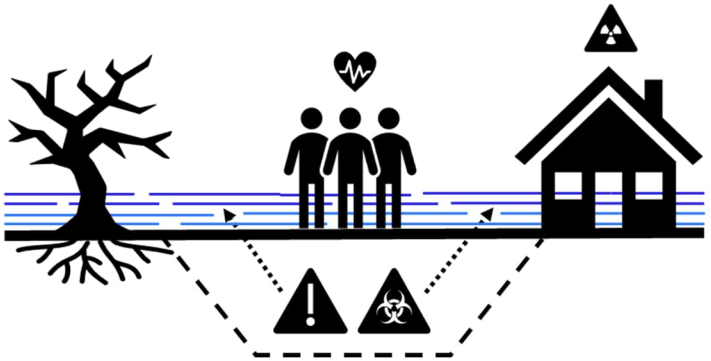
For hazard to buildings, we propose PRIs which reflect:

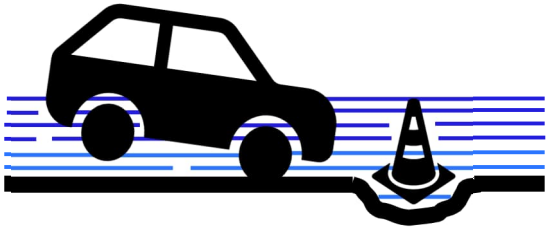
- The impacts of frequent underfloor flooding in more likely flood events (relevant modelled event 10% AEP), recognising a similar frequency of flooding as the Christchurch City Council Flood Intervention Policy
- Flood water entering property (above floor level flooding) in the 2% AEP (Building Code requirement)
- Limited damages for the smallest modelled event (0.5% AEP) corresponding to Riskscape Damage State DS1: 'light' damage (non-structural damage, or minor non-structural damage), define as damages of no more than 10% of the property value (Damage Ratio of 0.1).

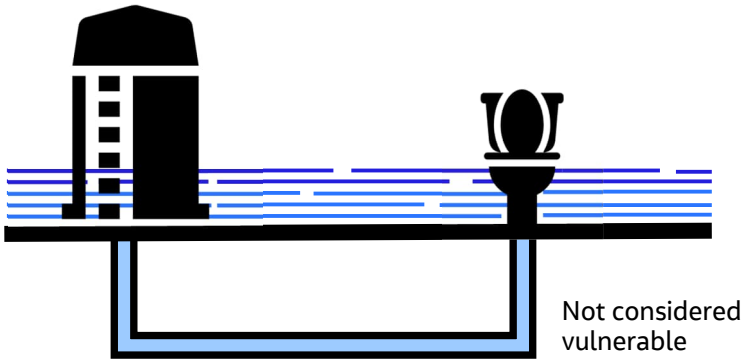
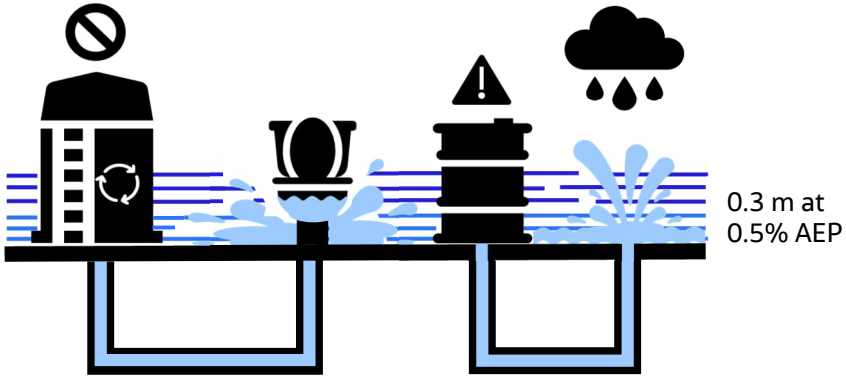
Together these PRIs form a risk-based approach where low-level, underfloor flooding, at higher frequencies and above floor flooding or level of damage to property at lower frequencies form the limits to viability of existing land use.

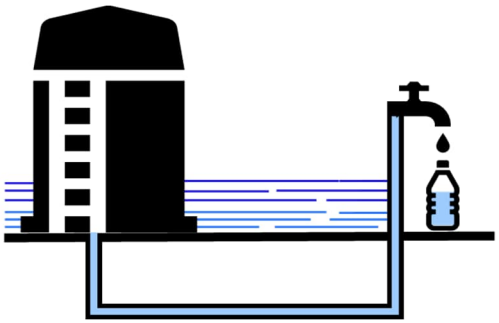
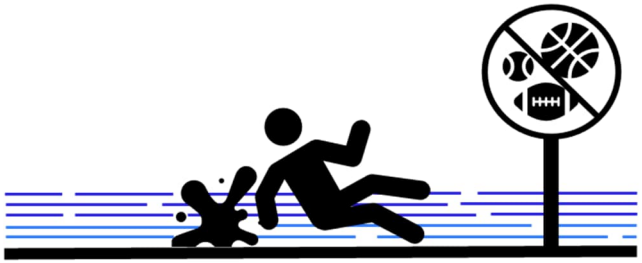
Table 7 Proposed Project Response Indicators for Flood Hazards

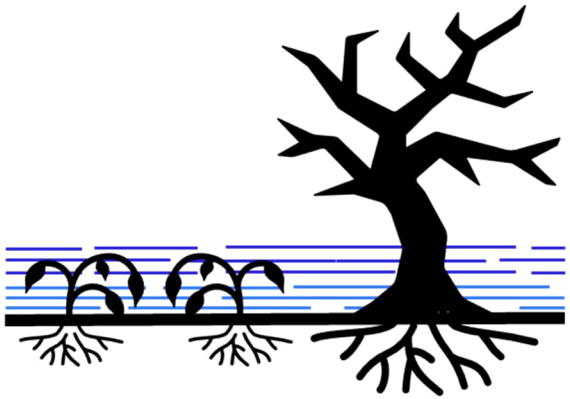
Domain	Subdomain	Indicator Graphic	Likelihood indicators	Hazard indicators	Basis
Life	People's safety (around properties and in access routes to properties)	1.2 m at 0.5% AEP 0.3 m at 10% AEP	0.5% AEP	0.4 m at 0.5% AEP	Risk Based Coastal Hazard Analysis for Land-use Planning Risk based approach using AR&R Guidelines for severity of hazards
Built	Cemeteries	 0 m at 0.5% AEP	None developed	None developed	CCC/UI Natural and Climate Hazard Risk & Vulnerability Assessment uses: No flooding at lowest likelihood considered (0.5% AEP) Depth <= 0 m at 0.5% AEP (nominal 'dry' condition) However this does not consider all sites and societal/cultural values or potential adverse effects hence noPRI is proposed fo this project.

Domain	Subdomain	Indicator Graphic	Likelihood indicators	Hazard indicators	Basis
	Commercial Buildings and Facilities / Council Housing / Industrial Buildings and Facilities / Residential Buildings / Schools	 <=DS1 at 0.5% AEP no above floor damages at 2% AEP no underfloor flooding (no damages) at 10%	10% AEP – no damage 2% AEP – no above floor damage 0.5% AEP - no structural damage (Riskscape Damage State 1 or less) [note that new buildings in the Flood Management Area have a minimum floor level 400 mm above the 0.5% AEP including climate change]	0 m depth at 10% AEP 0 Above floor damage at 2% AEP Damage Ratio < 10% at 0.5% AEP	Risk based approach taking note of NZBC E1 standard and Hazard thresholds from Riskscape building fragility assessment and CCC/UI Natural and Climate Hazard Risk & Vulnerability Assessment
	Contaminated Sites	 > 0.01 m at 0.5% AEP	No flooding at lowest likelihood considered (0.5% AEP)	Depth <= 0 m at 0.5% AEP (nominal 'dry' condition)	Precautionary threshold No specific information in CCC/UI Natural and Climate Hazard Risk & Vulnerability Assessment or other sources.
	Roads / State Highways		Lower damage ratio at high likelihood (0.5m depth = 2% damage,	Use indicator for people's safety	Based on CCC/UI Natural and Climate Hazard Risk &

Domain	Subdomain	Indicator Graphic	Likelihood indicators	Hazard indicators	Basis
		 1.5 m at 2% and 0.5% AEP 0.5 m at 10% AEP	equiv. to DS0 for buildings) Damage indicators higher than those for people's safety which will be triggered before damage	which is lower than for damage to road.	Vulnerability Assessment method (X Espinet) Damage thresholds applied in risk-based approach
	Service Stations	<=DS1 at 0.5% AEP <=DS0 at 10% and	Same as buildings	Same as buildings	Same as buildings
	Stormwater Laterals / Mains		None	None	Not considered vulnerable
	Wastewater Laterals / Mains		None	None	Not considered vulnerable

Domain	Subdomain	Indicator Graphic	Likelihood indicators	Hazard indicators	Basis
	Water Supply Laterals / Mains		None	None	Not considered vulnerable
	Stormwater Pump Station		0.3 m at 0.5%	0.3 m at 0.5%	Precautionary value to avoid flooding power supply or controls but generally not expected to be highly vulnerable
	Wastewater Pump Station		0.3 m at 0.5%	0.3 m at 0.5%	Precautionary value to avoid flooding power supply or controls but generally not expected to be highly vulnerable
	Wastewater Monitors		None	None	Not considered vulnerable

Domain	Subdomain	Indicator Graphic	Likelihood indicators	Hazard indicators	Basis
	Water Supply Station	 Not considered vulnerable	?? None	?? None	Not considered vulnerable?
Natural	Parks and Reserves / Sports Fields	 0.3 m at 0.5% AEP 0.1 m at 10% AEP	10% AEP - frequent flooding has greater impact	Depth 0.2 m at 10% AEP	Informed by vulnerability classification CCC/UI Natural and Climate Hazard Risk & Vulnerability Assessment

Domain	Subdomain	Indicator Graphic	Likelihood indicators	Hazard indicators	Basis
	Vegetation	 0.3 m at 0.5% AEP 0.1 m at 10% AEP	As for Parks and Reserves	Depth 0.2 m at 10% AEP	Informed by vulnerability classification CCC/UI Natural and Climate Hazard Risk & Vulnerability Assessment

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SBR, 2007. Ontwatering in stedelijk gebied (Dewatering in urban areas). SBR, Rotterdam. In Dutch.

Stephens, S A; Bell, R.G. and Lawrence, J., 2018. Developing signals to trigger adaptation to sea-level rise. Environ. Res. Lett. 13 104004

Urban Intelligence, 2023. Natural and Climate Hazard Risk & Vulnerability Assessment Methodology Report. Report prepared for Christchurch City Council. Version 2.0. March 2023.

Appendix B1. Literature Review Summary Information

Document	Flood hazard factors	Parameters
Developing signals to trigger adaptation to sea-level rise (Scott A Stephens et al 2018 Environ. Res. Lett. 13 104004) https://iopscience.iop.org/article/10.1088/1748-9326/aadf96/pdf	- Likelihood	1% AEP
Auckland Council: Natural Hazard Risk Communication Toolbox Natural Hazard Risk Management Action Plan, 2014 https://www.civildefence.govt.nz/assets/Uploads/NHRCToolbox/NHRCToolbox-Auckland-Council.pdf	- Depth - velocity - Likelihood - Consequence	N/A
Auckland Unitary Plan, update 9 July 2021 https://unitaryplan.aucklandcouncil.govt.nz/pages/plan/Book.aspx?exhibit=AucklandUnitaryPlan_Print	- Depth - Likelihood - Consequence	1% AEP flood event
Dunedin City Council 2020, 2nd Generation District Plan (2GP) https://www.dunedin.govt.nz/council/district-plan/2nd-generation-district-plan	- Likelihood - Velocity - Consequence[10] - Sensitivity[11]	N/A
Waikato Regional Council: General info on website: Flood Hazard Information Questions and Answers https://www.hamilton.govt.nz/our-council/council-publications/districtplans/flood/Pages/Flood-FAQ.aspx Hamilton City council (2012 information)	- Depth (for both inside and outside the River Zone) - Velocity (just for OUTSIDE the River Zone)	In a 1% AEP flood event: Waikato River flooding: Medium-High flood hazard area:

[10] The consequences of a natural hazard event occurring are considered in the context of health and safety, costs of damage to the built environment, and social and economic impacts on the wider community

[11] the sensitivity of land use activities is classified according to the health and safety implications of the land use. This helps to manage the consequences that may occur as a result of a natural hazard event. This sensitivity classification draws from, and broadly corresponds to, the building importance levels defined in the Building Regulations 1992 (Schedule 1: The building code).

Document	Flood hazard factors	Parameters
https://www.hamilton.govt.nz/our-council/council-publications/districtplans/flood/Documents/GIS%20-%20Metadata%20for%20Flood%20Hazard%20Modelling%20(FHM)%20Data%20-%20City%20Waters.pdf		i. The depth of the flood waters exceeds 1m; but ii. Excludes flood water depths less than 0.1m. Low flood hazard area: N/A **Outside River Zone:** High flood hazard area: i. The depth of the flood waters exceeds 1m, but ii. Excludes flood water depths less than 0.1m. Medium flood hazard area: • The depth of the flood waters is equal to or less than 1m but greater than 0.5m, but • Excludes flood water depths less than 0.1m. Low flood hazard area: • The depth of the flood waters is equal to or less than 0.5m, but • Excludes flood water depths less than 0.1m
Waimakariri District Council https://waimakariri.maps.arcgis.com/apps/MapSeries/index.html?appid=16d97d92a45f4b3081ffa3930b534553	- Velocity - Depth	In a 0.5% AEP flood event: - High Hazard depth >1 m - Medium Hazard – 0.3m <Depth< 1m - Low – Depth less than 0.3m
Thames Coromandel District Plan	- Depth - Velocity	High Flood Hazard Area: When the flow depth exceeds 1 m (i.e. adult waist depth)

Document	Flood hazard factors	Parameters
Christchurch District Plan https://districtplan.ccc.govt.nz/pages/plan/book.aspx?exhibit=DistrictPlan (based on Canterbury RPS Canterbury Regional Policy Statement | Environment Canterbury (ecan.govt.nz)	- Depth - Velocity - Likelihood	In a 0.2% AEP flood event, high hazard flood areas = >1 meter depth
Wellington city council https://gis.wcc.govt.nz/LocalMaps/Viewer/?map=5c3d903dc4c043e0953410033c5c0b3e	- Depth	1% AEP
Technical flood risk management guideline: Flood hazard Australian Disaster Resilience Handbook Collection 2012 https://knowledge.aidr.org.au/media/1891/guideline-7-3-technical-flood-risk-management.pdf	- Depth - Velocity	N/A
Department for Environment, Food & Rural Affairs (Defra) Flood Risks to People-Phase 2, 2006	- Depth - Velocity	N/A
Managing natural hazard risk in New Zealand – towards more resilient communities 2014 https://www.lgnz.co.nz/assets/Publications/de504aaea2/Managing-natural-hazards-LGNZ-think-piece.pdf	- Likelihood - Consequence	N/A
The National Flood Risk Analysis for the Netherlands FINAL REPORT, 2017? https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/english/flood-risk-the/	- Likelihood - Consequence	N/A

Document	Flood hazard factors	Parameters
World Meteorological Organization https://public.wmo.int/en/resources/bulletin/chinas-implementation-of-impact-and-risk-based-early-warning	- Depth	N/A

Appendix B2. Risk and Vulnerability Viewer Groundwater Vulnerability Categories

Table 8. Risk and Vulnerability Viewer Groundwater Vulnerability Categories

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Boats Ramps	tbd	tbd	tbd	Not considered for current assessment
Boat Sheds	tbd	tbd	tbd	Not considered for current assessment
Bridges	Based on subgrade 0.7 to 0.9 mbgl	Based on subgrade 0.2 to 0.7 mbgl	Based on subgrade above 0.2 mbgl	Superseded by roads as bridges would typically be elevated.
Carparks	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Refer to roads Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently in medium range and occasionally in high range, suggesting tolerance may be higher than indicated.
Cemeteries	Below depth of double internment Below 1.8 mbgl	Between depth of single and double internment 1.4 to 1.8 mbgl	Above depth of single internment above 1.4 mbgl	Any groundwater encountered in internment excavation would require adaptation. The adaptation indicator is therefore below the depth of a single internment.
Coastal Barriers and Sea Walls	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not considered for current assessment
Commercial Buildings and Facilities	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Contaminated Sites	tbd	tbd	tbd	Risk of exposure and or mobilisation
Community Facilities	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed
Council Housing	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Cycleways	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Refer to roads

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Electrical Structures	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Dependant on above/below ground
Gas Infrastructure	tbd	tbd	tbd	Not considered for current assessment
Heritage Sites	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed – refer buildings
Industrial Buildings and Facilities	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Jetties	tbd	tbd	tbd	Not considered for current assessment
Landfills	tbd	tbd	tbd	Dependant on elevation of base of landfill – refer Contaminated Sites
Marae	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed – refer buildings
Mobile Towers	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed – refer buildings
Parks and Reserves	Below 0.7 mbgl	0.3 to 0.7mbgl	Above 0.3 mbgl	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Playgrounds	tbd	tbd	tbd	Not specifically assessed – refer parks
Port Access	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Not specifically assessed – refer roads
Port Facilities	tbd	tbd	tbd	Not specifically assessed
Port Operations	tbd	tbd	tbd	Not specifically assessed
Port Storage	tbd	tbd	tbd	Not specifically assessed
Public Artwork	tbd	tbd	tbd	Not specifically assessed
Public Barbeques	tbd	tbd	tbd	Not specifically assessed
Public Transport	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Not specifically assessed – refer roads

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Rail	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Not specifically assessed – groundwater would typically be above adjacent ground level to be within ballast – no significant effect.
Residential Buildings	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Roads	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Service Stations	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Older service stations and USTs likely less tolerant than new builds.
Sports Areas	Below 0.7 mbgl	0.3 to 0.7mbgl	Above 0.3 mbgl	Consistent with literature review, however there are numerous examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
State Highways	Based on subgrade depth 0.7 to 0.9 mbgl	Based on base layer depth 0.2 to 0.7 mbgl	Based on pavement depth above 0.2 mbgl	Consistent with literature review, however there are examples in Christchurch where groundwater is consistently within medium range, suggesting tolerance may be higher than indicated.
Stopbanks	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed
Stormwater Laterals	At or <u>above</u> a pipe including allowance for seasonal fluctuation	At or above a pipe that is not metal or concrete	At or above a concrete or metal pipe	Low should be below pipe? Does not state at or above top or invert of pipe – assume invert?
Stormwater Mains	At or <u>above</u> a pipe including allowance for seasonal fluctuation	At or above a pipe that is not metal or concrete	At or above a concrete or metal pipe	Low should be below pipe? Does not state at or above top or invert of pipe – assume invert?
Stormwater Pump Station	Below 0.5 mbgl	0 to 0.5mbgl	At or above ground surface	Dependant on depth of service
Transfer Stations	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Walkways	Below 0.3 mbgl (note – element data sheet says above)	0.1 to 0.3mbgl	Above 0.1 mbgl	Not specifically assessed
Wastewater Monitors	tbd	tbd	tbd	Not specifically assessed
Wastewater Laterals	Not stated	Not stated	Not stated	Dependant on pressure/suction or gravity and depth
Wastewater Mains	Not stated	Not stated	Not stated	Dependant on pressure/suction or gravity and depth
Wastewater Pump Station	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Dependant on depth of service
Wastewater Treatment Plant	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed Dependant on depth of in-ground structures.
Water Supply Laterals	At or above a pipe including allowance for seasonal fluctuation	At or above a pipe that is not metal or concrete	At or above a concrete or metal pipe	Low should be below pipe? Groundwater low risk to water supply pipes? Could hinder repairs or replacement?
Water Supply Mains	At or above a pipe including allowance for seasonal fluctuation	At or above a pipe that is not metal or concrete	At or above a concrete or metal pipe	Low should be below pipe? Groundwater low risk to water supply pipes? Could hinder repairs or replacement?
Water Supply Station	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Dependant on depth of service
Water Supply Treatment Plant	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed
Water Supply Tower	tbd	tbd	tbd	Not specifically assessed
Religious Facilities	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed – refer buildings
Schools	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed – refer buildings / parks
Social Deprivation	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed – refer buildings / parks / contamination
Archaeological Sites	tbd	tbd	tbd	Not specifically assessed

Domain / Subdomain	Groundwater Vulnerability			Comment
	Low	Medium	High	
Native Bird Habitats	tbd	tbd	tbd	Not specifically assessed
Māori Land Claims	Below 0.7 mbgl	0 to 0.7mbgl	At or above ground surface	Not specifically assessed
Papakainga Zones	tbd	tbd	tbd	Not specifically assessed
Sites of Ecological Significance	tbd	tbd	tbd	Not specifically assessed

Appendix C. Task 3 OARC scheme modelling memo

Ōtākaro Avon River Corridor Regeneration Plan flood model results

Date: 27 November 2024
Project name: LDRP97 Multi Hazards Stage 3
Project no: IZ084400
Attention: Martin Densham, Tom Parsons
Company: Christchurch City Council
Prepared by: Charlotte Doogue, Damian Debski
Reviewed by: Matt Balkham
Document no: IZ084400-NW_MEM-0010
Revision no: 3 FINAL

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1. Introduction

Stage 3 of the Christchurch Multi Hazards project examines the flood hazards in the Ōtākaro Avon catchment over a range of future scenarios. These include scenarios following implementation of the new flood management measures which have been agreed for the lower Ōtākaro Avon catchment – setback stopbanks and stormwater pumping – as part of the Ōtākaro Avon River Corridor (OARC) Regeneration Plan. These mitigation measures have been assessed using outline details from the OARC Regeneration Plan. Their design will be refined through further hydrological analysis and engineering evaluation.

The Avon City Wide Model ('Avon CWM'), a detailed flood model of the Ōtākaro Avon catchment, has been used previously as a 'Baseline' model to simulate flooding with the existing flood management infrastructure. Results of the Baseline model simulations are presented in the 'Analysis of baseline flood model results' memo (ref. IZ084400-NW-MEM-0007, January 2024).

To assess the effects of the new stopbanks and pumpstations (the 'OARC Scheme'), a new version of the Avon CWM (the OARC Scheme model) has been developed. The OARC Scheme model has been used to simulate flooding for the 10%, 2% and 0.5% Annual Exceedance Probability (AEP) in the same set of flood scenarios as the Baseline model, listed in Table 1-1.

Table 1-1 Scenarios simulated with the OARC Scheme model.

Sea level rise & indicative timing#		Land settlement from earthquake**	Groundwater levels	Scenario No. *
0 m	(2020)	no	85th percentile	2+Scheme
0.19 m	(2030)	no	85th percentile	4+Scheme
0.45 m	(2060)	no	85th percentile	6+Scheme
		yes	85th percentile	8+Scheme
1.06 m	(2100)	no	85th percentile	9+Scheme
		yes	85th percentile	10+Scheme
1.88 m	(2150)	no	85th percentile	12+Scheme
2.4 m	(>2150)	no	85th percentile	13+Scheme

Modelled scenarios were defined early in the Multi Hazards project using climate change projections at the time. The implications of updated projections and of new information on vertical land movement on the scenarios and model results is assessed in memo IZ084400-NW-MEM-0011

* Scenario number corresponds to the stopbanks down baseline scenario – ref. memo IZ084400-NW-MEM-0007

** The magnitude and distribution of land settlement which has been included in the modelled scenarios is detailed in memo IZ084400-NW-MEM-0011

This memorandum presents an overview of the OARC Scheme model and the results of the scenario simulations. The results of the model simulations will be further analysed in Task 4 and Task 5 of the project to assess the performance of the new flood management measures in relation to Project Response Indicators and other sources of hazard.

The results presented in this memo are as follows:

- Flood extent and depth

Sample maps showing the extent and depth of flooding with the OARC Scheme in comparison to the Baseline model results and to show how flooding varies over the future scenarios and the effect of earthquake induced land settlement. Flood depths are classified according to the flood hazard ratings defined in the Australian Rainfall and Runoff (AR&R) Guideline[1].

- River water levels and pumpstation discharges

Profiles of the maximum modelled water levels retained by the stopbanks along the Ōtākaro Avon River for the 0.5% AEP in each scenario. Plots of the modelled flows at selected new pump stations to show how these vary over the future scenarios in the model simulations.

- Properties flooded and flood damages

Number of properties flooded and financial flood damages calculated using the FloodFX[2] tool in terms of estimated Annual Average Damage (AAD) for individual model scenarios and Present Value Damages for a set of potential future pathways of climate change and earthquake-induced land settlement.

It is important to note that the purpose of this damage assessment is to allow the relative performance of the existing flood protection measures and the OARC Scheme to be compared within the Multi Hazards project. The results of the damage calculations are sensitive to the method and parameter values adopted for several key aspects of flood damage in the FloodFX tool. The approach adopted in the tool is based on comprehensive research undertaken at the time of its development. However, it is acknowledged that considerable uncertainty remains in some aspects of the calculations and some of the values adopted are subject to change for economic reasons. These limitations must be recognised should the results be considered for use in any other purpose.

In particular, we note that:

- In the short term, underfloor damages comprise a large proportion of the direct flood damages. This reflects the general nature of flooding outside the area of the OARC Regeneration Plan, i.e., extensive but relatively shallow flooding affecting a large number of properties but with a smaller proportion experiencing above floor flooding, particularly for higher probability events (e.g., 10% AEP) which are significant for the AAD calculation. These underfloor damages are calculated in a simple way in FloodFX and there is uncertainty in the current costs of such damages.
- Intangible damage values represent a large proportion of the total damages – approximately 50% – but there is considerable uncertainty in the valuation of this component of damage. Since these damage values are calculated as a proportion of the direct damages, uncertainty in the underfloor damages is further escalated through the intangible damage calculation.
- The Riskscape fragility curves used to calculate damage to individual buildings are capped to the value of the property. However, as agreed with Council, we have not capped Present Value damages

[1] Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff: A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

[2] FloodFX is a Christchurch City Council tool (developed by Jacobs). It uses flood model outputs and a database of house floor levels and types to identify properties at risk of flooding and estimate damages (based on intangible and tangible factors).

to properties which allows for buildings to be repeatedly repaired, typically through insurance cover, after each flood event. It is possible that some properties may not be repaired following multiple flood events due to withdrawal of insurance cover. However, this is considered less likely for the OARC Scheme model scenarios given these measures function to actively manage flood risk. Whilst we have not assessed the effect of capping present value damages of individual properties, an initial review of average property damages suggests the extent to which damages would be capped may be limited, reflecting the generally shallow, though extensive, nature of flooding in the near future, although it is possible that uncapped damages from individual large value properties may influence the total damage value. It should be noted that further intensification within the project area is not allowed for within the assessment. This may to some degree counterbalance the effect of Present Value damages to properties being uncapped.

The sensitivity of the results to these factors, and the corresponding outcomes, should be considered if the data or method are to be used for any other purposes.

2. OARC Scheme model

As shown in Figure 1, the OARC Scheme model covers the whole of the Ōtākaro Avon River catchment. A more detailed view of the layout of the model within the study area showing the indicative arrangement of the new stopbanks and pumpstations, as represented in the model, and the alignment of the existing stopbanks is given in Figure 2.

The OARC Scheme model was constructed from the 'stopbanks down' version of the Avon CWM. This version of the CWM excludes the existing stopbanks along the Ōtākaro Avon River by setting the levels of the lateral links between the 1D model of the river channel and the 2D model of the floodplain to the ground levels in the 2D model, from which the stopbanks have been erased.

The new stopbanks are represented in the 2D model using linear 'Dike' elements with artificially high crest levels to contain water levels in the river corridor in all the scenarios modelled. Stormwater pump stations are represented in the 1D pipe network model at existing stormwater pipe outfalls. The model pump capacities are set artificially high in order to maintain free discharge in the pipes at the outfalls in all the scenarios modelled. It should be noted that the flood model is not coupled to a groundwater model and therefore does not simulate any ingress of groundwater into the piped networks or modifications of this through pumping. Additional pumps to extract surface water at the vicinity of outfalls are included as point 'sinks' in the 2D model. A total of 19 new pumpstations are included in the model. In addition, new non-return valves (60) and sealed manholes (35) have been added to the model stormwater network to prevent water in the river bypassing the setback stopbanks.

The OARC Scheme model simulates the effect of the water table on runoff and flooding from rainfall. The groundwater surfaces used in the model were developed separately through groundwater modelling by Aqualinc and include the effect of sea level rise. In that model the stormwater network is defined by fixed elevation drains. This mitigates the modelled effects of sea level rise on groundwater levels to some degree. In reality, the drain outlets may be submerged by higher river levels such that gravity drainage of groundwater through the drains is reduced. If the drains are not pumped then the rise in water table with sea level rise could be greater than that simulated in the Aqualinc groundwater model and the effects of groundwater on runoff may be underestimated in the OARC Scheme model. However the effect of different groundwater levels on the hydraulic model was tested in sensitivity tests as reported in IZ0844000-NM-MEM- 0007 and found to generally have little impact on modelled flooding.

The OARC Scheme model was peer reviewed by DHI Water & Environment Limited. Further details on the model construction and the peer review are provided in the Model Build Statement (IZ084400-NW-MEM-0008, also appended to the final Stage 3 project report).

For each AEP in each scenario, the model has been used to simulate a range of storm durations and combinations of pluvial and tidal conditions. In the future scenarios simulated, historic rainfall depths and sea level are increased to allow for the effects of climate change in accordance with current guidance. A total of 130 model simulations were performed. The raw model results have been processed using GIS scripts to obtain the maximum flood levels and water depths in each individual event and subsequently the 'maximum of maximum' values over all the events simulated for each AEP to define the flooding for each AEP.

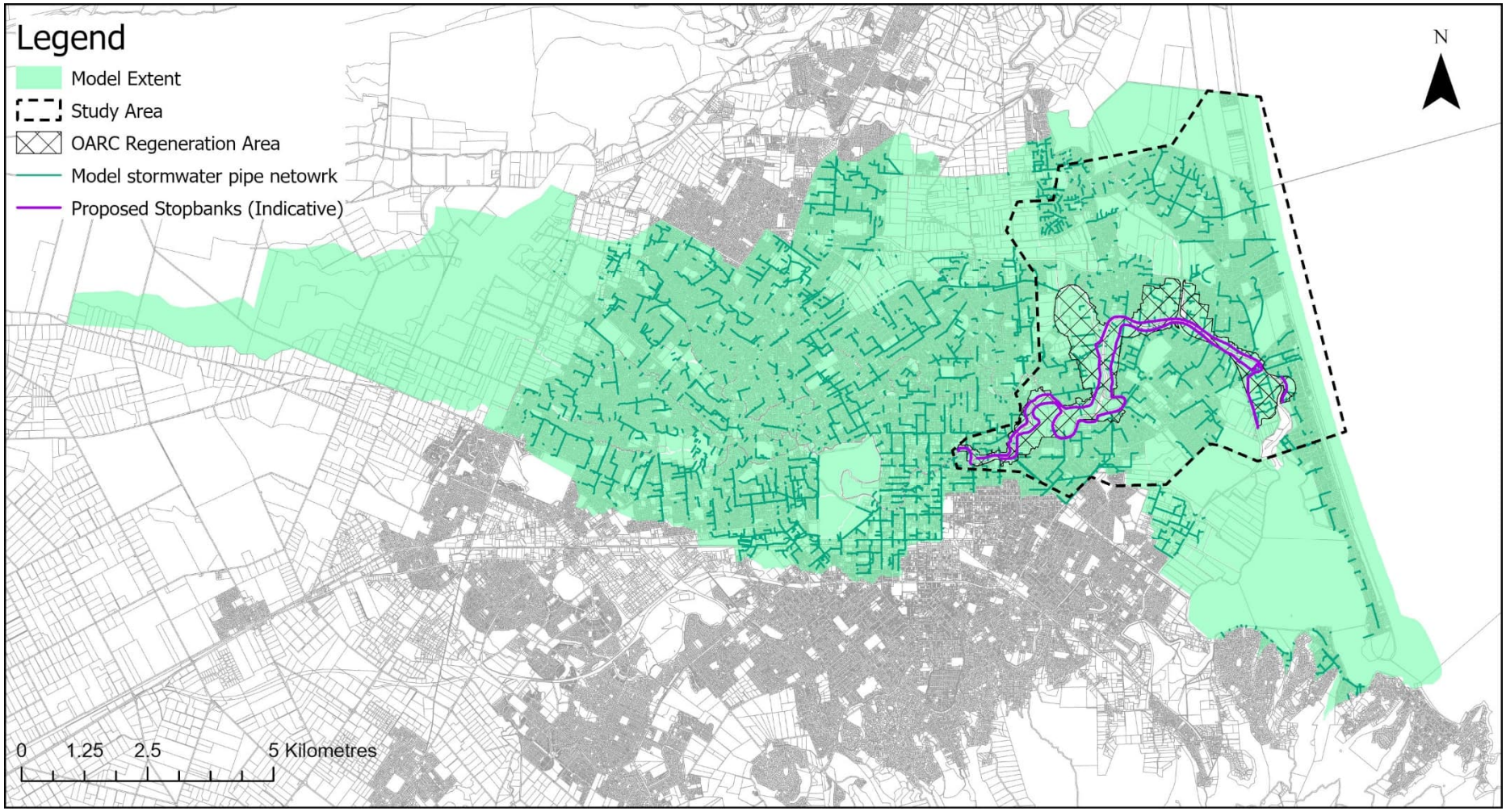

Figure 1: Map of the OARC Scheme model extent showing location of the Multi Hazards Stage 3 study area.

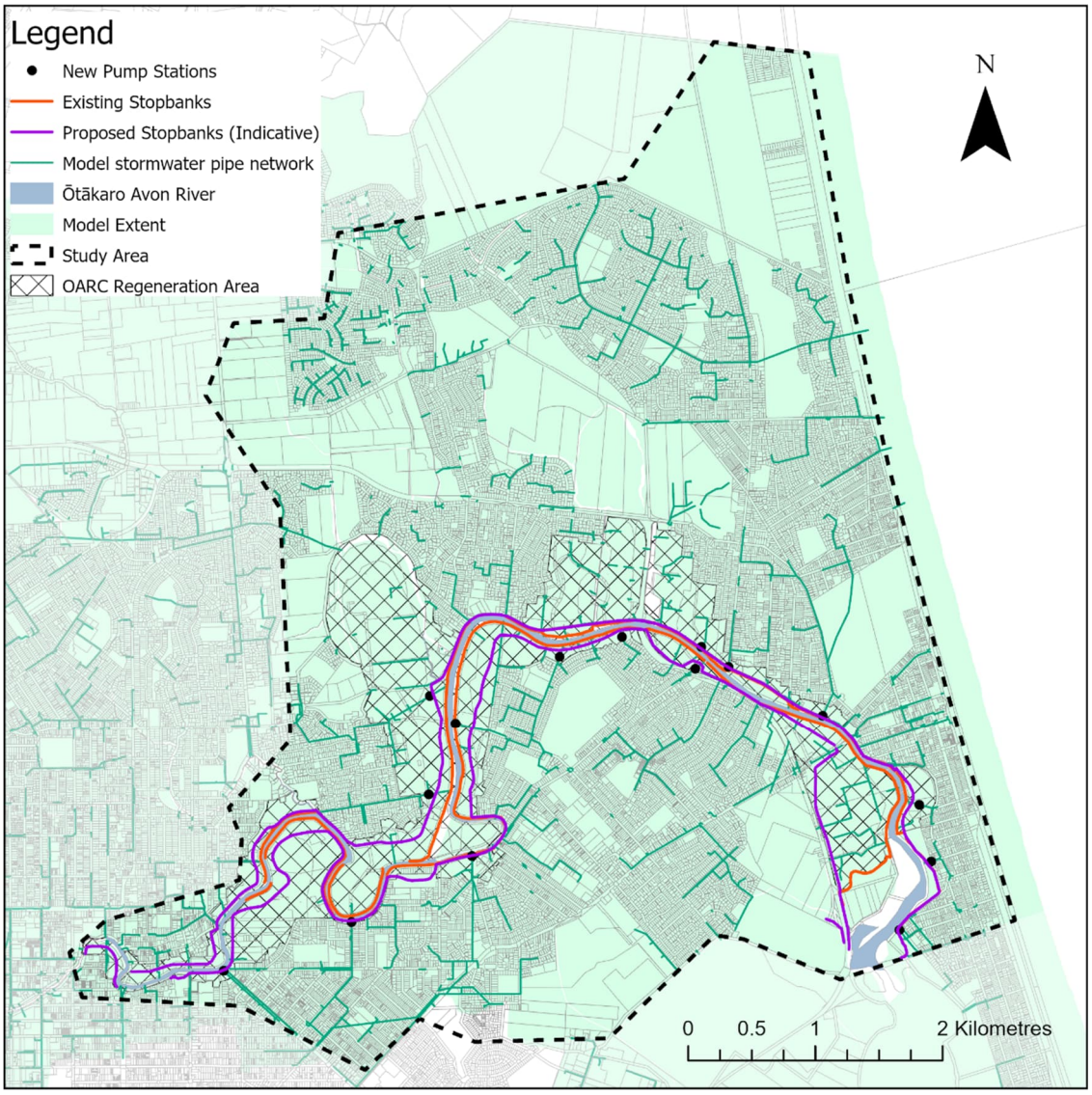

Figure 2: Location of new stopbanks and pumpstations in the in the OARC Scheme model

3. Flood extent and depth

We have prepared sample maps showing the extent and depth of flooding with the OARC Scheme in comparison to the Baseline model results to show the overall effects of the OARC Scheme as modelled and how flooding with the OARC Scheme varies over the future scenarios. We have mapped model depths using the AR&R Guideline hazard classification system. The system is presented in Table 3-1 in terms of the still water depth. As explained in the Baseline model results memo, the still water depth thresholds also apply where the velocity of flood water is less than 0.5 m/s which is the case for the majority of the project area.

Table 3-1: AR&R guidelines Flood Hazard Classifications for still water

Class	Depth	Description
H1	(<0.3 m)	generally safe for people, vehicles and buildings
H2	(0.3 to 0.5 m)	unsafe for small vehicles
H3	(0.5 to 1.2 m)	unsafe for vehicles, children, and the elderly
H4	(1.2 to 2.0 m)	unsafe for people and vehicles
H5	(2.0 to 4.0 m)	unsafe for vehicles and people. All buildings vulnerable to structural damage. Some less robust building types vulnerable to failure.
H6	(>4.0 m)	unsafe for vehicles and people. All building types considered vulnerable to failure.

Figure 3 and Figure 4 compare the extent and depth of flooding in the OARC Scheme model (new stopbanks and pumpstations) to that in the Baseline model (existing stopbanks) for the 10% AEP and 0.5% AEP in an example future scenario – 0.45 m SLR and the corresponding increase in rainfall intensity to approximately 2060.

For the 10% AEP, the reduction in flood extent and depth outside the new stopbanks is relatively small. In this scenario and AEP, the existing stopbanks are generally high enough to prevent flooding from the Ōtākaro Avon River. Flood hazard outside the stopbanks is primarily due to rainfall over the catchments draining to the river. The new pumpstations in the OARC Scheme model reduce the flooding from the stormwater network to some degree in this AEP but the difference in flood hazard outside the OARC Regeneration Plan area is small.

For the 0.5% AEP, flood extent and depth along the river corridor outside the new stopbanks is substantially reduced in the OARC Scheme model, particularly in the Avondale, Aranui, Bexley and New Brighton areas. In the Baseline model the existing stopbanks are overtopped over most of their length resulting in extensive flooding along the river corridor. Further away from the river where flooding is due primarily to local rainfall and is beyond the influence of the new pumpstations, flood hazard in the OARC Scheme model is similar to the Baseline model.

Table 3-2 shows the total area for each class of flood hazard in each AEP and scenario simulated. The eight scenarios cover a range of future climatic conditions corresponding to projections for 2020 through to beyond 2150 and scenarios including the effects of earthquake-induced land settlement.

Table 3-2: Distribution of AR&R Guideline flood hazard categories for OARC Scheme model scenarios

Scenario	AEP	Area in each flood hazard class (km^2)						
		ALL	H1 (< 0.3 m)	H2 (0.3 - 0.5 m)	H3 (0.5 - 1.2 m)	H4 (1.2 - 2.0 m)	H5 (2.0 - 4.0 m)	H6 (> 4.0 m)
S2+Scheme 0 m SLR ~2020	10%	4.5	3.9	0.5	0.1	< 0.1	< 0.1	Nil
	2%	6.7	5.2	1	0.5	< 0.1	< 0.1	Nil
	0.50%	8.4	5.8	1.4	1.1	< 0.1	< 0.1	Nil
S4+Scheme 0.19 m SLR ~2030	10%	4.7	4	0.5	0.2	< 0.1	< 0.1	Nil
	2%	7	5.2	1.1	0.7	< 0.1	< 0.1	Nil
	0.50%	8.7	5.9	1.5	1.3	< 0.1	< 0.1	Nil
S6+Scheme 0.45 m SLR ~2060	10%	5.6	4.6	0.7	0.4	< 0.1	< 0.1	Nil
	2%	8	5.7	1.3	0.9	< 0.1	< 0.1	Nil
	0.50%	9.6	6.1	1.7	1.7	0.2	< 0.1	Nil
S8+Scheme 0.45 m SLR ~2060 with Earthquake	10%	5.8	4.6	0.8	0.5	< 0.1	< 0.1	Nil
	2%	8.1	5.6	1.4	1	< 0.1	< 0.1	Nil
	0.50%	9.8	6.1	1.8	1.8	0.2	< 0.1	Nil
S9+Scheme 1.06 m SLR ~2100	10%	6.8	4.9	1.1	0.7	< 0.1	< 0.1	Nil
	2%	9.1	5.7	1.6	1.6	0.2	< 0.1	Nil
	0.50%	10.9	6.2	1.9	2.4	0.4	< 0.1	Nil
S10+Scheme 1.06 m SLR ~2100 with Earthquake	10%	7.1	5	1.1	0.9	0.1	< 0.1	Nil
	2%	9.4	5.8	1.6	1.7	0.2	< 0.1	Nil
	0.50%	11.1	6.2	2	2.4	0.5	< 0.1	Nil
S12+Scheme 1.88 m SLR ~2150	10%	9.2	5.4	1.6	1.8	0.3	< 0.1	Nil
	2%	12.2	5.9	2.2	3.4	0.7	< 0.1	Nil
	0.50%	14.3	5.9	2.4	4.4	1.4	0.2	Nil
S13+Scheme 2.40 m SLR ~2150+	10%	12.3	5.1	1.9	3.6	1.6	0.2	Nil
	2%	15.5	4.9	2	4.6	3.4	0.7	< 0.1
	0.50%	17.5	5	2.1	4.5	4.1	1.8	< 0.1

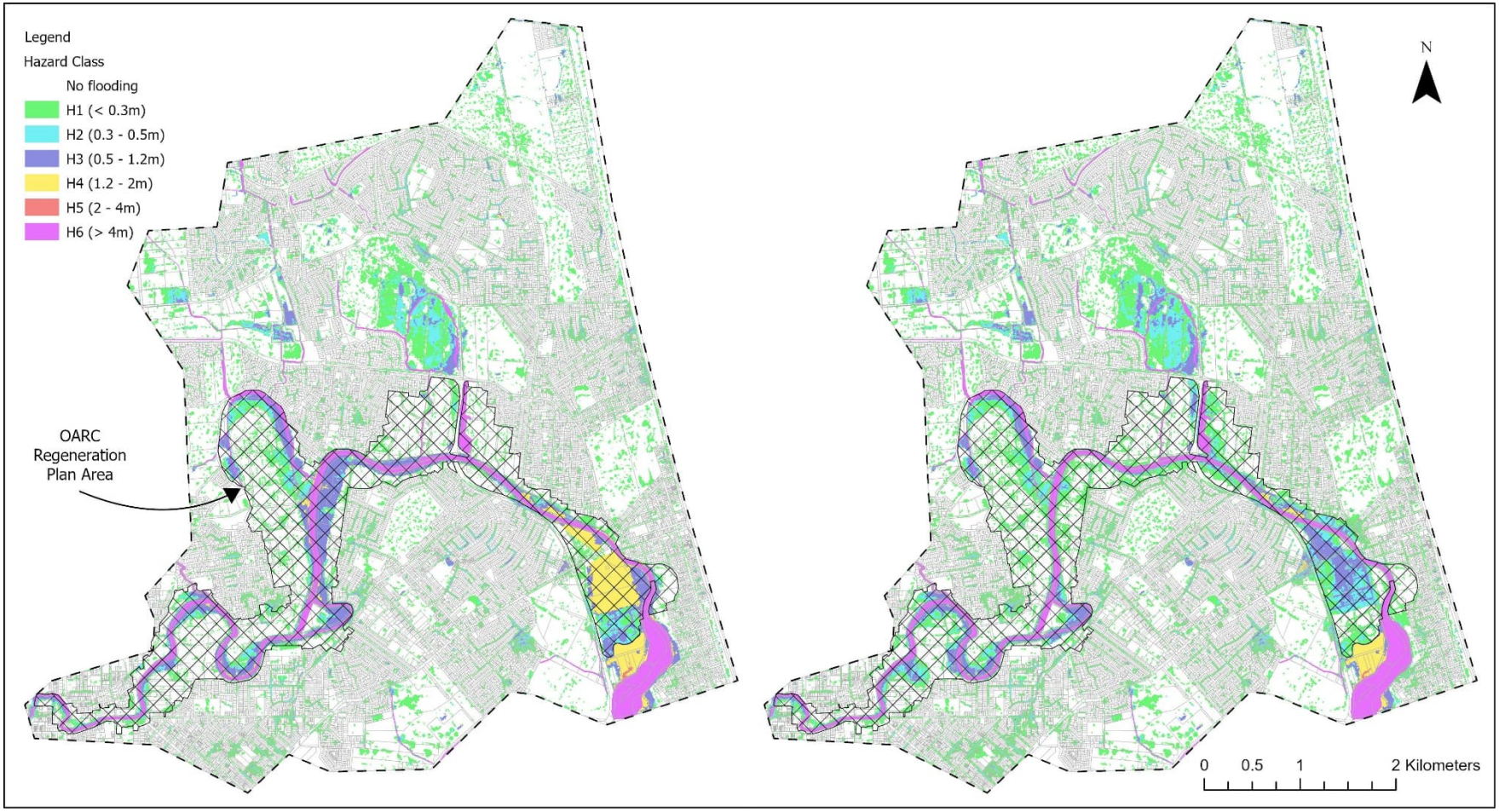

Figure 3: Flood hazard map of scenario 6+Scheme (~2060) 10% AEP event under the OARC Scheme (left) and Baseline with existing stopbanks (right).

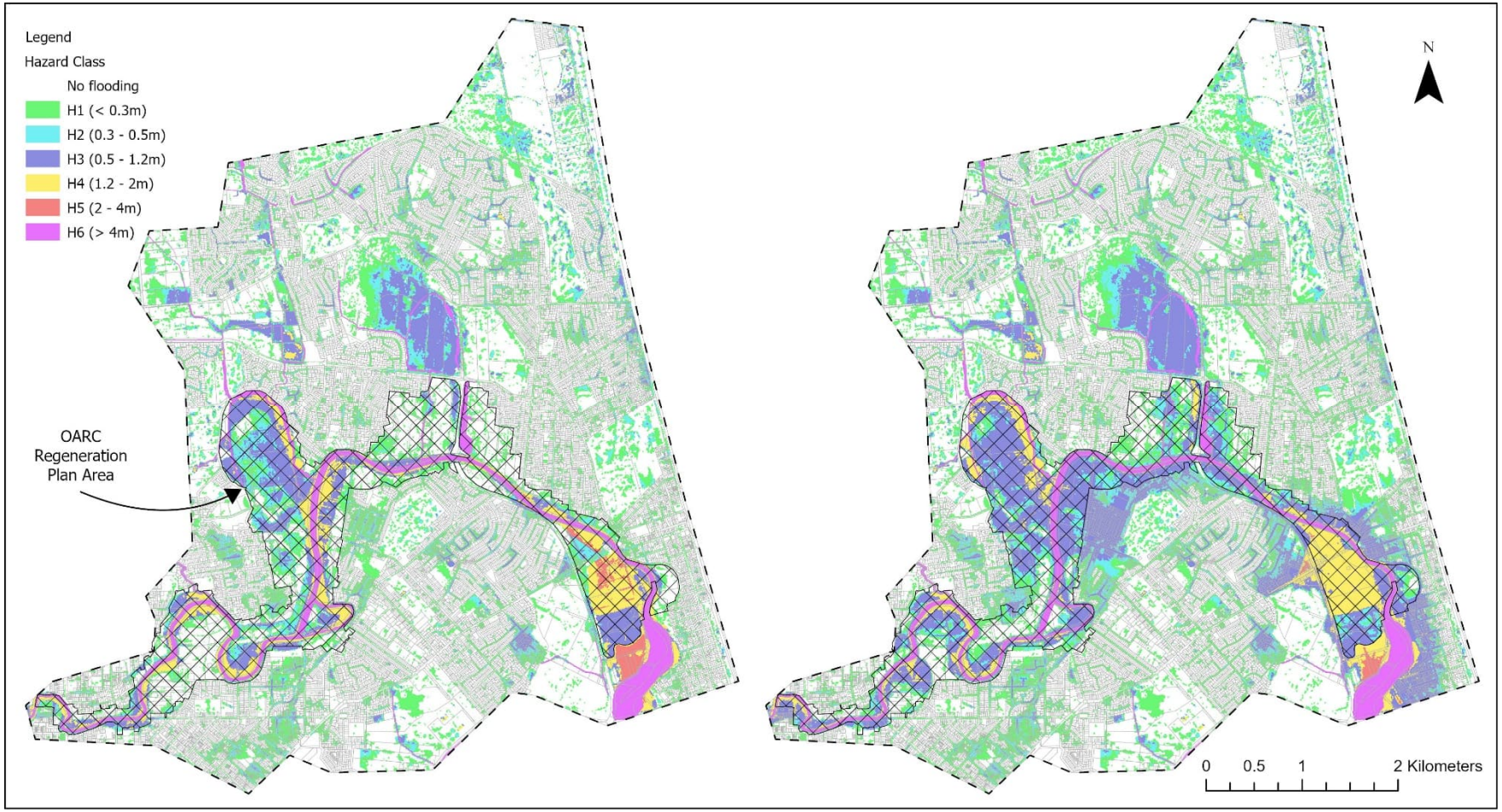

Figure 4: Flood hazard map of scenario 6+Scheme (~2060) 0.5% AEP event under the OARC Scheme (left) and Baseline with existing stopbanks (right).

Figure 5 shows the distribution of flood hazard class, excluding the beach and river channel area, for future Scenario 2+Scheme (~2020), Scenario 6+Scheme (~2060) and Scenario 9+Scheme (~2120). In all OARC Scheme scenarios under 1.88 m SLR, the majority of the total flooded area is within hazard classes H1 and H2 – i.e., less than 0.5 m depth above ground level. The deeper, higher hazard class flooding occurs within the OARC Regeneration Plan Area, the Travis Wetland, Clare Park and South New Brighton.

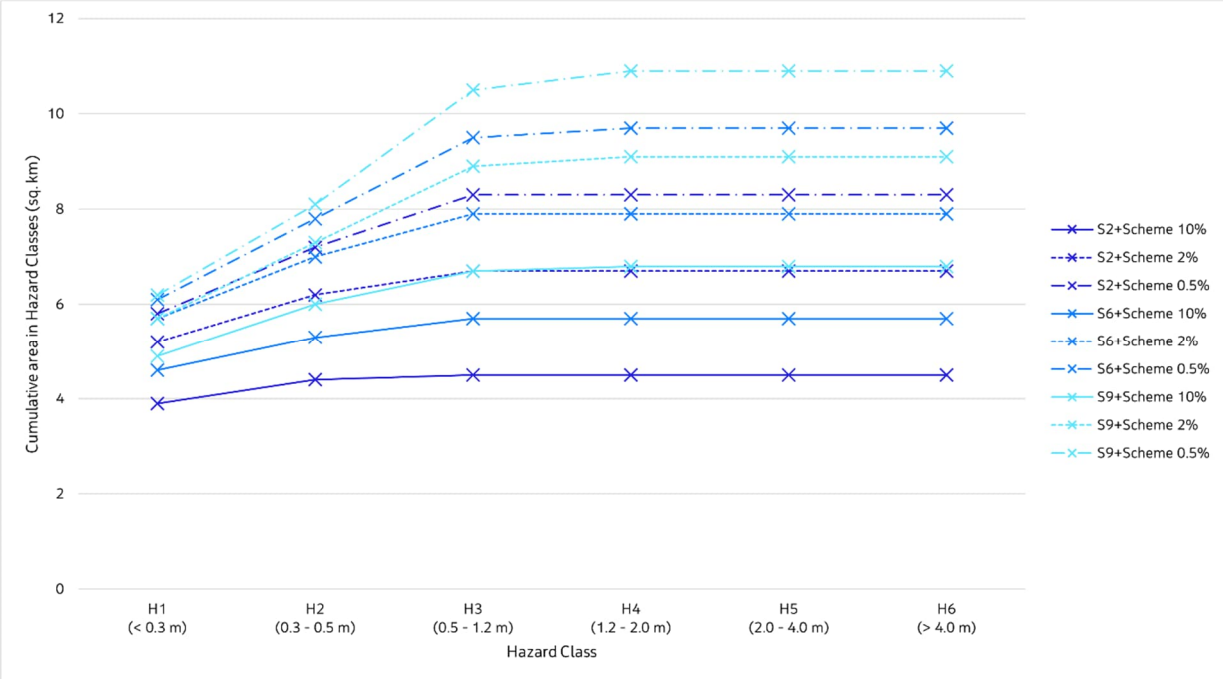

Figure 5: Distribution of AR&R Guideline flood hazard categories classified by depth, excluding beach and area within indicative proposed stopbanks.

Figure 6 and Figure 7 show how the modelled flood extent and depths for the 2% AEP in the OARC Scheme model changes over the future scenarios of ~2030, ~2060 and ~2100. Figure 6 shows the flooding without any land settlement and Figure 7 shows the flooding with earthquake-induced land settlement in 2060 and 2100.

The model results show that both with and without land settlement, the largest changes in flood depths are within the river corridor, the OARC Regeneration Plan area and Travis Wetland. Outside these areas there is some increase in flooding from stormwater from ~2030 to ~2060 and less of an increase from ~2060 to ~2100.

Figure 8 shows the effect of earthquake-induced land settlement on the modelled maximum 2% AEP flood depths in ~2060 and ~2100. The results show that flood depths are increased in some areas and reduced in other areas. This reflects the modelled spatial variation in settlement with increased depth of flooding tending to occur in areas of greater land settlement through ponding of runoff from areas of less settlement where flood depths are reduced.

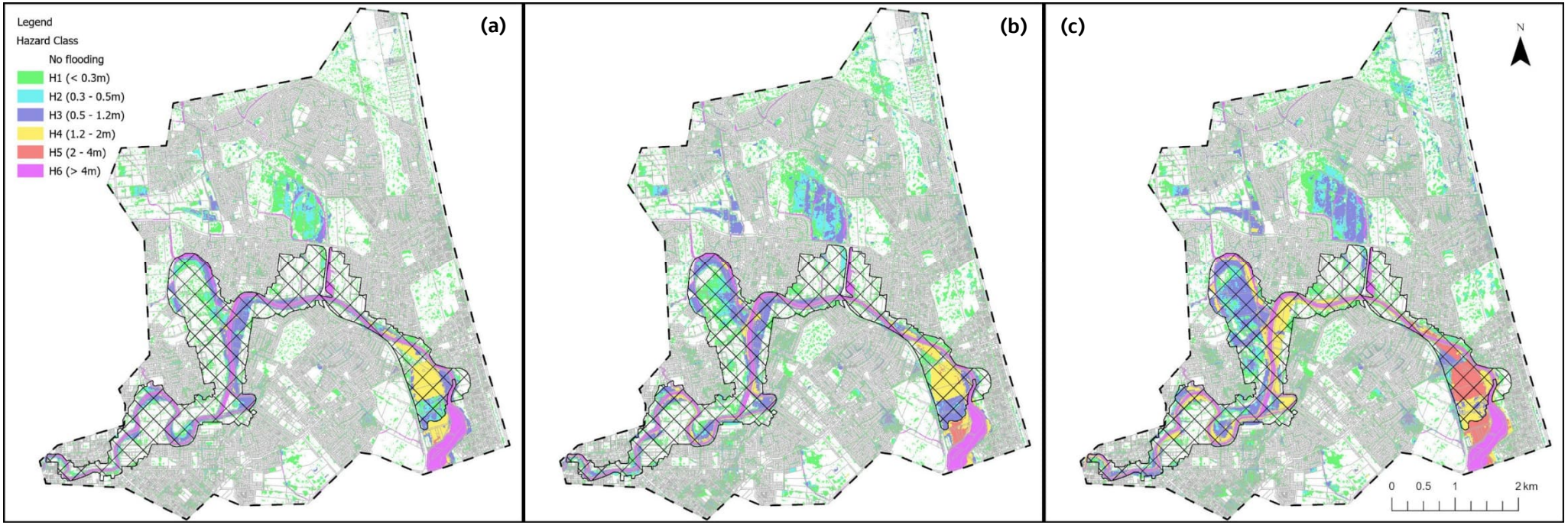

Figure 6: Flood hazard map for 2% AEP – (a) Scenario 4+Scheme (~2030); (b) Scenario 6+Scheme (~2060); (c) Scenario 9+Scheme (~2100).

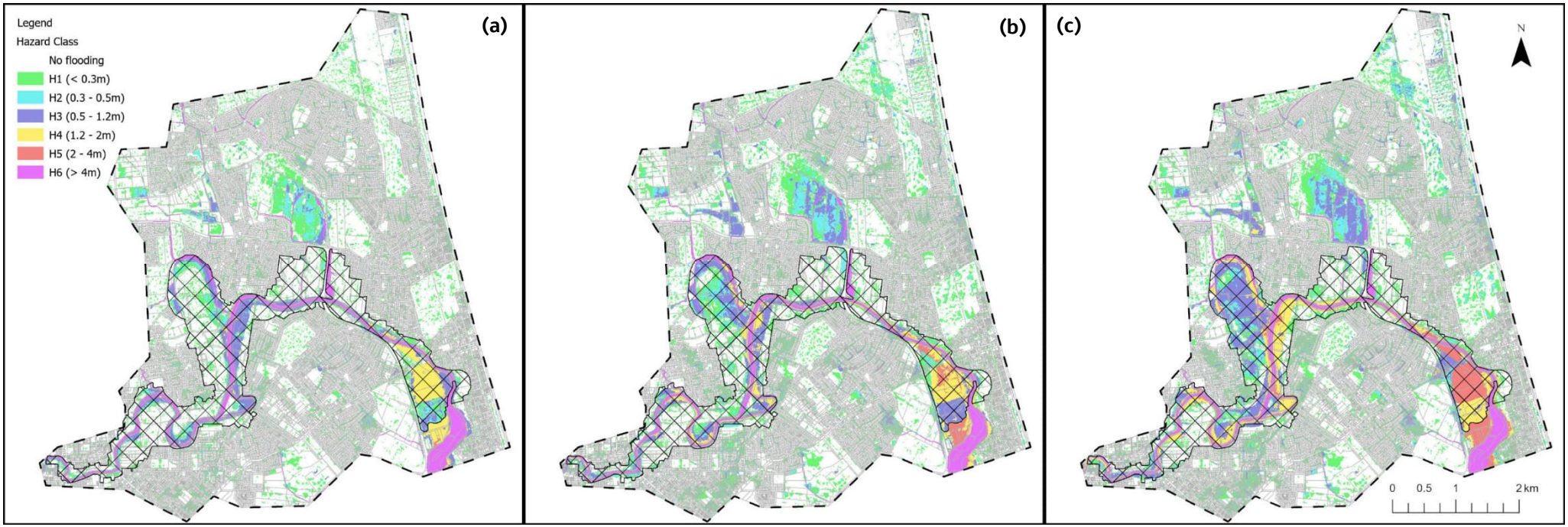

Figure 7: Flood hazard map for 2% AEP – (a) Scenario 4+Scheme (~2030); and, with earthquake-induced land settlement, (b) Scenario 6+Scheme (~2060); (c) Scenario 9+Scheme (~2100).

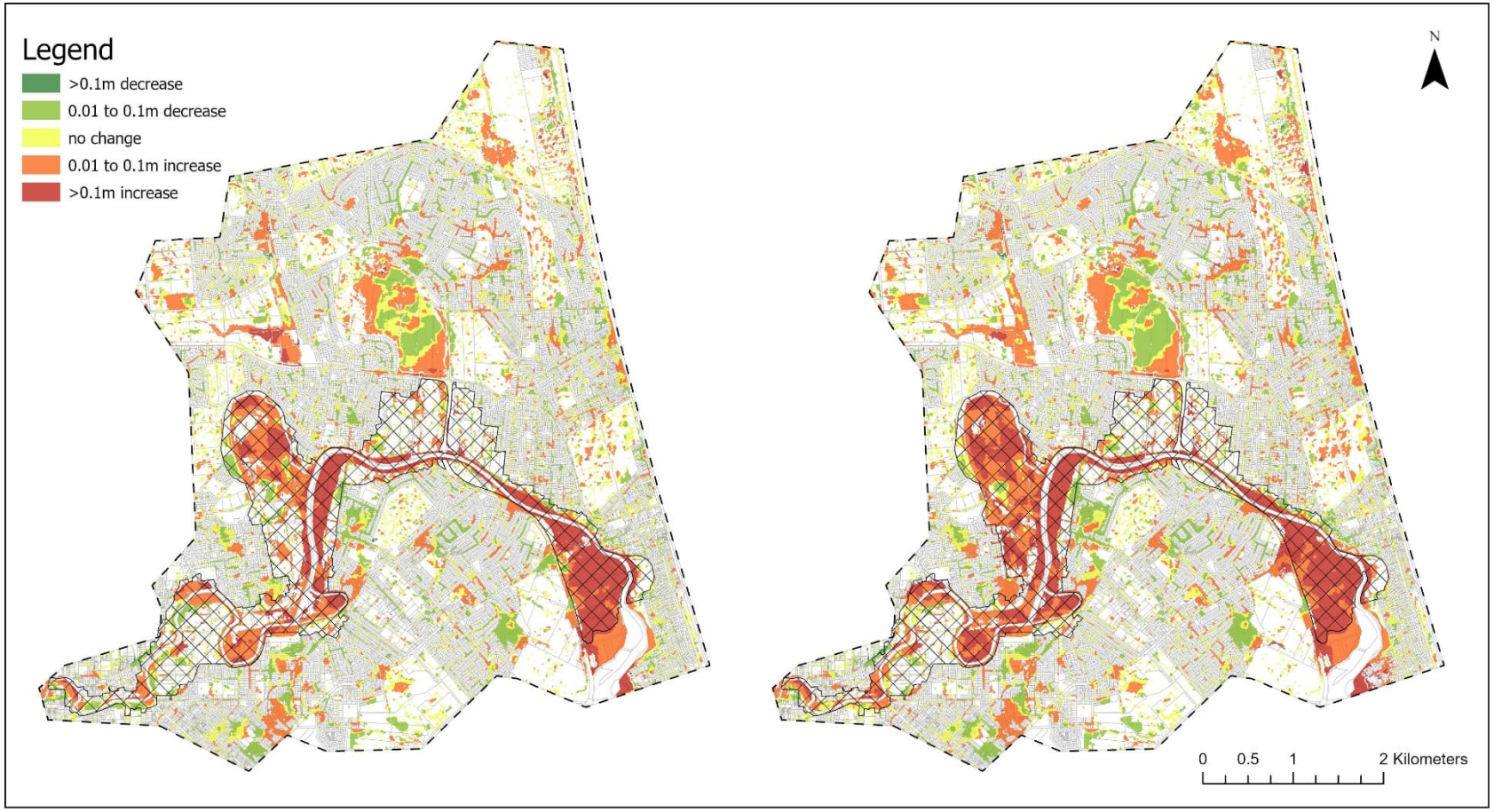

Figure 8: Change in 2% AEP flood depth with earthquake-induced land settlement for: (a) 0.45 m SLR (~2060) and (b) 1.06 m SLR (~2100) scenarios

4. River water levels and pumpstation discharges

4.1 River water levels

The OARC Scheme model results for the maximum 0.5% AEP water levels in the Ōtākaro Avon River are plotted in Figure 9, Figure 10, Figure 11 and Figure 12 for the model scenarios of 0.19 m SLR (~2030), 0.45 m SLR (~2060), 1.06 m SLR (~2100) and 1.88 m SLR (~2150) respectively. Results for each of the rainfall scenarios are shown together with the overall maximum levels for the 0.5% AEP. For the 0.45 m and 1.06 m SLR scenarios water levels are plotted for both the 'without' and 'with' earthquake scenarios.

Maximum water levels are tidally dominated as far upstream as around the Avondale Road bridge in all scenarios. Further upstream, the highest water levels are for the 18-hour duration rainfall event, the same critical duration as for the Baseline model. The reductions in ground level in the 'with earthquake' scenarios result in a small reduction in peak water levels in the river, up to around 0.1 m locally, in both the 0.45 m SLR and 1.06 m SLR scenarios.

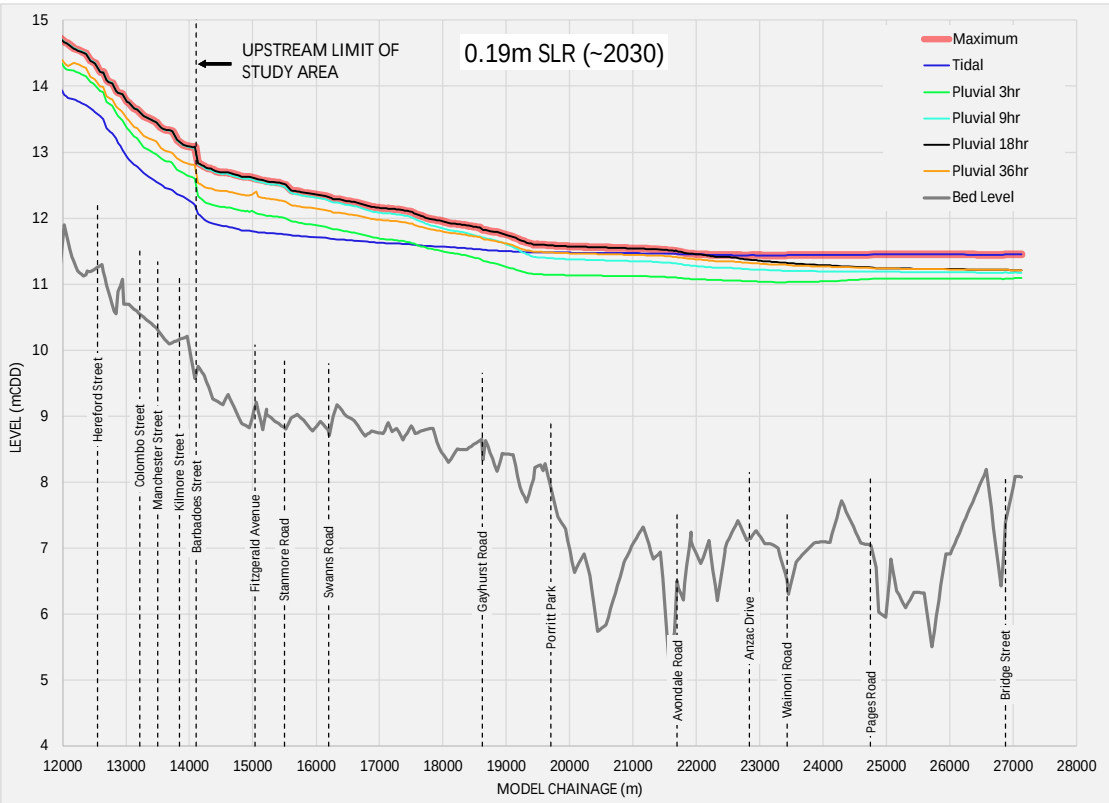

Figure 9: Maximum OARC Scheme model 0.5% AEP water levels in Ōtākaro Avon River in ~2030

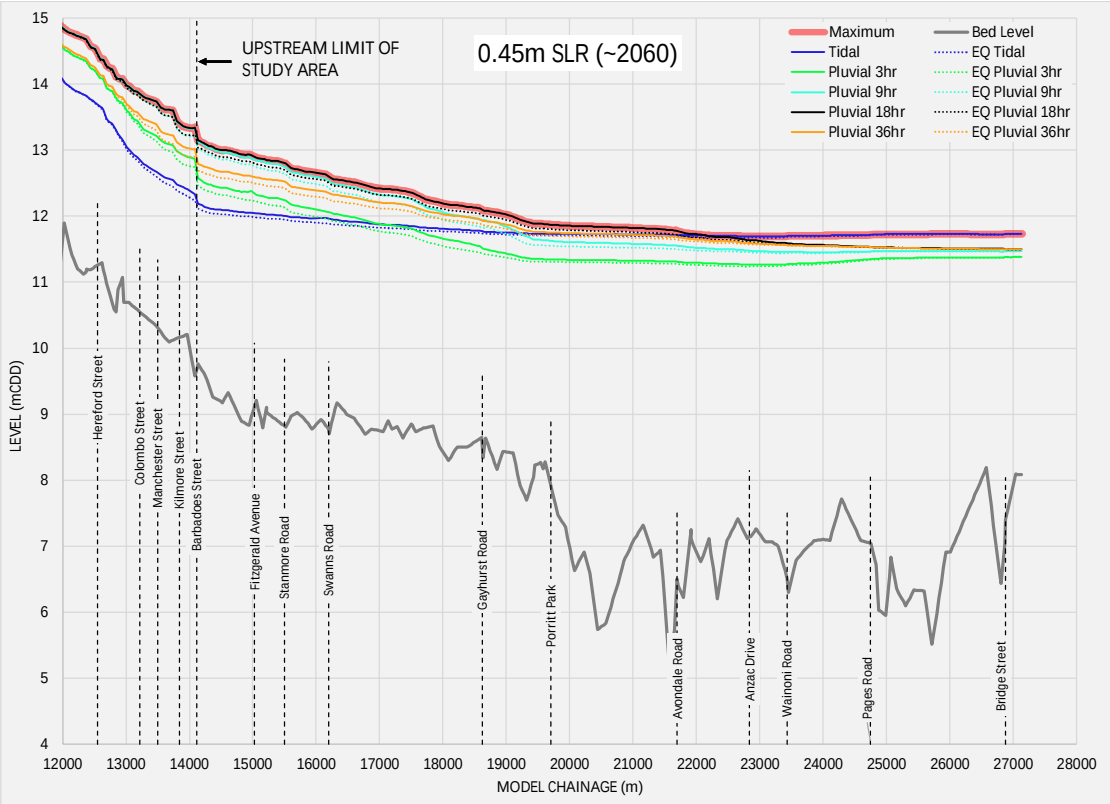

Figure 10: Maximum OARC Scheme model 0.5% AEP water levels in Ōtākaro Avon River in ~2060 ('EQ' indicates scenario with earthquake-induced ground settlement).

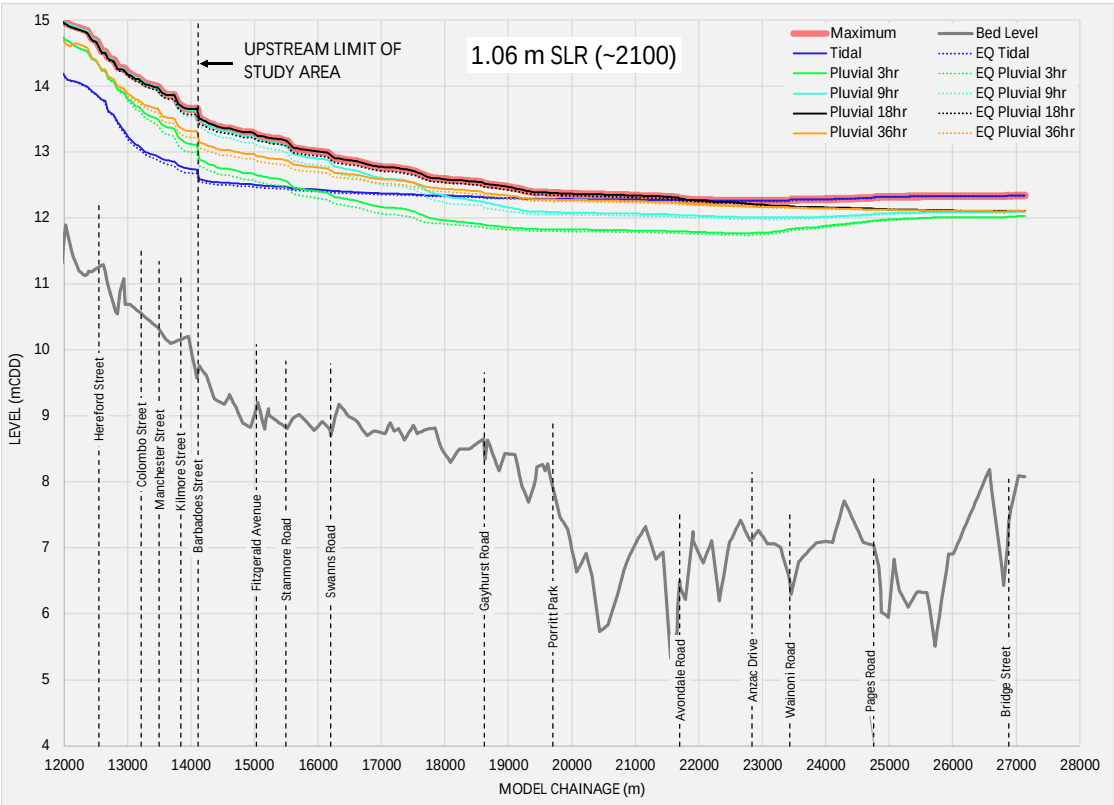

Figure 11: Maximum OARC Scheme model 0.5% AEP water levels in Ōtākaro Avon River in ~2100 ('EQ' indicates scenario with earthquake-induced ground settlement)

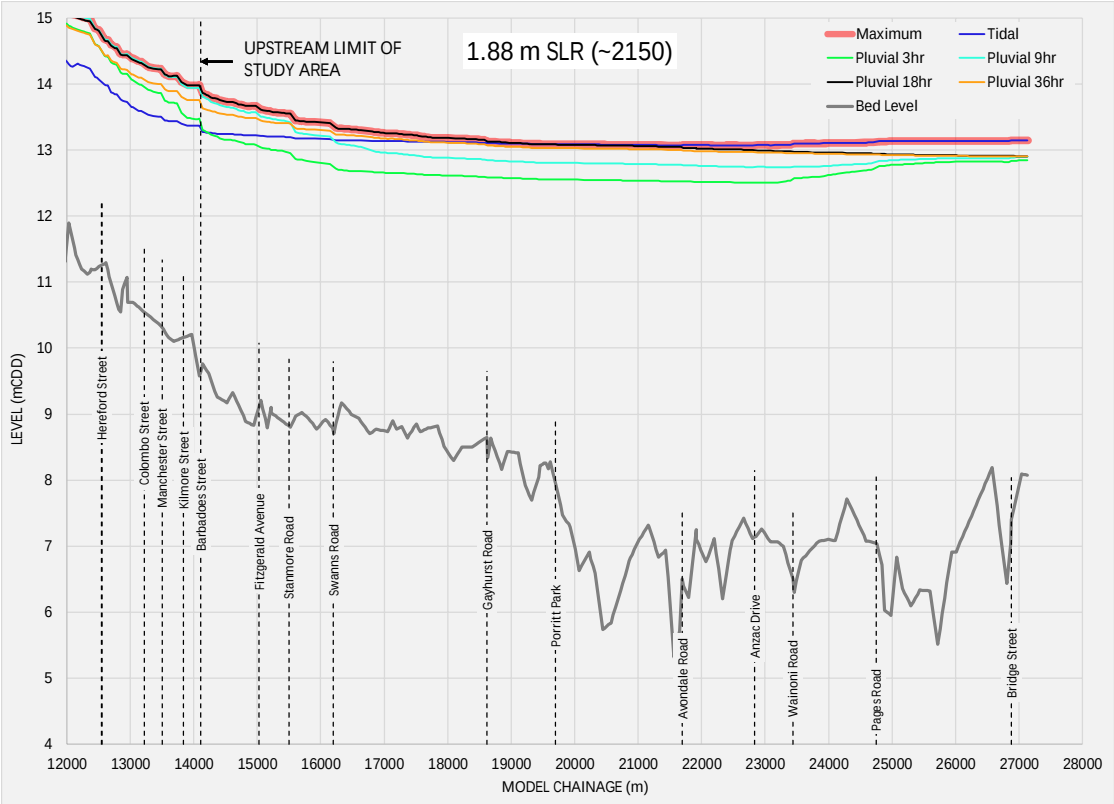

Figure 12: Maximum OARC Scheme model 0.5% AEP water levels in Ōtākaro Avon River in ~2150

4.2 Pumpstation discharges

The OARC Scheme model results for discharge at a sample selection of the new pumpstations for the 0.19 m SLR (~2030), 0.45 m SLR (~2060) and 1.06 m SLR (~2100) scenarios[3] are plotted in Figure 14 and Figure 15. The locations of these pumpstations are shown in Figure 13.

The results show that for most pumpstations the maximum pumped flowrate does not increase substantially with future climate change. However, as shown in Figure 14, the volume of water that is pumped does increase, reflecting the increases in total rainfall depth and runoff volume in the catchments. The duration of pumping and therefore of ponding in the catchment both increase. In the model, the available pump capacity is larger than the simulated pumped flows. This suggests that for most pumpstations the flow reaching the pumps is determined by the inletting and conveyance capacity of the pipe network serving the pumpstation, as represented in the model, rather than the catchment runoff.

The model results show that there are 'pockets' of flooding that are primarily ponding of pluvial flooding within catchments. These are not drained by the stormwater network to the pump stations and are prevented from draining through overland flow to pump stations by higher ground. The flood hazard maps indicate that areas of ponding adjacent to the stopbanks are largely within the OARC Regeneration Plan area. Council plans to use part of this area for stormwater treatment facilities which will include flood detention storage to manage the required pump capacity. Pumps may therefore not need to be sized for the maximum modelled flow, including the overland flow, if detention storage is

[3] The future scenarios shown in Figure 14 and Figure 15 are labelled according to their respective SLR component, though each scenario includes both SLR and the corresponding increase in rainfall depth for the dates indicated. To avoid referring to scenarios by the nominal dates (as these are dependent on the SSP scenario) they are primarily referred to by the value of SLR.

feasible. While the pump capacities adopted in the model are appropriate for understanding the effects of pumped drainage on flooding, further analysis will be undertaken to size pumps as part of the scheme design. This will take account of both overland and pipe network flows, any planned detention basins and stormwater treatment ponds, and any network reticulation upgrades or other stormwater management measures that may be implemented by Council to address the 'pockets' of pluvial flooding in the catchments. These other works may modify the rate or volume of water being pumped over a storm as the optimisation process would seek to balance capital cost of infrastructure against operational cost, local flood reduction benefit and changes in water levels in the Avon River.

In future scenarios which include the earthquake-induced land settlement values derived for the project (which vary over the project area) the modelled pump flows are generally very similar to the scenarios without land settlement. The modelled flows at pumpstation OARC.PS15A are a little lower in the earthquake-induced land settlement scenario, possibly reflecting additional ponding in the catchment to this pumpstation in the earthquake scenario (ref. Figure 8). The actual changes in flow reaching the pumps could vary according to the spatial distribution of settlement.

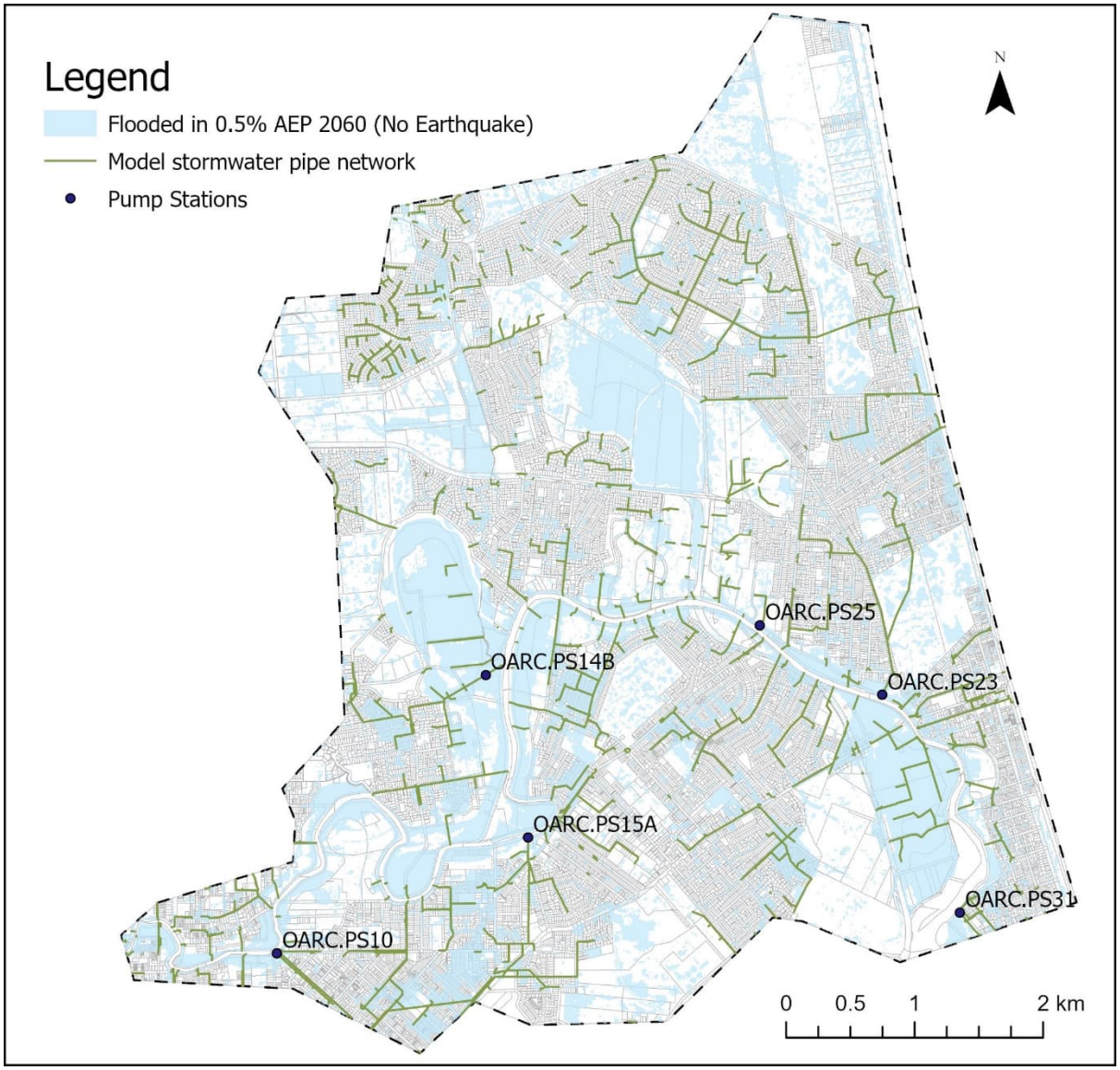

Figure 13: Locations of sample new pumpstations for which results are plotted in Figure 14 and Figure 15.

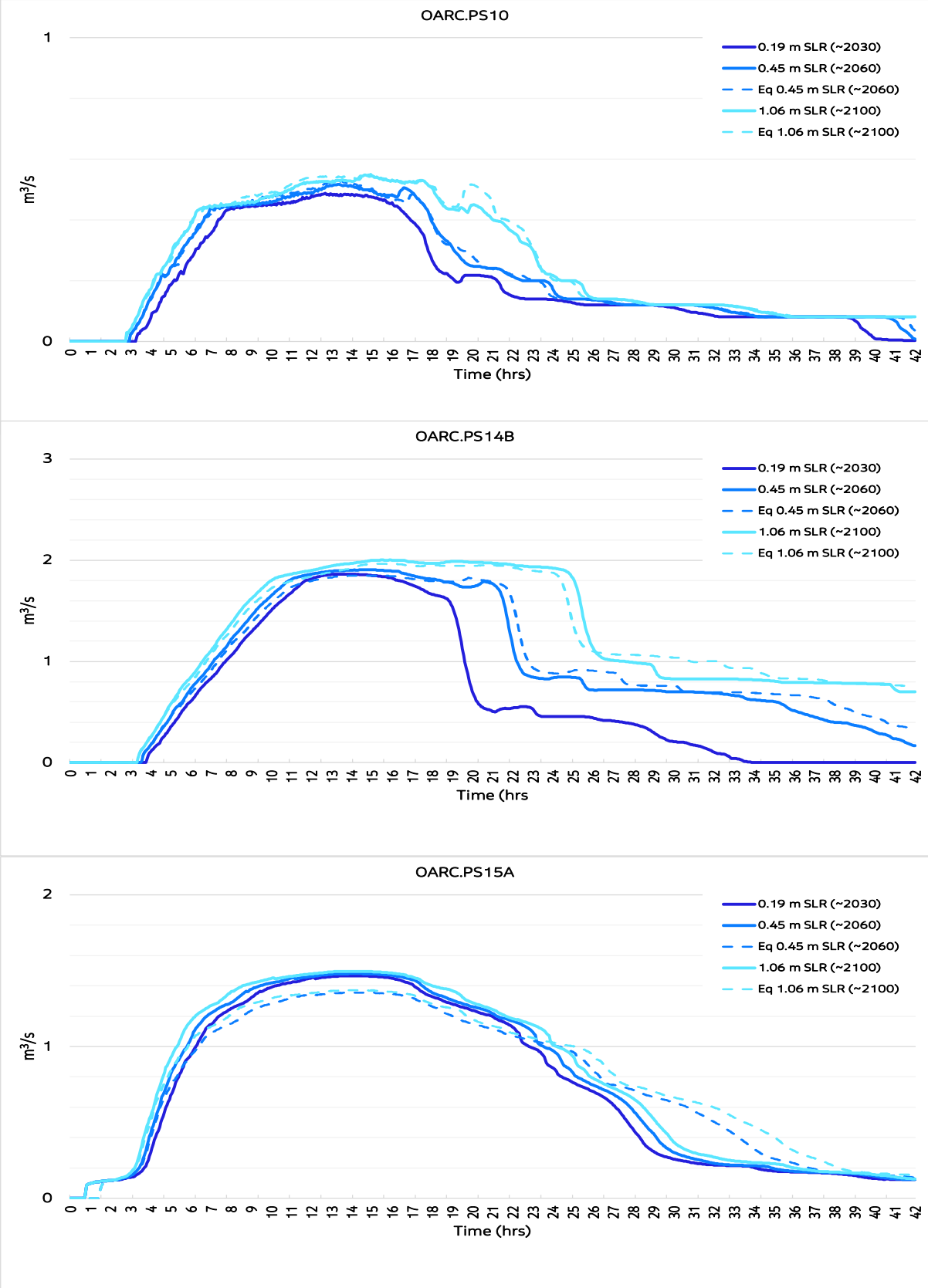

Figure 14: OARC Scheme model results for discharge in the 0.5% AEP 18-hour duration rainfall event at new pumpstations OARC.PS.10, OARC.PS.14B and OARC.PS.15A ('Eq' indicates scenario with earthquake-induced ground settlement).

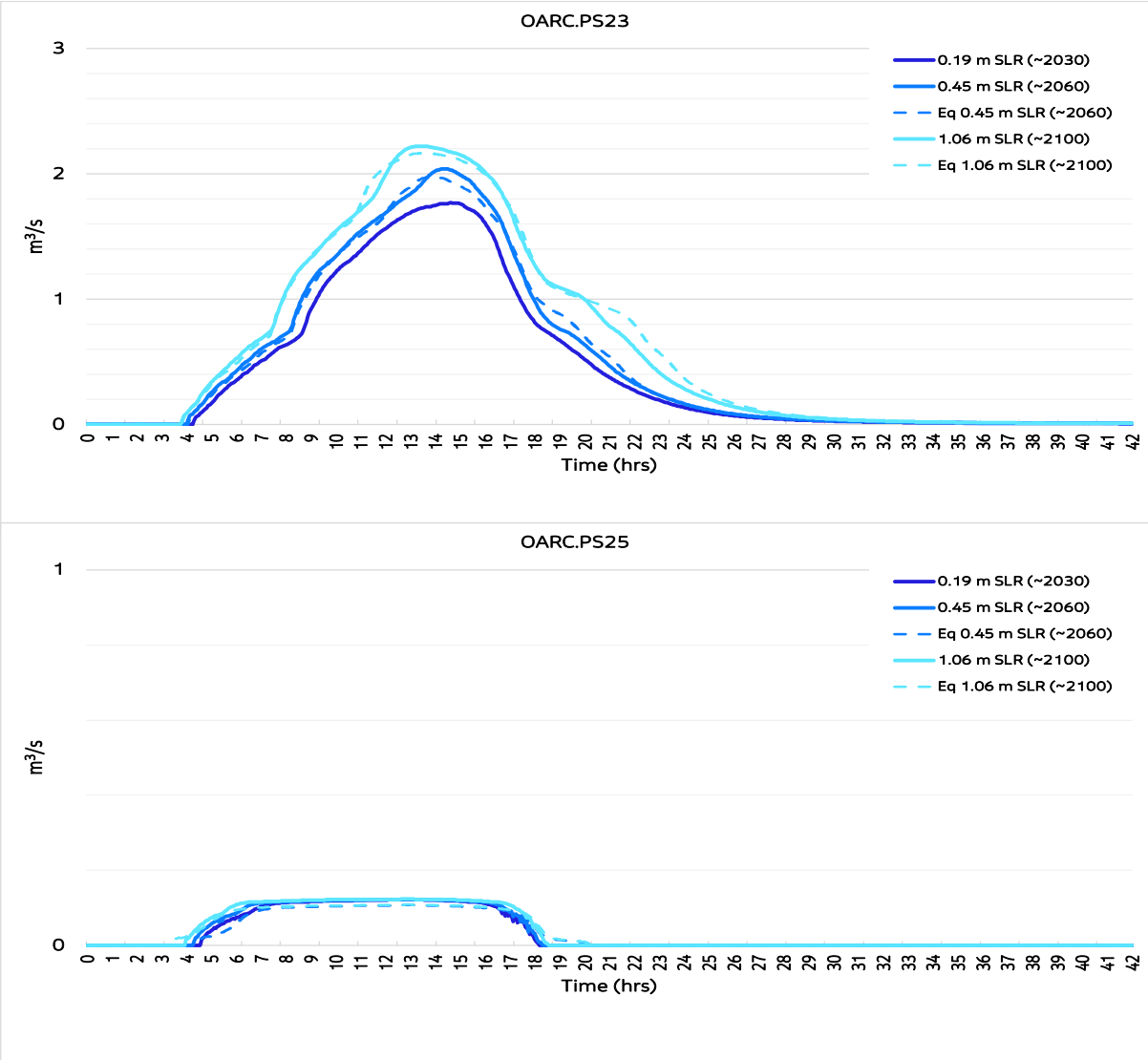

Figure 15: OARC Scheme model results for discharge in the 0.5% AEP 18-hour duration rainfall event at new pumpstations OARC.PS.23 and OARC.PS.25 ('Eq' indicates scenario with earthquake-induced ground settlement).

5. Properties flooded and flood damages

5.1 Method

We have used the OARC Scheme model results and the FloodFX tool to make a quantitative assessment of the effects of flooding for the OARC Scheme in terms of the number of properties affected by flooding and the financial damages for comparison with the baseline model results. The assessment is restricted to the lower Ōtākaro Avon catchment project area, shown in Figure 2.

We have used the same method for calculating flood damages as for the Baseline model results. Detailed descriptions of the FloodFX calculation methods are provided in the FloodFX User Guide[4] and

[4] Stormwater Infrastructure Economic Tool, Christchurch City Council, FloodFX User Guide, IZ057301-NCM-GL-0001 Rev 2, 19 October 2016

Calculation Theory Report[5]. Further details of the input datasets and calculation parameters adopted for the Multi Hazards project are provided in the FloodFX Methodology and Parameters memorandum for the project[6].

5.1.1 Property counts

Counts of properties affected by flooding are computed in FloodFX as follows:

- 'Buildings subject to overfloor flooding': the number of building footprints in which the modelled flood level is within 100 mm of the building floor level as defined in the FloodFX database, a composite of surveyed and inferred floor levels.
- 'Buildings subject to underfloor flooding': the number of building footprints which intersect the modelled flood extent.

5.1.2 Flood Damages

In FloodFX, flood damages are calculated as Annual Average Damages (AAD) for each building affected by flooding using calculations of the damages to the building for individual probabilities of flooding (10% AEP, 2% AEP and 0.5% AEP in the Multi Hazards project). Damages in each event are calculated using the NIWA Riskscape method, capped at the property value for the purposes of calculating AAD. Riskscape fragility curves are used to create data in the FloodFX tool for different building construction types (including different foundation types). Building types relate to the CCC buildings dataset (September 2018) within FloodFX. No intensification of housing from 2018 is allowed for or reduction in buildings at risk due to replacement of old building stock at higher floor levels.

The total damages are the sum of direct damages, indirect damages, and intangible damages. Indirect damages are costs of emergency response. Intangible damages allow for the costs of stress, anxiety, and ill health along with indirect costs such as evacuation, temporary accommodation, loss of earnings, increased outgoings. The same approach is also applied to non-residential properties to cover loss of income. Damages are capped at each date they are calculated. Property values (and damages) are based on 2022 values by uplifting the 2015 RV dataset in FloodFX by a factor of 1.5 to represent the house price rise from Nov 2016 to Dec 2022 in CoreLogic data[7]. Further information on the calculation method for direct and indirect damages is described in IZ084400-NW-MEM-0007 Analysis of baseline flood model results (18/01/2024).

Due to the 'rain on grid' approach to the flood modelling, the raw model results include some areas of very shallow water depths which are unlikely to result in damage to buildings. For the FloodFX analysis we have used the processed model water depth grids, which exclude flooding of less than 50 mm in depth.

5.2 Pathways

We have used FloodFX to calculate the number of properties affected by flooding and the AAD for each of the 8 future scenarios simulated with the OARC Scheme model listed in Table 1-1. We have used the AAD values calculated by FloodFX to calculate the Present Value of flood damages over 100

[5] Stormwater Infrastructure Economic Tool, Christchurch City Council, Calculation Theory Report, IZ057301-OEC-RP-0002 Rev 2, 19 October 2016

[6] FloodFX Methodology and Parameters, IZ084400-NW-MEM-0005, 10 April 2023

[7] CoreLogic data accessed January 2023 for statistics on residential house values.

years from 2020 for three future pathways of climate change and permanent, earthquake-induced, land settlement as set out in Table 5-1.

For reference, the pathways considered for the Baseline model results are also included in Table 5-1. To calculate Present Values we have interpolated AADs linearly between the modelled scenario values. For pathways including earthquake-induced land settlement we have used a 'step' change in AAD at the time of the earthquake.

For the period beyond 2100 we have adopted a constant value equal to the AAD at 2100 because the modelled scenarios beyond 2100 (2150) do not include allowance for earthquake-induced land settlement, which may have previously occurred in some pathways. These damages (2100 to 2120) do not contribute significantly to the Present Value due to the substantial discounting of damages in the far future. As for the Baseline model results, we have not capped the total present value of damage to a property to the property value. This allows for properties to be repaired or rebuilt multiple times in the future rather than relocating or removing buildings. However, further intensification has not been allowed for within the assessment, which may to some degree counterbalance the impact of Present Value damages to properties being uncapped.

Table 5-1: Future pathways from 2020 to 2120 for assessment of Baseline and OARC Scheme Present Value flood damages.

Pathway	2020	2030	2060	2100	2120
Up1	<---------- With Existing Stopbanks ---------->			<---------- No Stopbanks ---------->	
Up2	<---------- With Existing Stopbanks ---------->			No Stopbanks + Earthquake settlement	
Up3	<------ With Existing Stopbanks ----->		Existing Stopbanks & Earthquake settlement	No Stopbanks + Earthquake settlement	
Down1	<---------- No Stopbanks ---------->				
Down2	<---------- No Stopbanks ---------->			←----No Stopbanks + Earthquake settlement----->	
Down3	<---------- No Stopbanks --------->		<-------- No Stopbanks + Earthquake settlement ------->		
OARC1	<---------- With OARC Scheme Infrastructure---------->				
OARC2	<---------- With OARC Scheme Infrastructure ---------->			With OARC Scheme Infrastructure + Earthquake settlement	
OARC3	With OARC Scheme Infrastructure		With OARC Scheme Infrastructure + Earthquake settlement		

5.3 Results

5.3.1 Number of properties flooded

The number of properties affected by flooding in the three AEPs for each of the 8 modelled scenarios are presented in Table 5-2 in terms of the total number of building footprints intersecting the modelled flood extent, the number of those properties where the flood level is within 100 mm of the floor level and the number of properties where the flood level is above floor level. For comparison, Table 5-3 presents the number of properties affected by flooding in the Baseline model.

The results at an individual property or building are subject to uncertainty due to the nature of the inferred floor level data set, however, the overall analysis is considered sufficiently robust for the purposes of this study. An extensive floor level survey would be required to increase certainty in the output, but this is not practicable within the current assessment.

Figure 16 shows how the number of buildings affected by flooding in the 0.5% AEP increases with time in each of the future pathways defined in Table 5-1. Figure 16(a) shows that the total number of building footprints flooded under the OARC Scheme is significantly less in future sea level rise pathways than under the current temporary stopbanks or 'stopbanks down' pathways. Earthquake-induced land settlement does not greatly increase the total number of buildings footprints affected by flooding.

The number of buildings where the flood level is close to, or above, floor level – Figure 16(b) and Figure 16(c) – is also lower in the OARC Scheme model. Land settlement results in a large increase in the number of buildings where the flood level is close to, or above, floor level in all pathways.

Table 5-2: Approximate number of buildings subject to flooding in the OARC Scheme model simulations for each scenario*.

			Total building footprints intersecting modelled flood extent			Buildings where flood level within 100 mm of floor level			Buildings where flood level above floor level		
SLR and indicative timing	Land settlement from earthquake	Scenario	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP
0 m SLR (2020)	no	2+Scheme	2964	4322	5288	412	670	963	114	208	349
0.19 m SLR (2030)	no	4+Scheme	3069	4419	5467	433	702	1048	116	230	385
0.45 m SLR (2060)	no	6+Scheme	3549	5008	5964	507	876	1245	154	303	487
	yes	8+Scheme	3560	4968	6006	1364	2062	2763	595	973	1435
1.06 m SLR (2100)	no	9+Scheme	4052	5509	6714	661	1066	1646	211	422	756
	yes	10+Scheme	4153	5611	6807	1634	2486	3422	762	1262	1982
1.88 m SLR (2150)	no	12+Scheme	5613	7789	9255	1513	3057	4227	804	2138	3129
2.4 m SLR (>2150)	no	13+Scheme	7729	9927	11343	3609	5438	6630	2850	4470	5527

Table 5-3: Approximate number of buildings subject to flooding in the Baseline model (stopbanks up)*.

			Total building footprints intersecting modelled flood extent			Buildings where flood level within 100 mm of floor level			Buildings where flood level above floor level		
SLR and indicative timing	Land settlement from earthquake	Scenario	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP	10% AEP	2% AEP	0.5% AEP
0 m SLR (2020)	no	S1	3018	4375	5528	410	693	1203	112	217	458
0.19 m SLR (2030)	no	S3	3133	4559	5954	441	764	1560	114	267	809
0.45 m SLR (2060)	no	S5	3725	6014	7291	576	1862	2827	180	1116	1915
	yes	S7	4210	6295	7561	1782	3621	4657	888	2461	3378
1.06 m SLR (2100)	no	S9	6358	8011	9177	2921	4030	4993	2303	3239	4042
	yes	S10	6699	8351	9480	4372	5832	7007	3445	4655	5733
1.88 m SLR (2150)	no	S12	9556	11153	12336	6341	7828	8790	5559	6938	7894
2.4 m SLR (>2150)	no	S13	12506	14144	15121	9570	11237	12341	8733	10387	11453

* Groundwater levels for all scenarios are 85th percentile.

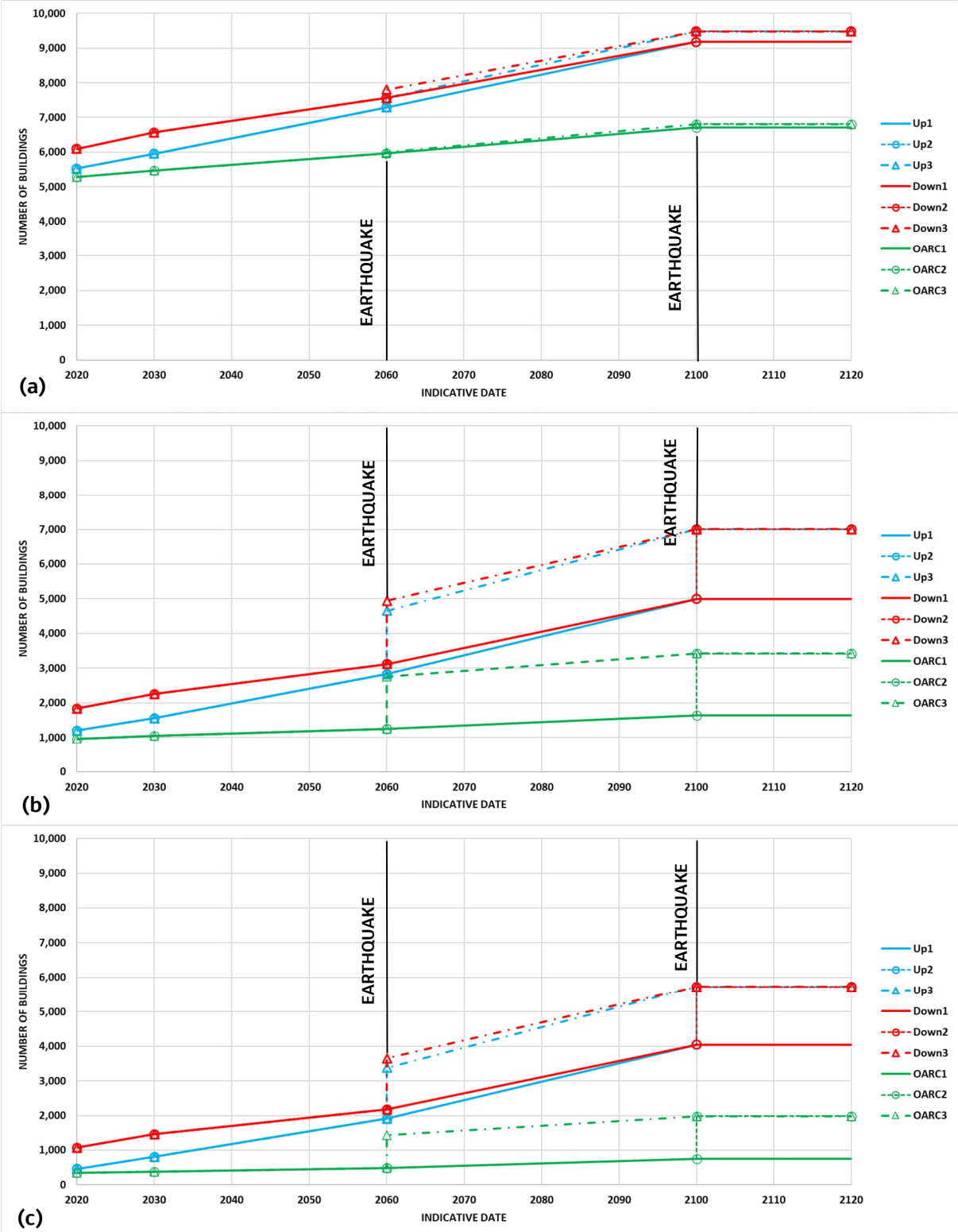

Figure 16: Number of properties in the project area affected by flooding in the 0.5% AEP for each pathway – (a) total number of building footprints affected by flooding; (b) number of buildings with water level within 100 mm of floor levels; (c) number of buildings with water level above floor level. (Note that variation in building numbers between modelled scenarios will not necessarily be linear as shown on the charts)

5.3.2 Flood Damages

The total AADs calculated for each of the 13 Baseline model scenarios are presented in Table 5-5. The total AADs calculated for each of the 8 OARC Scheme model scenarios are presented in Table 5-5 together with the differences to the Baseline model with existing stopbanks. Figure 17 shows how the AADs from these scenarios are used to define the change in AAD with time for each of the nine future pathways defined in Table 5-1 over the period 2020 to 2120. AAD values are interpolated between those calculated at the indicative date of each modelled scenario. Where a pathway includes the shock hazard of earthquake-induced land settlement, a step change in AAD is applied from the AAD value without land settlement to the AAD with land settlement at the time of the shock hazard.

The assessment of flood damages does not allow for the effects of any structural failure of stopbanks or of pump stations failing to operate during flood events. Increasing the dependency on an increasingly larger number of structural features (such as pumps and stopbanks) introduces residual risks from failure with consequent potential effects on damages which are not included in this analysis.

Table 5-4: Total AADs for the Baseline model scenario simulations

Scenario No.	SLR and indicative timing	Land settlement from earthquake	Stopbanks	Groundwater levels	Total AAD
1	0 m SLR (2020)	no	Up	85th %ile	$10.8 M
2		no	Down	85th %ile	$17.6 M
3	0.19 m SLR (2030)	no	Up	85th %ile	$12.8 M
4		no	Down	85th %ile	$27.0 M
5	0.45 m SLR (2060)	no	Up	85th %ile	$31.0 M
6		no	Down	85th %ile	$50.1 M
7		yes	Up	85th %ile	$69.4 M
8		yes	Down	85th %ile	$90.2 M
9	1.06 m SLR (2100)	no	Down	85th %ile	$134.9 M
10		yes	Down	85th %ile	$202.0 M
11		no	Down	50th %ile	$134.2 M
12	1.88 m SLR (2150)	no	Down	85th %ile	$359.4 M
13	2.4 m SLR (>2150)	no	Down	85th %ile	$603.5 M

Table 5-5: Total AADs for the OARC Scheme model scenario simulations

Scenario No.	SLR and indicative timing	Land settlement from earthquake	Groundwater levels	Total AAD	Difference (compared to existing stopbanks)
2+Scheme	0 m SLR (2020)	no	85th %ile	$10.6 M	-$0.2 M
4+Scheme	0.19 m SLR (2030)	no	85th %ile	$11.3 M	-$1.5 M
6+Scheme	0.45 m SLR (2060)	no	85th %ile	$13.9 M	-$17.1 M
8+Scheme		yes	85th %ile	$30.7 M	-$38.7 M
9+Scheme	1.06 m SLR (2100)	no	85th %ile	$19.4 M	-$115.5 M
10+Scheme		yes	85th %ile	$41.4 M	-$160.6 M
12+Scheme	1.88 m SLR (2150)	no	85th %ile	$71.1 M	-$288.3 M
13+Scheme	2.4 m SLR (>2150)	no	85th %ile	$216.5 M	-$387 M

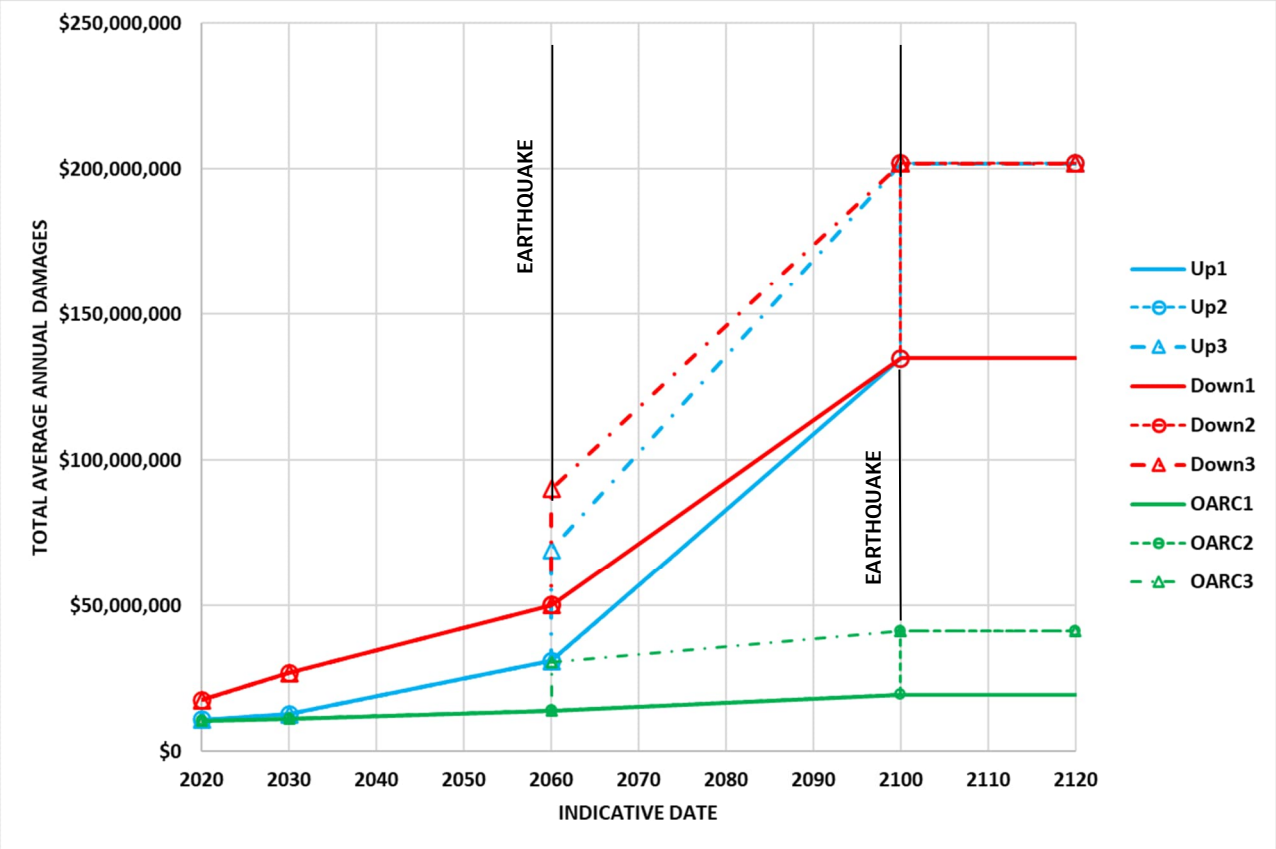

Figure 17: Average Annual Damages (AAD) through time for each of the nine future pathways considered.

We have used the AAD time series for each future pathway in Figure 17 to calculate the cumulative present value of total flood damages. In the present value calculations, we have discounted future damages by an annual rate of 5%. This is the value of discount rate currently recommended by Treasury New Zealand for economic analyses for infrastructure[8]. We also calculated present values using values of 3% and 7% to test the sensitivity of the outcomes of the analysis to the value of discount rate applied. The cumulative present values of flood damages at selected indicative dates are presented in Table 5-6 and illustrated in Figure 18-Figure 20.

[8] https://www.treasury.govt.nz/information-and-services/state-sector-leadership/guidance/reporting-financial/discount-rates

Table 5-6 Cumulative present value total flood damages for nine future pathways using a discount rate of 3%, 5%, and 7%.

Pathway	Up1			Down1			OARC1		
Discount Rate	3%	5%	7%	3%	5%	7%	3%	5%	7%
2020	$11 M	$11 M	$11 M	$18 M	$18 M	$18 M	$11 M	$11 M	$11 M
2030	$112 M	$102 M	$94 M	$210 M	$190 M	$174 M	$104 M	$95 M	$88 M
2060	$417 M	$292 M	$216 M	$753 M	$532 M	$396 M	$286 M	$212 M	$165 M
2100	$943 M	$458 M	$272 M	$1,358 M	$729 M	$464 M	$401 M	$251 M	$179 M
2120	$1,124 M	$491 M	$278 M	$1,540 M	$762 M	$471 M	$427 M	$255 M	$180 M
Pathway	Up2			Down2			OARC2		
Discount Rate	3%	5%	7%	3%	5%	7%	3%	5%	7%
2020	$11 M	$11 M	$11 M	$18 M	$18 M	$18 M	$11 M	$11 M	$11 M
2030	$112 M	$102 M	$94 M	$210 M	$190 M	$174 M	$104 M	$95 M	$88 M
2060	$417 M	$292 M	$216 M	$753 M	$532 M	$396 M	$286 M	$212 M	$165 M
2100	$943 M	$458 M	$272 M	$1,358 M	$729 M	$464 M	$401 M	$251 M	$179 M
2120	$1,215 M	$507 M	$281 M	$1,630 M	$778 M	$474 M	$457 M	$261 M	$181 M
Pathway	Up3			Down3			OARC3		
Discount Rate	3%	5%	7%	3%	5%	7%	3%	5%	7%
2020	$11 M	$11 M	$11 M	$18 M	$18 M	$18 M	$11 M	$11 M	$11 M
2030	$112 M	$102 M	$94 M	$210 M	$190 M	$174 M	$104 M	$95 M	$88 M
2060	$417 M	$292 M	$216 M	$753 M	$532 M	$396 M	$286 M	$212 M	$165 M
2100	$1,299 M	$577 M	$314 M	$1,722 M	$850 M	$507 M	$535 M	$296 M	$195 M
2120	$1,571 M	$626 M	$323 M	$1,994 M	$899 M	$517 M	$591 M	$306 M	$197 M

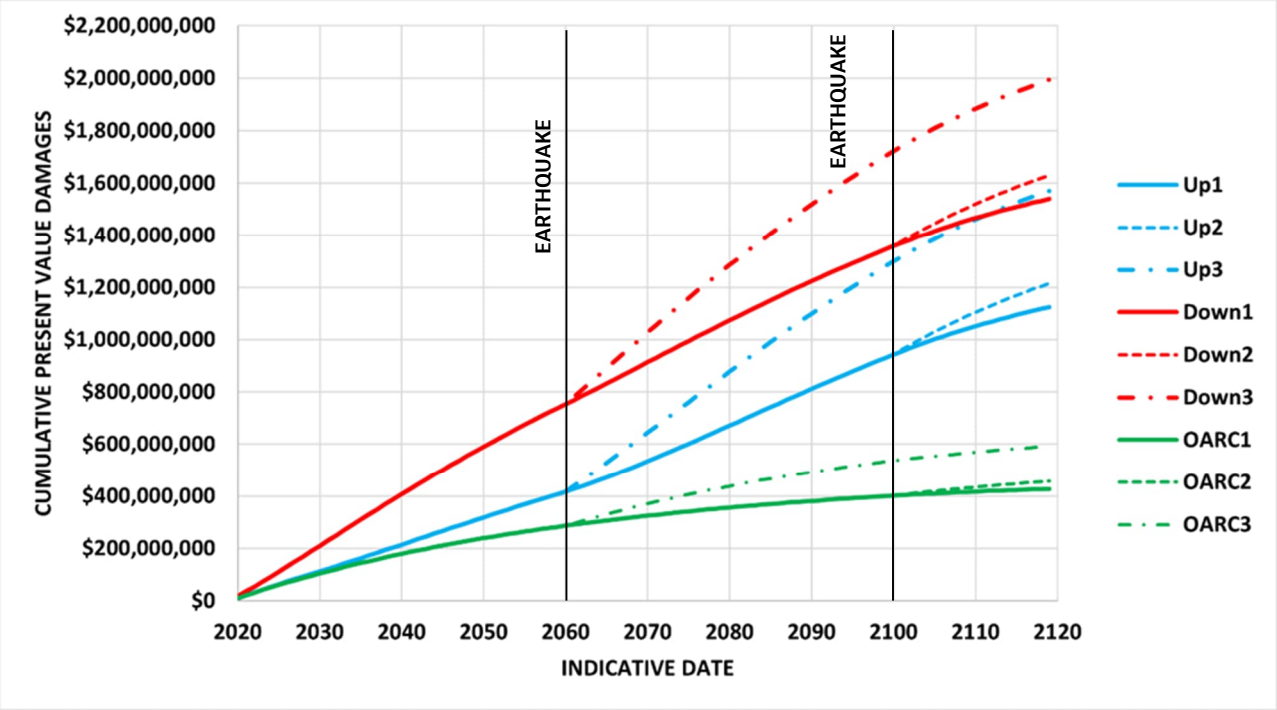

Figure 18 Cumulative Present Value of total flood damages through time for each of the nine future pathways using a discount rate of 3%.

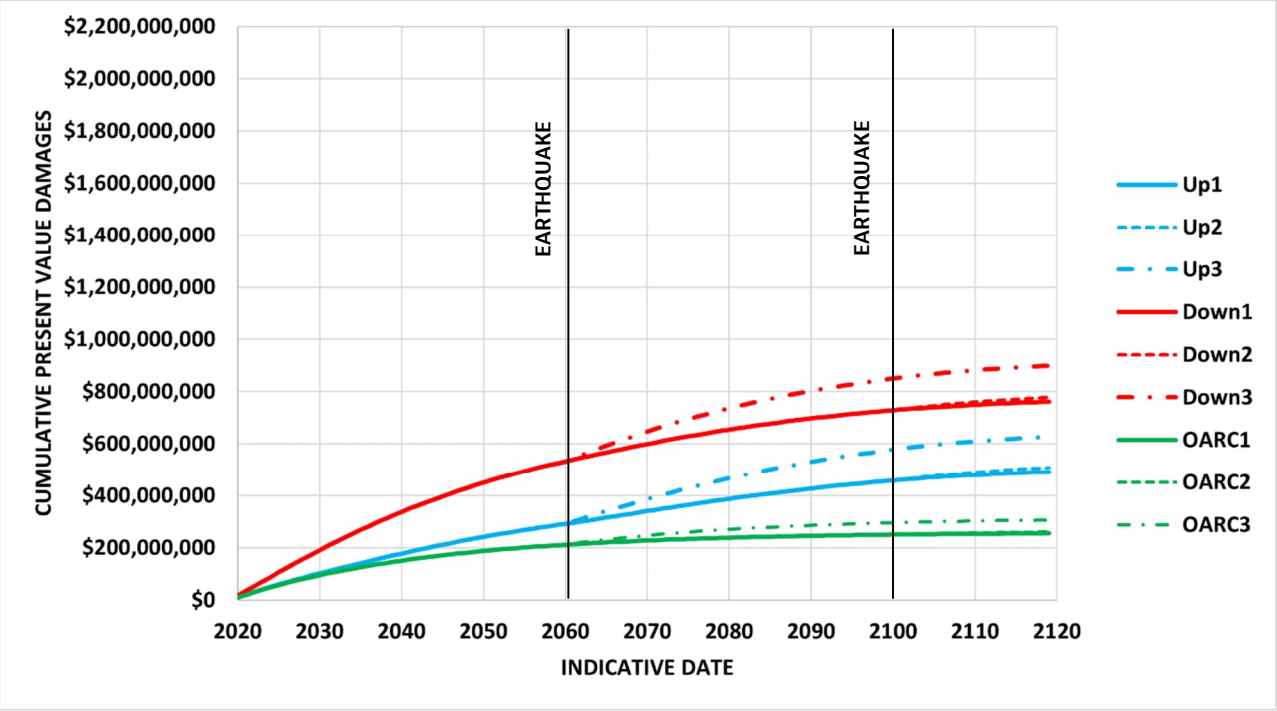

Figure 19: Cumulative Present Value of total flood damages through time for each of the nine future pathways using a discount rate of 5%.

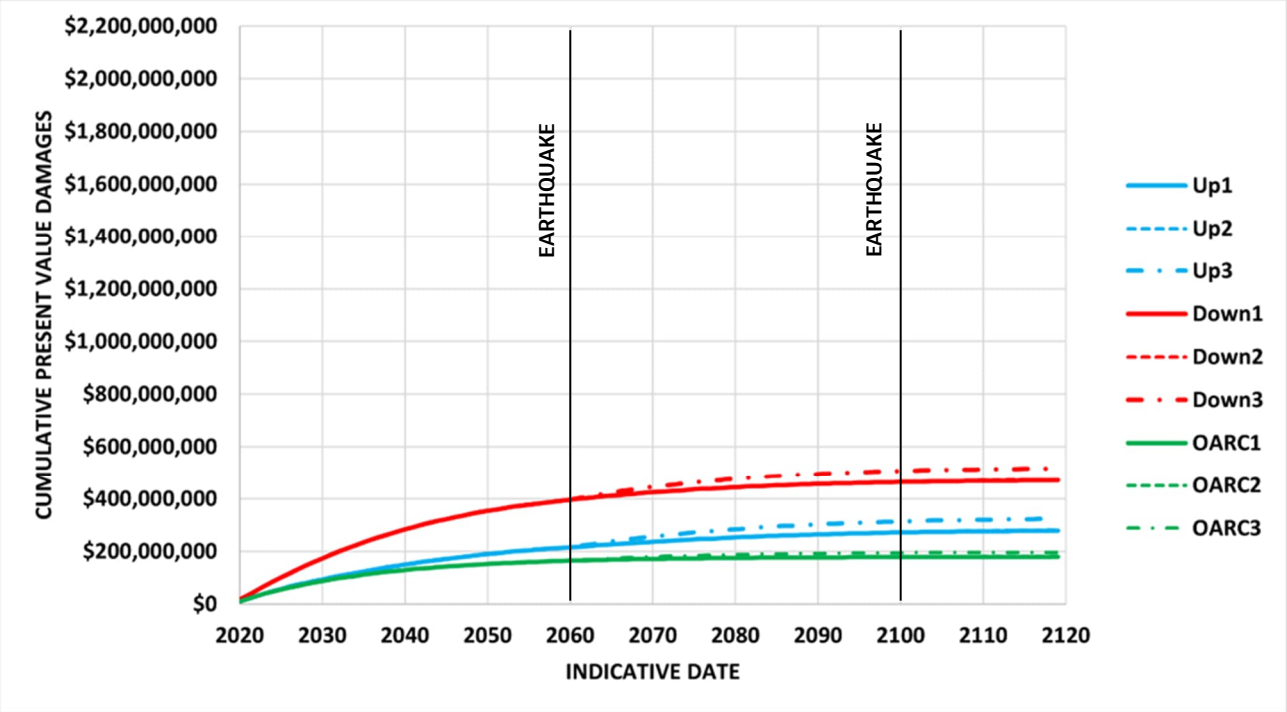

Figure 20 Cumulative Present Value of total flood damages through time for each of the nine future pathways using a discount rate of 7%.

The results presented in Table 5-6 and Figure 19 show that for a 5% discount rate the cumulative present value total damages for the OARC Scheme model and Baseline model 'stopbanks up' pathways are very similar in the first two decades of the assessment period. In the OARC pathways the rate of increase in cumulative present value damages declines more rapidly than any of the baseline pathways. Earthquake-induced land subsidence results has far less effect on present value damages for the OARC Scheme than in the Baseline pathways.

Table 9 and Figure 18 and Figure 20 show the results of the discount rate sensitivity test using 3% and 7% as two alternative discount rate values. The results indicate that the absolute cumulative present value of damages is very sensitive to the choice of discount rate. Table 5-7 compares the cumulative present value damages to 2060 and to 2120 in the OARC scheme (OARC1) pathway with those in the present day stopbanks to 2060 (Up1) pathway. The differences in cumulative present value damages up to 2060 (or damages potentially avoided through implementing the OARC scheme) vary from $131M at 3% discount rate to $51M at 7% discount rate. The damages potentially avoided up to 2120 vary from $787M at 3% discount rate to $98M at 7% discount rate.

Table 5-7 also compares cumulative present value damages for the OARC scheme (OARC1) pathway with those for the no stopbanks (Down1) pathway. The differences in cumulative present value damages up to 2060 (or damages potentially avoided through implementing the OARC scheme) vary from $467M at 3% discount rate to $231M at 7% discount rate. The damages potentially avoided up to 2120 vary from $1,113M at 3% discount rate to $291M at 7% discount rate.

The performance of the OARC Scheme can also be considered in terms of the relative change in damages, expressed as the percentage reduction of the two baseline pathway damages that may be achieved through implementing the OARC scheme. As shown in Table 5-7:

- Using a 5% discount rate, estimated baseline present value damages to 2120 (with the existing stopbanks functional to 2060) may be reduced by 48% by the OARC Scheme. For a baseline with no stopbanks the damages may be reduced by 66%.

- Alternatively, using a 3% discount rate, estimated baseline present value damages to 2120 may be reduced by 65% or 72% by the OARC Scheme for the baseline (existing stopbanks to 2060) and no stopbanks scenarios respectively.
- Using a 7% discount rate, estimated baseline present value damages to 2120 may be reduced by 35% or 62% by the OARC Scheme for the baseline (existing stopbanks to 2060) and no stopbanks scenarios respectively.

Table 5-7 indicates that the effect of the discount rate on relative difference in cumulative damages between pathways is small in the medium term (up to 2060). Ranges are 24-31% reduction between OARC1 and Up1 and 58-62% between OARC1 and Down1. This reflects the shorter time period over which damages are accumulated which reduces the impact of discounting. The difference in damage reductions for the two different baselines is due to the lack of any protection from flooding in the no stopbanks scenario (Down1) compared to the continued protection of a proportion of fluvial and tidal flooding by the present day stopbanks to 2060 in the Up1 scenario. This is reflected in lower baseline damages in the Up1 scenario leading to less damages avoided.

The range of percentage reduction in damages due to the OARC Scheme up to 2120 is relatively small for the Down1 baseline pathway (62-72% reduction) but larger for the Up1 baseline pathway (35-65%). This reflects the increased damages accruing after 2060 in the Up1 scenario once the present day stopbanks no longer provide protection from flooding from the Avon River. The effect of discounting on these future damages is greater than on earlier damages and so the present values are more sensitive to the choice of discount rate.

In summary, for the range of rates considered, the relative proportion of baseline present value damages that may be avoided through implementing the OARC Scheme is generally not very sensitive to the value of discount rate selected. However, in some scenarios (damages accumulated to 2120 in Up1) the results are more sensitive to discount rate. Absolute present values of the damages potentially avoided are far more sensitive to the discount rate in all scenarios and this needs to be borne in mind in interpreting these results. These tests indicate that the effects of applying alternative discount rates should be considered in any further economic analyses making use of the flood damage data in order to show the possible range in results and outcomes arising from the choice of rate.

Table 5-7: Differences in cumulative present value total flood damages/damages avoided in 2060 and 2120 for two example pathways using a discount rate of 3%, 5%, and 7%. Values as $M.

	Discount rate	Up1*	OARC1	Damages avoided (Difference between Up1 and OARC1)	% reduction of Up1 damages by OARC1	Down1*	OARC1	Damages avoided (Difference between Down1 and OARC1)	% reduction of Down1 damages by OARC1
2060	3%	417	286	131	31%	753	286	467	62%
	5%	292	212	80	27%	532	212	320	60%
	7%	216	165	51	24%	396	165	231	58%
2120	3%	1214	427	787	65%	1540	427	1113	72%
	5%	491	255	236	48%	762	255	507	66%
	7%	278	180	98	35%	471	180	291	62%

Note: *Up1 is baseline model with existing stopbanks functional to 2060, Down1 is baseline model with no stopbanks, OARC1 is with the proposed OARC Scheme

POST-ANALYSIS NOTE: 2024 TREASURY DISCOUNT RATES

Following production of this memorandum, the Treasury has issued updated guidance on the public sector discount rates to be used in cost benefit analysis. These are available below:

Public Sector Discount Rates (Real)	Year 1-30	Year 31-100	Year 101+	Sensitivity test (mandatory)
Non-commercial proposals (SRTP)	2%	1.5%	1%	8%

Note: 'Social rate of time preference' (SRTP)

While it was concluded that the relative proportion of baseline present value damages that may be avoided through implementing the OARC Scheme is generally not very sensitive to the value of discount rate selected, the absolute present values of potentially avoided damages are highly sensitive to the discount rate across all scenarios. Therefore, it is expected that the relative proportion of present value damages will increase as treasury discount rates decrease to 2%, 1.5%, and 1%.
Analysis within this memorandum employed discount rates of 3%, 5%, and 7%. Therefore, the new lower discount rates would result in outcomes more similar to the 3% rate and would likely show higher damages avoided than the 3% values. The sensitivity test at 8% would be closer to the 7% values and would likely have lower damages avoided.
While the general concepts of increasing or decreasing damages can be understood from the calculations in this memo the present value damages would require recalculation to accurately reflect their response to the updated Treasury discount rates if more certainty were needed by council.

Figure 21 shows the composition of the Cumulative Present Value Damages (using a 5% discount rate) for the three pathways for the OARC Scheme model compared to the corresponding pathways for the Baseline model 'stopbanks up'. For the OARC Scheme model pathways, overfloor flood damages and underfloor flood damages both account for around 50% of the total damages. This differs to the Baseline model pathways where overfloor flood damages make up a larger proportion of the cumulative present value total damages. Underfloor damages are broadly similar in both the OARC Scheme and Baseline model pathways.

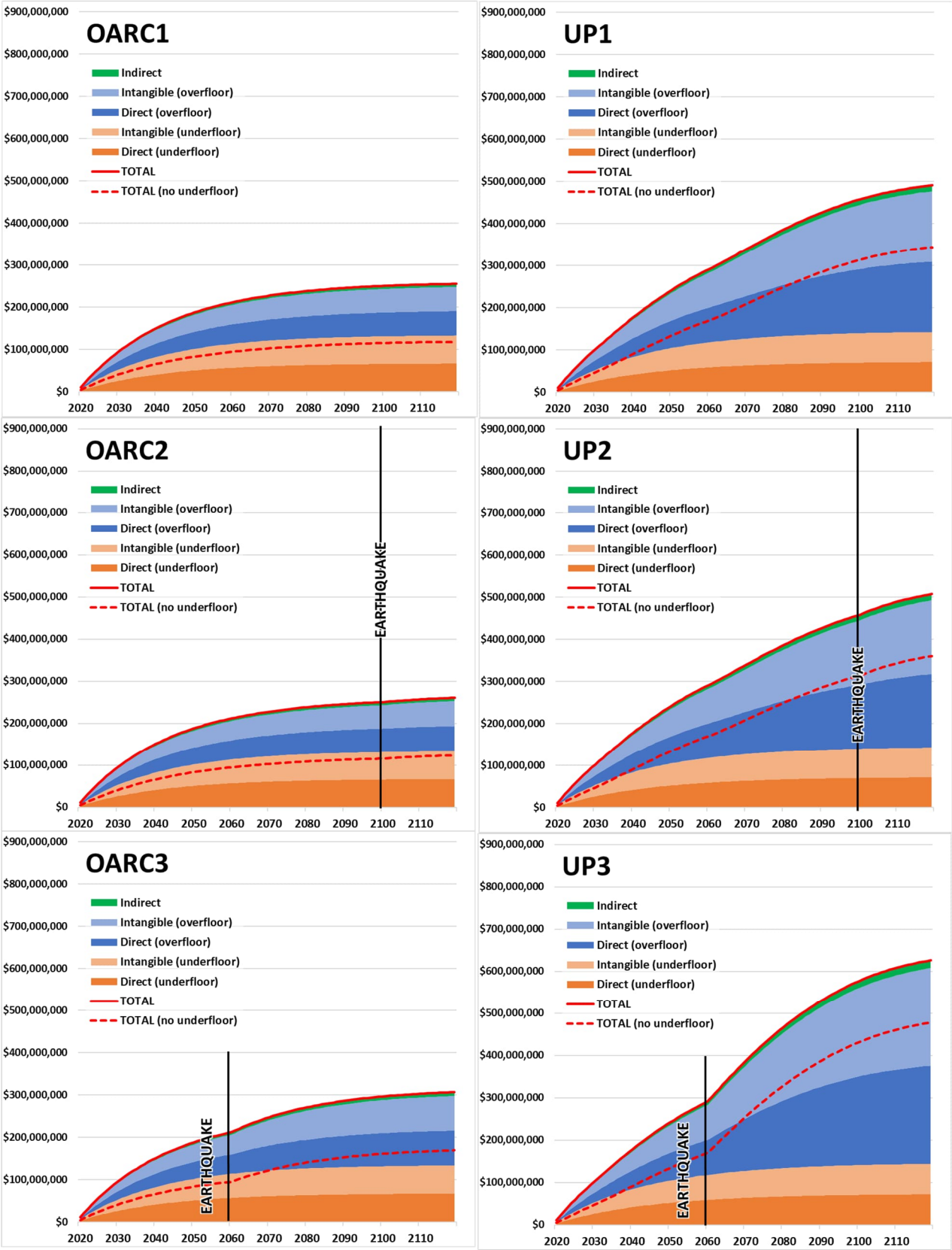

Figure 21: Composition of cumulative present value damages for each of the OARC Scheme future pathways and the Baseline pathways with 'stopbanks up' using a discount rate of 5%

In calculating the present value total flood damages presented in Table 5-6 and Figure 19 (using a 5% discount rate), the present values of damage to individual buildings have not been capped at the building value. This allows for buildings to be repeatedly repaired, typically through insurance cover, after each flood event. It is possible that some properties may not be repaired following multiple flood events due to withdrawal of insurance cover. However, this is considered less likely for the OARC Scheme model scenarios given these measures function to actively manage flood risk.

We have not assessed the effect of capping present value damages of individual properties on total damages in the project area in detail. An initial assessment, Figure 22, shows the average present value of direct damages per flooded building for each of the future pathways using a 5% discount rate, calculated as the total present value of direct damages (underfloor and above floor) divided by the total number of buildings intersecting the flood extents, as shown in Figure 16(a). Given the value of buildings in the project area (estimated typical values of $0.75 M for residential and $2.4 M for non-residential buildings) the results suggest that the extent to which damages would be capped may be limited, reflecting the generally shallow but extensive nature of flooding, particularly in the near future (Table 3-2, Figure 3, Figure 4, Figure 5).

There may be some properties where the Present Value of damage exceeds the value of the buildings and if the individual property damage were particularly high – such as for large commercial properties – this might result in the total damages being overestimated. Conversely, additional intensification has not been allowed for within the assessment, which may to some degree, counterbalance the impact of Present Value damages to properties being uncapped.

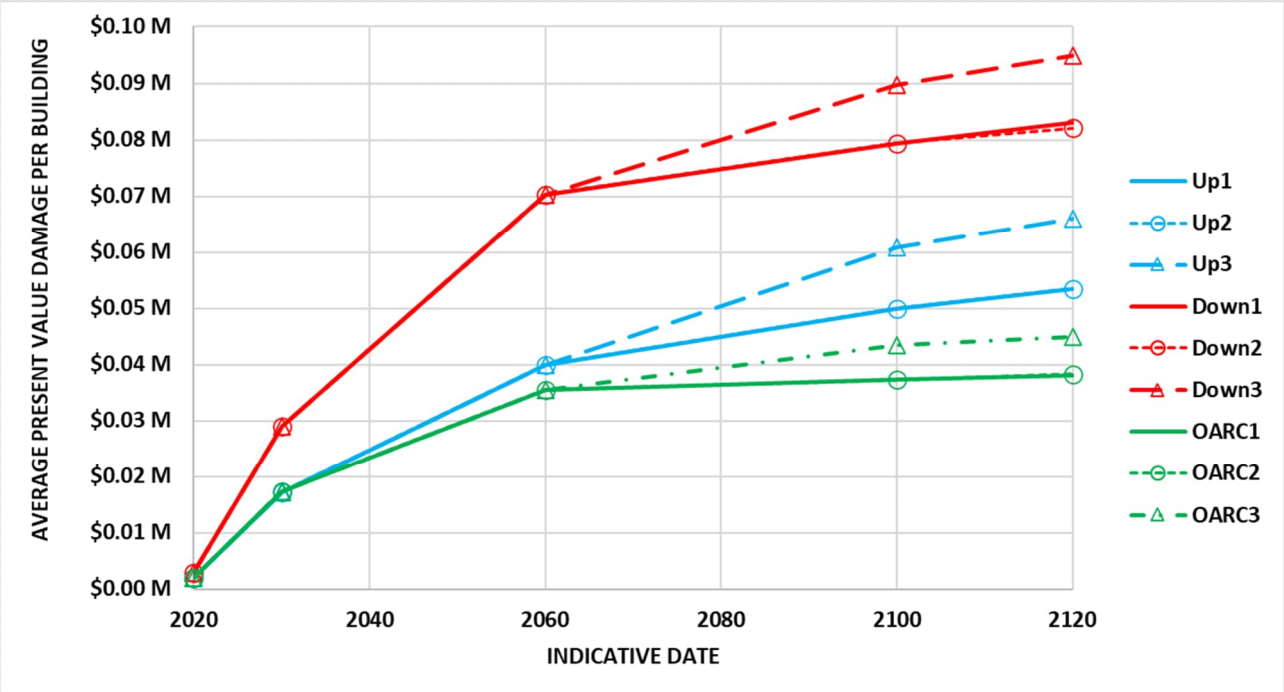

Figure 22. Average cumulative Present Value direct flood damages per building through time for each of the future pathways using a discount rate of 5%

6. Summary

1. We have represented the new flood management measures proposed for the lower Ōtākaro Avon catchment under the Ōtākaro Avon River Corridor (OARC) Regeneration Plan – setback stopbanks and stormwater pumpstations – in the 'Baseline' Avon City Wide Model. We have used the new 'OARC Scheme' model to simulate the same future scenarios as the Baseline model. The model has been peer reviewed by DHI Water & Environment Limited and the model results will be further analysed in Task 4 and Task 5 of Stage 3 of the Multi Hazards project to assess the performance of the new flood management measures in relation to Project Response Indicators and other sources of hazard.

2. Compared to the Baseline model, the OARC Scheme model results show that for more likely flood events (10% AEP) flood events in the near future (~2060) the reduction in flood hazard outside the new stopbanks is relatively small. In these scenarios the existing stopbanks are generally high enough to prevent flooding from the Ōtākaro Avon River and flood hazard outside the stopbanks is primarily due to rainfall over the catchments draining to the river. The new pumpstations in the OARC Scheme model reduce the flooding from the stormwater network to some degree in this AEP but the difference in flood hazard outside the OARC Regeneration Plan area is small.

3. For less likely events (0.5% AEP) in the same timescale, flood hazard along the river corridor outside the new stopbanks is substantially reduced in the OARC Scheme model, particularly in the Avondale, Aranui, Bexley and New Brighton areas. Further away from the river where flooding is due primarily to local rainfall and is beyond the influence of the new pumpstations, flood hazard in the OARC Scheme model is similar to the Baseline model.

4. In the OARC Scheme model, the modelled earthquake-induced land settlement increases flood depths in some areas and reduces depths in other areas. This reflects the modelled spatial variation in settlement with increased depth of flooding tending to occur in areas of greater land settlement through ponding of runoff from areas of less settlement where flood depths are reduced.

5. Maximum modelled water levels in the Ōtākaro Avon River are tidally dominated from the mouth of the river up to approximately the Avondale Road bridge in all scenarios. Further upstream, the highest water levels are for the 18-hour duration rainfall event. The reduction in ground levels in the 'with earthquake' scenarios results in a small reduction in peak water levels in the river, up to around 0.1 m locally.

6. For most of the new pumpstations, the maximum pumped flow does not increase substantially with future climate change although the volume of water pumped does increase due to the consequence of future climate change on rainfall. This suggests that for most pumpstations the flow reaching the pumps is determined by the inletting and conveyance capacity of the pipe network serving the pumpstation, as represented in the model, rather than the catchment runoff. The modelled pump flows for the scenarios with earthquake-induced land settlement are generally very similar to the scenarios without land settlement. Pump representation within the model is suitable for this study however optimisation of the pump stations will be required during later design stages to account for overland flow, storage and pipe upgrades among other factors.

7. We have used the FloodFX tool to calculate the number of properties affected by flooding and the AADs for each of the future scenarios simulated with the OARC Scheme model. We have used the AAD values to calculate Present Value damages for six future scenarios. The data are intended to be used within the Multi Hazards project and to compare the relative performance – e.g., 'better' or 'worse' – of the OARC Scheme and the Baseline over the future scenarios simulated with the flood model.

8. The total number of building footprints flooded under the OARC Scheme is significantly less in future pathways than under the current temporary stopbanks or 'stopbanks down' pathways. Earthquake-

induced land settlement does not greatly increase the total number of buildings footprints affected by flooding.

9. The number of buildings where the flood level is close to, or above, floor level is also lower in the OARC Scheme model. Land settlement results in a large increase in the number of buildings where the flood level is close to, or above, floor level.

10. Calculations of present day damages avoided are very sensitive to the discount rate chosen. For example compared to the UP1 present day stopbanks to 2060 pathway the difference in PV damages (or damages potentially avoided through implementing the OARC scheme) in 2060 vary from $131M at 3% discount rate to $51M at 7% discount rate. In 2120 these damages potentially avoided vary from $787M at 3% discount rate to $98M at 7% discount rate.

11. Using a 5% discount rate, estimated cumulative present value damages to 2120 in the baseline, existing stopbanks functional to 2060 scenario, are reduced by 48% by the OARC Scheme as modelled. Damages for the baseline, no stopbanks scenario are reduced by 66%.

    a. Alternatively, using a 3% discount rate, estimated present value damages to 2120 in the baseline, existing stopbanks functional to 2060 scenario, are reduced by 65% by the OARC Scheme as modelled. Damages for the baseline, no stopbanks scenario are reduced by 72%.

    b. Using a 7% discount rate, estimated present value damages to 2120 in the baseline, existing stopbanks functional to 2060 scenario, are reduced by35% by the OARC Scheme as modelled. Damages for the baseline, no stopbanks scenario are reduced by 62%.

12. Overall, for most scenarios the proportion of present value damages potentially avoided with the OARC Scheme (as modelled) is not sensitive to the choice of discount rate. However, in some scenarios the damages avoided are more sensitive to the rate. The absolute present value damages and damages potentially avoided are far more sensitive to the choice of discount rate in all scenarios and this needs to be borne in mind in interpreting these results. The sensitivity tests indicate that the effects of applying alternative discount rates should be considered in any further economic analyses making use of the flood damage data in order to show the possible range in results and outcomes arising from the choice of rate.

13. Over the whole assessment period from 2020 to 2120, around 50% of the total damages is due to underfloor flooding, both in terms of direct damages and through its contribution to intangible damages. Underfloor damages also contribute to indirect damages, but this forms only a small proportion of the total damages.

14. As agreed with Council, we have not capped Present Value damages to properties. This allows for buildings to be repeatedly repaired, typically through insurance cover, after each flood event. It is possible that some properties may not be repaired following multiple flood events due to withdrawal of insurance cover. However, this is considered less likely for the OARC Scheme model scenarios given these measures function to actively manage flood risk.

15. We have not assessed the effect of capping present value damages of individual properties, but an initial review of average property damages suggests the extent to which damages would be capped may be limited, reflecting the generally shallow, though extensive, nature of flooding in the near future. However it is possible that uncapped damages from individual large value properties may influence the total damage value.

16. Intangible damage values represent a large proportion of the total damages – approximately 50%. There is considerable uncertainty in the valuation of this component of damage. Since these damage values are calculated as a proportion of the direct damages, uncertainty in the underfloor damages is further escalated through the intangible damage calculation. The sensitivity of the results to these factors (underfloor damages, intangible damages), and the corresponding outcomes, should be considered if the data or method are to be used for any other purposes.

7. Limitations

The sole purpose of this report and the associated services performed by Jacobs is to further the understanding of the effects of multiple hazards in flood risk in the lower Ōtākaro Avon catchment in accordance with the scope of services set out in the contract between Jacobs and Christchurch City Council ('the Client'). That scope of services, as described in this report, was developed with the Client.

In preparing this report, Jacobs has relied upon, and presumed accurate, any information (or confirmation of the absence thereof) provided by the Client and/or from other sources. Except as otherwise stated in the report, Jacobs has not attempted to verify the accuracy or completeness of any such information. If the information is subsequently determined to be false, inaccurate or incomplete then it is possible that our observations and conclusions as expressed in this report may change.

Jacobs derived the data in this report from information sourced from the Client and/or available in the public domain at the time or times outlined in this report. The passage of time, manifestation of latent conditions or impacts of future events may require further examination of the project and subsequent data analysis, and re-evaluation of the data, findings, observations and conclusions expressed in this report. Jacobs has prepared this report in accordance with the usual care and thoroughness of the consulting profession, for the sole purpose described above and by reference to applicable standards, guidelines, procedures and practices at the date of issue of this report. For the reasons outlined above, however, no other warranty or guarantee, whether expressed or implied, is made as to the data, observations and findings expressed in this report, to the extent permitted by law.

This report should be read in full, and no excerpts are to be taken as representative of the findings. No responsibility is accepted by Jacobs for use of any part of this report in any other context. The baseline flood model and simulations analysed in this assessment were developed by GHD for Christchurch City Council and this information has been used as provided with no review of the accuracy of that information or its method of development.

This report has been prepared on behalf of, and for the exclusive use of, the Client, and is subject to, and issued in accordance with, the provisions of the contract between Jacobs and the Client. Jacobs accepts no liability or responsibility whatsoever for, or in respect of, any use of, or reliance upon, this report by any third party.

Appendix D. Implications of new vertical land movement data and new climate change projections memo

Implications of new vertical land movement data and new climate change projections

Date: 5 July 2024
Project name: LDRP97 Multi Hazards Stage 3
Project no: IZ084400
Attention: Martin Densham, Tom Parsons
Company: Christchurch City Council
Prepared by: Damian Debski
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Document no: IZ084400-NW-MEM-0011
Revision no: 0 DRAFT

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1. Purpose

In Stage 3 of the Multi Hazards project we have used a flood model to simulate flooding in the lower Ōtākaro Avon River catchment arising from coincident rainfall, fluvial flow and storm tide. We have simulated eight scenarios of the anticipated effects of climate change on future mean sea level and rainfall intensity (estimated from temperature change) as listed in Table 1. The effects of 'instantaneous' liquefaction-induced land settlement on flooding are included in two future climate scenarios (+0.45 m SLR and +1.06 m SLR).

The future scenarios were established in Stage 2 of the project and do not explicitly include the effects of ongoing vertical land movement (VLM). Since the commencement of the project, a greater understanding of the magnitudes of ongoing VLM in Aotearoa New Zealand – and in Ōtautahi Christchurch in particular – and the potential effects of VLM on coastal flood hazards has emerged[1,2]. In this memorandum we consider the latest data for VLM in the project area, compare them to the liquefaction-induced land settlement which we have modelled and consider the implications of VLM for the flood model results as well as other hazards.

The modelled scenarios were defined through reference to climate change guidance available at the time of Stage 2 of the project – MfE (2017) Coastal Hazards and Climate Change[3] and MfE (2018) Climate Change Projections for New Zealand[4]. The guidance on increases in temperature and extreme rainfall intensity has not changed but new guidance on SLR[5,6] is now available. In this memorandum we consider the implications of the latest sea level rise guidance for the model results.

Table 1. Scenarios for modelling flood hazards in Stage 3 of the Multi Hazards project.

Indicative date	2020	2030	2060	*2060**	2100	*2100**	2150	2150+
SLR (m) from 2020	0	+0.19	+0.45	*+0.45*	+1.06	*+1.06*	+1.88	+2.4
Temperature increase (°C) from 2020	0	+0.3	+1.4	*+1.4*	+2.8	*+2.8*	+4.6	+5.0
*Liquefaction-induced settlement	×	×	×	✓	×	✓	×	×

[1] NZ SeaRise: Te Tai Pari O Aotearoa programme (2022)

[2] Inter-seismic, co-seismic and post-seismic rates of vertical land movement in the Christchurch district and implications for future changes in sea level. IJ Hamling J Kearse, GNS Science Consultancy Report 2023/81 October 2023 (Addendum report in 2024)

[3] Ministry for the Environment 2017. Coastal Hazards and Climate Change. Guidance for Local Government.

[4] Ministry for the Environment 2018. Climate Change Projections for New Zealand: Atmosphere Projections Based on Simulations from the IPCC Fifth Assessment, 2nd Edition. Wellington: MfE.

[5] Ministry for the Environment. 2022. Interim guidance on the use of new sea-level rise projections. Wellington: MfE.

[6] Ministry for the Environment. 2024. Coastal hazards and climate change guidance. Wellington: MfE.

2. Vertical land movement (VLM)

2.1 Liquefaction-induced land settlement from a future earthquake

In Stage 2 of the Multi Hazards project a surface of the estimated ground level changes resulting from a magnitude 6 earthquake causing 0.5g peak ground acceleration was developed through modelling (Tonkin + Taylor, 2019). The simulation encompasses the strength of shaking over much of Christchurch City over the course of the 2010-2011 Canterbury Earthquake Sequence.

The model was based on a uniform level of ground shaking across the entire city which is unlikely to be the case in an actual earthquake event, where shaking will be stronger closer to the fault and therefore any settlement in an actual event will differ to that modelled. The model results are also influenced by noise artefacts in the LiDAR data used in the model, such as flight path lines and local extreme changes in elevation. These have been smoothed out to some degree but will also result in differences between the modelled settlement and any actual settlement.

The modelled change in ground levels was used to modify the level of the ground surface, watercourses and relevant components of the stormwater network in the flood model and simulate its effect on flooding for the 0.45 m and 1.06 m SLR scenarios. Figure 1 shows the change in ground levels applied to the flood model.

Within the project area, the modelled **liquefaction-induced land settlement** ranges from -300 mm to -9 mm with a **median value of -118 mm** and an interquartile range of -160 mm to -80 mm.

Figure 1. Change in ground levels due to liquefaction-induced settlement applied in the flood model.

2.2 Inter-seismic and post-seismic ongoing VLM

In 2022, updated sea-level rise projections from the 2021 Intergovernmental Panel on Climate Change Sixth Assessment Report sea-level data, downscaled to Aotearoa New Zealand, were published by MfE and the NZ SeaRise Te Tai Pari O Aotearoa programme. NZ SeaRise also published estimates of local rates of ongoing vertical land movement (VLM) at 2 km intervals along the coastline of the country. The VLM rates were estimated from historic Envisat Synthetic Aperture Radar (SAR) satellite data acquired between 2003 and 2011. This period was chosen to exclude effects of local earthquakes around the country so that the rates therefore represent the ongoing 'inter-seismic' VLM at each location between individual seismic events.

Measurements in Christchurch[7] following the 2010-11 Canterbury Earthquake Sequence and the Valentine's Day and Kaikōura earthquakes in 2016 indicate a higher rate of ongoing VLM than the NZ SeaRise inter-seismic data. To better understand the 'post-seismic' VLM rates, Christchurch City Council commissioned additional analysis by GNS[2] of recent satellite data to quantify the magnitude and spatial variation of VLM in the city. Figure 2 compares the NZ SeaRise inter-seismic VLM and GNS post-seismic VLM data.

Around the boundary of the project area, the estimated **inter-seismic VLM rates** range from -1.0 mm/year to -0.3 mm/year with a median value of **-0.8 mm/year**. Inter-seismic VLM rates within the wider project area are not readily available.

Within the project area, the estimated **post-seismic VLM rates** range from -20.9 mm/year to -0.5 mm/year with a **median value of -3.9 mm/year** and an interquartile range of -4.5 mm/year to -3.4 mm/year.

The post-seismic data is understood to be less reliable in more vegetated areas such as the Ōtākaro Avon River Corridor Regeneration Area where buildings have been removed following the 2010-11 earthquakes. Extrapolation of data is more extensive in this area resulting in lower accuracy in VLM rates and possibly a bias to measurements outside the area.

2.3 Long term VLM

VLM rates are expected to return to the inter-seismic rates in the future but the actual period over which the post-seismic rates will persist is unknown. Current data do not indicate any reduction in VLM rates at present and the GNS study indicates the post-seismic rates could continue for several decades. To understand whether the effects of long term VLM on flooding can be informed by the modelled scenarios which include liquefaction-induced settlement, we have calculated the changes in ground levels resulting from applying the GNS post-seismic annual rates for a further 30 years from 2020 to 2050 and applying the NZ SeaRise inter-seismic annual rates thereafter.

Figure 3 compares the change in ground levels due to liquefaction-induced settlement used in the flood model with the total calculated VLM to 2060 and 2100, the indicative dates of model scenarios which include the effect of future earthquakes. Figure 4 shows the projected value of VLM in the modelled scenarios using median values of post-seismic and inter-seismic rates across the project area, together with the median value of liquefaction-induced settlement applied to the model in the 2060 and 2100 earthquake scenarios.

The median value of VLM to 2030 (37 mm) is small and we do not consider this would materially affect the modelled flooding. The median values of VLM to 2060 (125 mm) and liquefaction-induced settlement (118 mm) are very similar but in 2100 the difference between the two settlement values is greater (VLM of 157 mm). Figure 3 shows that **there is a greater variation in the modelled ground level changes for liquefaction-induced settlement than in the VLM data, which is more uniform over the project area**. The spatial distribution of liquefaction-induced settlement and VLM also differ.

[7] School of Surveying, Otago University (2022). Christchurch City Ground Height Monitoring. Vertical land motion in Eastern Christchurch. Report to Environment Canterbury.

Figure 2. Comparison of data for ongoing VLM in the project area: (a) NZ SeaRise – Te Tai Pari O Aotearoa (inter-seismic); (b) GNS 2023 data (post-seismic)

(a) (b) (c)

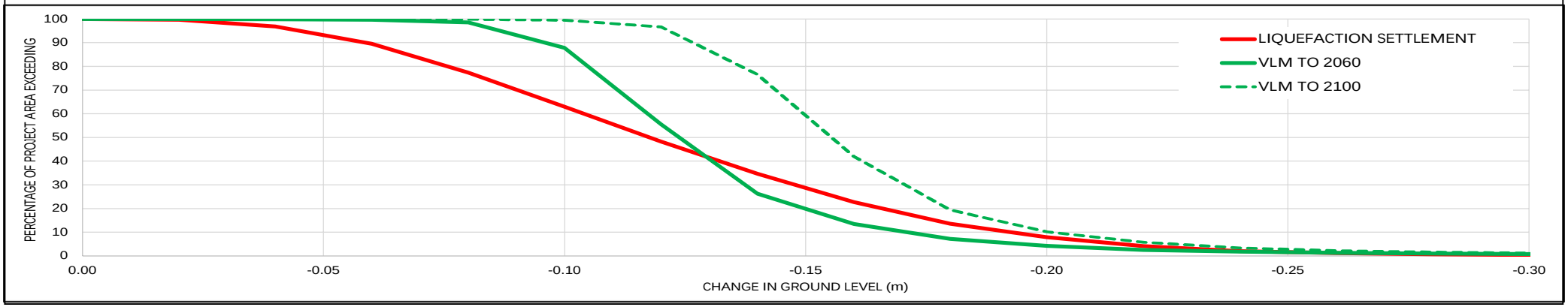

Figure 3. Change in ground level from (a) liquefaction-induced settlement; (b) VLM to 2060; (c) VLM to 2100 and (d) distribution of ground level change in the project area.

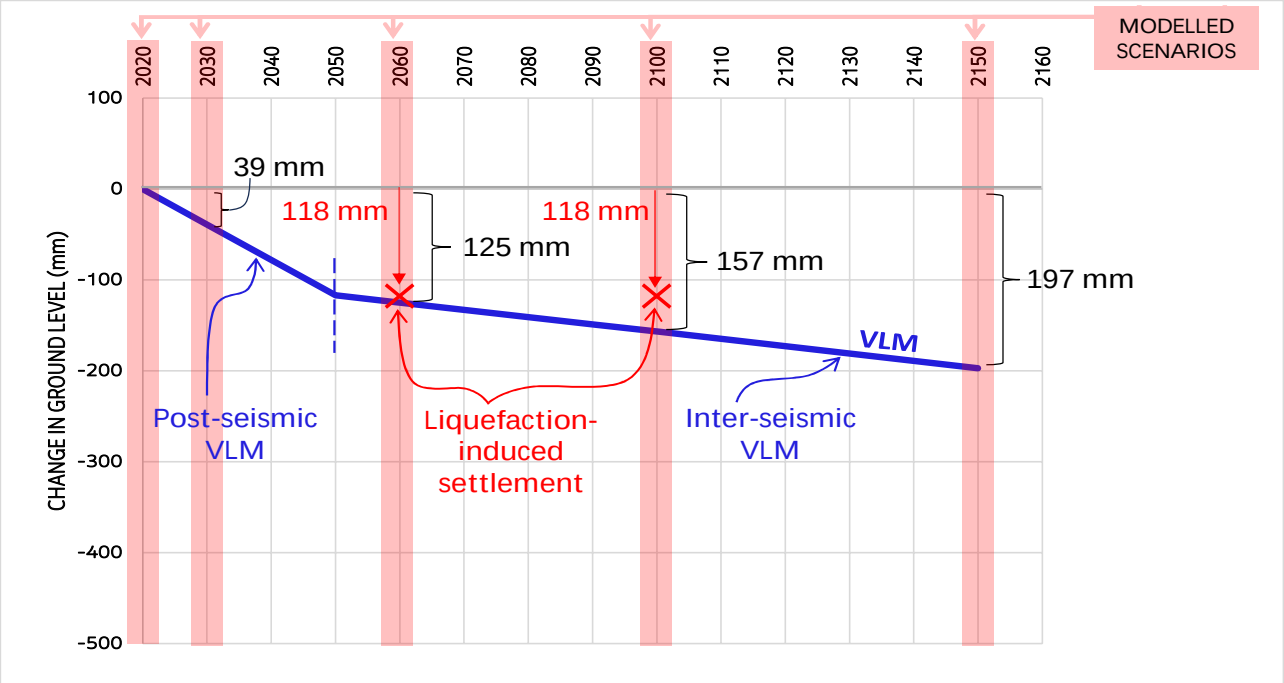

Figure 4. Projected VLM for the future scenarios simulated with the flood model using median values of post-seismic and inter-seismic VLM and a period of 30 years of post-seismic VLM from 2020 compared to median value of liquefaction-induced settlement applied in model earthquake scenarios.

2.4 Combined VLM and liquefaction-induced settlement

Any actual immediate land settlement following a future earthquake will be further enhanced by ongoing post-seismic VLM following such a future earthquake. The modelled liquefaction-induced settlement therefore underestimates potential future deformation since it relates only to immediate settlement rather than the ongoing post-seismic VLM.

We have estimated the combined change in ground level resulting from earthquake events in 2060 or 2100 by adding the modelled liquefaction-induced settlement at the time of the event, to the post-seismic VLM rate for 30 years after each event (based on recent observations of VLM) and the inter-seismic rate thereafter. Figure 5 shows the spatial variation and distribution of the changes in ground level. Figure 6 shows the potential combined ground level changes based on median values of post-seismic and inter-seismic VLM.

Thes data show that although the magnitude of combined settlement is greater than liquefaction-induced settlement alone, the range and spatial distribution of combined settlement and liquefaction-induced settlement are very similar. This reflects the small range of variation in the VLM.

Liquefaction-induced settlement

Liquefaction-induced settlement & VLM to 2060

Liquefaction-induced settlement & VLM to 2100

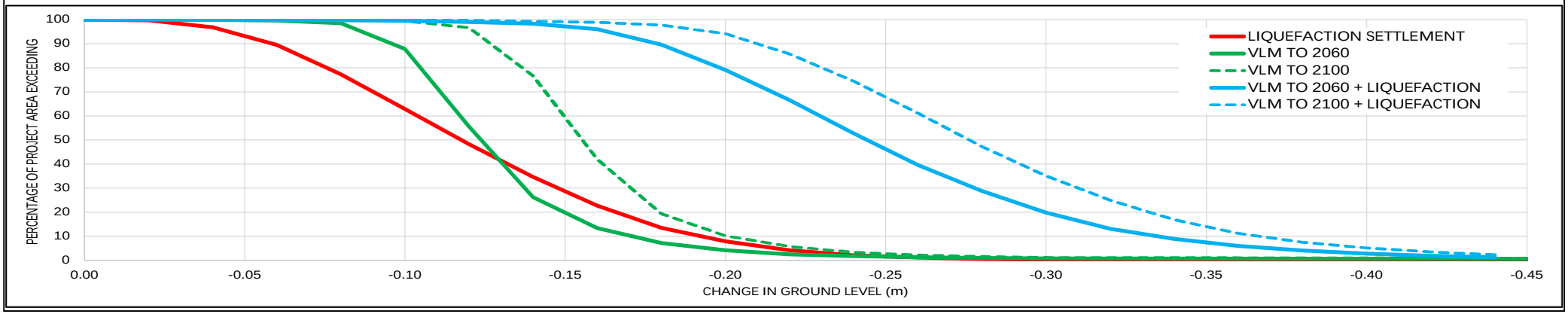

Figure 5. Change in ground level from liquefaction-induced settlement alone and in combination with VLM to 2060 and 2100.

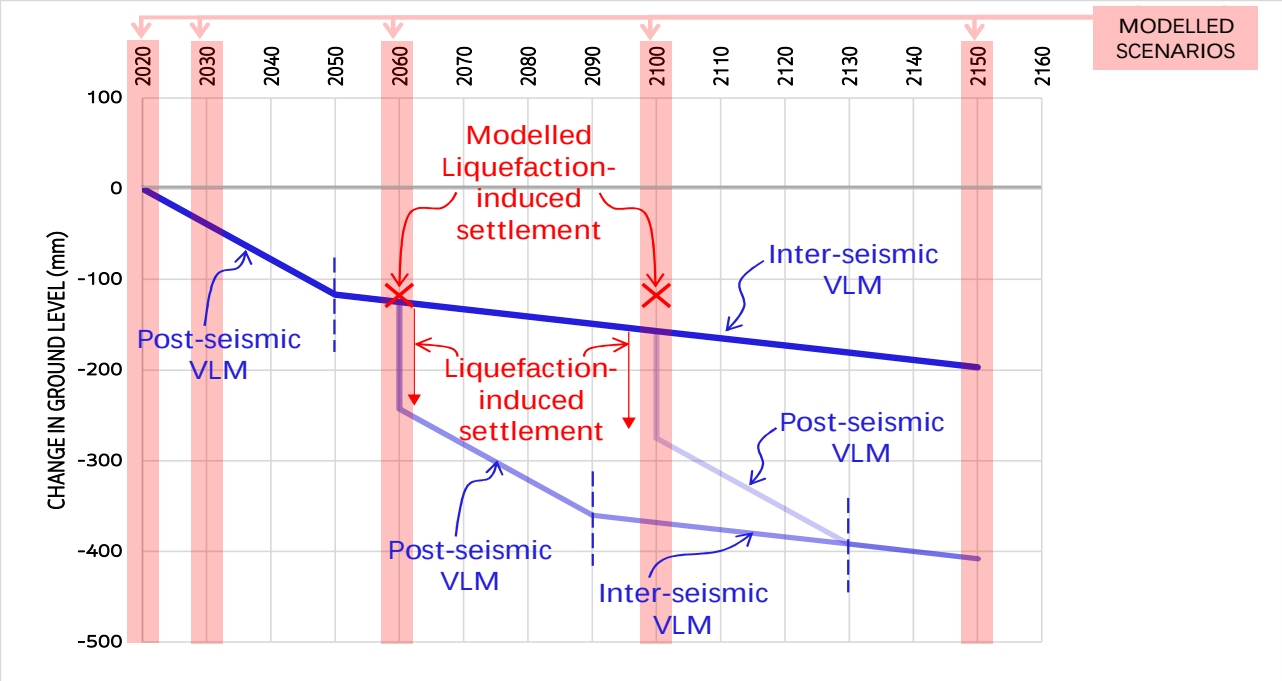

Figure 6. Potential ground level changes arising from the combination of ongoing VLM and modelled earthquake scenarios in 2060 or 2100 (based on median values of VLM and liquefaction induced settlement over the project area).

2.5 Effect of changes in ground level on flooding

Flooding has been modelled, with and without liquefaction-induced settlement, for three stopbank configurations:

i. With the new setback stopbanks proposed as part of the Ōtākaro Avon River Corridor (OARC) Regeneration Plan (together with stormwater pump stations), for the 0.45 m and 1.06 m SLR scenarios.

ii. With the existing stopbanks, for the 0.45 m SLR only.

iii. With no stopbanks, for the 0.45 m and 1.06 m SLR scenarios.

For the new OARC stopbanks configuration, the stopbanks are modelled on the basis that the crest levels will be designed to contain the highest modelled water levels in the river – 0.5% Annual Exceedance Probability (AEP) – and include allowances for settlement. In this way flooding from the river is prevented in all scenarios.

Figure 7 shows the effect of the liquefaction-induced settlement on the modelled 2% AEP flood extent with 0.45 m SLR for the three stopbank configurations. Figure 8 shows the corresponding changes in maximum flood depths.

For all three stopbank configurations, the effect of the settlement on the extent of flooding is relatively small, the largest changes occurring for the existing stopbanks configuration. As shown in Figure 9, flooding from the river is delimited by a higher ground (1 m to 3 m typically) around the floodplain. Since the changes in water level and ground level resulting from settlement are relatively small in comparison, the extent of flooding does not change significantly. Outside the main river corridor, the effect of settlement on flood depths is similar in all three cases. In these areas flooding originates from direct rainfall rather than the river or sea. Due to spatial variations in the liquefaction-induced settlement, flood depths are locally increased where settlement is greater and reduced where settlement is smaller due to re-distribution of runoff and increased ponding in areas of greater settlement.

(a) **(b)** **(c)**

Figure 7. Changes in simulated 2% AEP flood extent in +0.45 m SLR (+1.4°C) scenario (~2060) due to modelled liquefaction-induced settlement: (a) with proposed OARC stopbanks; (b) with existing stopbanks; (c) with no stopbanks.

(a) **(b)** **(c)**

Figure 8. Changes in simulated 2% AEP flood depth in +0.45 m SLR (+1.4°C) scenario (~2060) due to modelled liquefaction-induced settlement: (a) with proposed OARC stopbanks; (b) with existing stopbanks; (c) with no stopbanks.

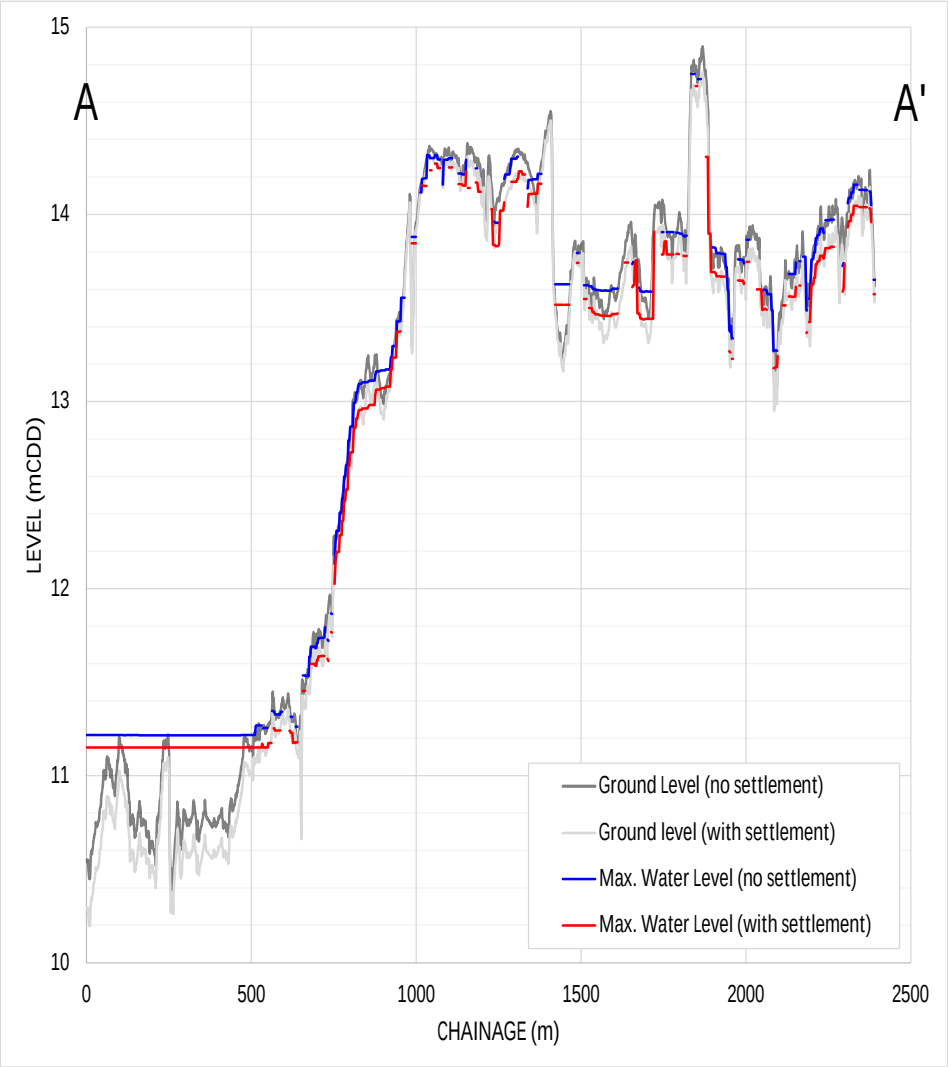

Figure 9. (a) Changes in simulated 2% AEP flood extent in +0.45 m SLR (+1.4°C) scenario (~2060) due to modelled liquefaction-induced settlement with no stopbanks; and (b) Profile of ground levels along example section A-A' with and without settlement and modelled water levels for the same scenarios.

With the OARC stopbanks, flooding from the river is prevented along the river corridor and any flooding arises from direct rainfall. As elsewhere in the project area, the settlement results in areas of locally deeper and shallower flooding. For the existing stopbank configuration the settlement results in a more general increase in flood depth along the river corridor due to increased overtopping of the stopbanks. With no stopbanks, water levels in the floodplain are similar to those in the main river and settlement results in more variable changes in depth according to the amount of settlement.

Figure 10 shows the effect of the liquefaction-induced settlement on the number of buildings within the modelled 0.5% AEP flood extent for the three stopbank configurations. Figure 11 shows the effect of the settlement on the estimated annual average damages from flooding.

In all three cases, the increase in the total number of buildings affected by flooding due to the settlement is very small – between 1% and 3%. However, annual average damages are substantially increased by the settlement – approximately doubling in the +0.45 m SLR (+1.4°C) scenario (~2060) in both model versions – although the absolute increase with the OARC stopbanks is around half that with the existing stopbanks. This reflects the fact that the settlement tends to increase the depth of flooding more than the extent of flooding.

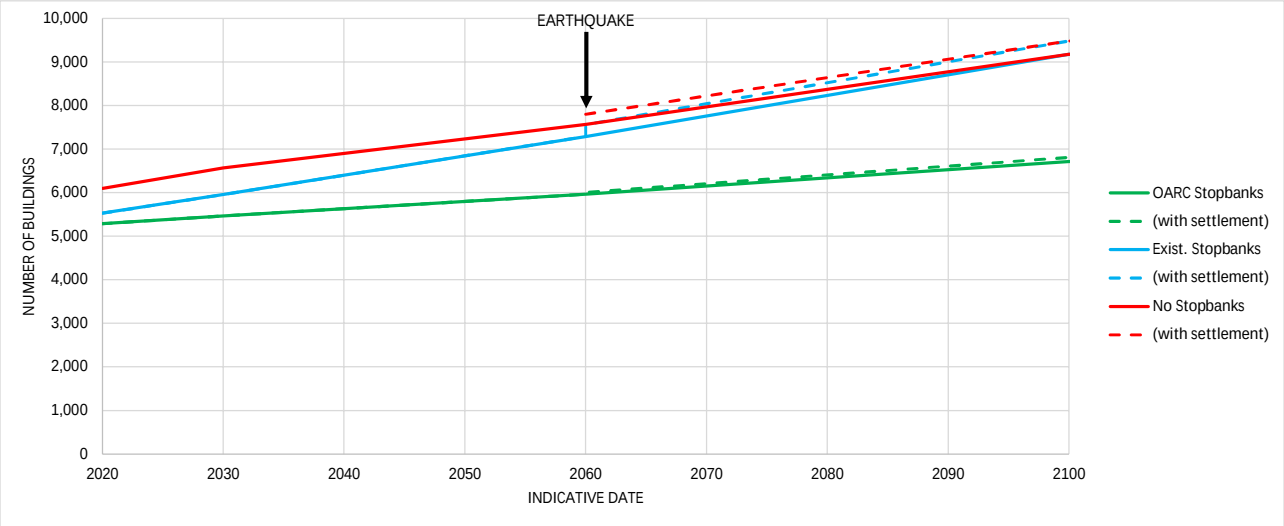

Figure 10. Estimated number of buildings within the 0.5% AEP flood extent with and without liquefaction-induced settlement for existing stopbanks and OARC stopbanks.

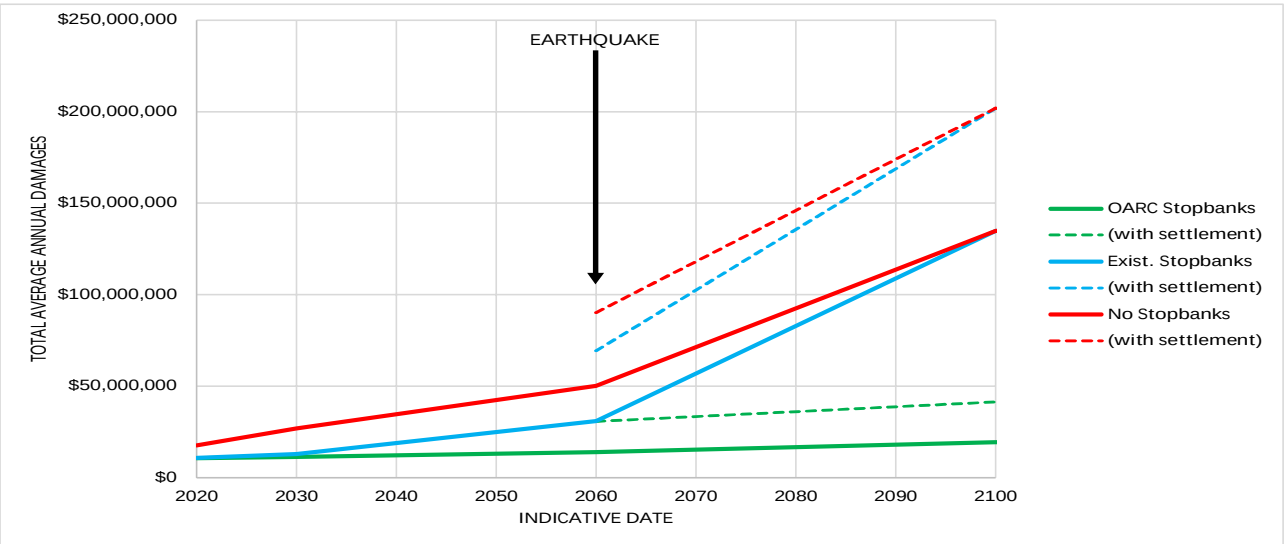

Figure 11. Estimated average annual damages due to flooding with and without liquefaction-induced settlement for existing stopbanks and OARC stopbanks.

The effect of the modelled settlement on flooding of buildings is further illustrated in Figure 12 which shows how the distribution of depth above floor level is affected by settlement and how this varies between the three stopbank configurations. In each case the depths tend to be increased by settlement but the change in depths is relatively small – median depths increase by between around 130 mm and 160 mm, similar to the median ground level settlement applied to the model (118 mm). However, since water levels are mostly close to floor levels, the relatively small increases in depth result in a relatively large increase in flood damages, as shown in Figure 11. This is because more buildings become subject to above floor flooding, for which the damage value is generally greater than under floor damages, and the number of affected properties is large.

In summary, the model results show that the effect of settlement on the extent of flooding is very small. Flood depths are generally increased by settlement and although the changes in depth are also generally small, the increase in flood damages is relatively large. This is because flood levels are close to floor levels and a large number of properties are affected. Spatial variation in settlement results in a reduction in flood depths at some properties and an increase at others.

OARC Scheme

(a)

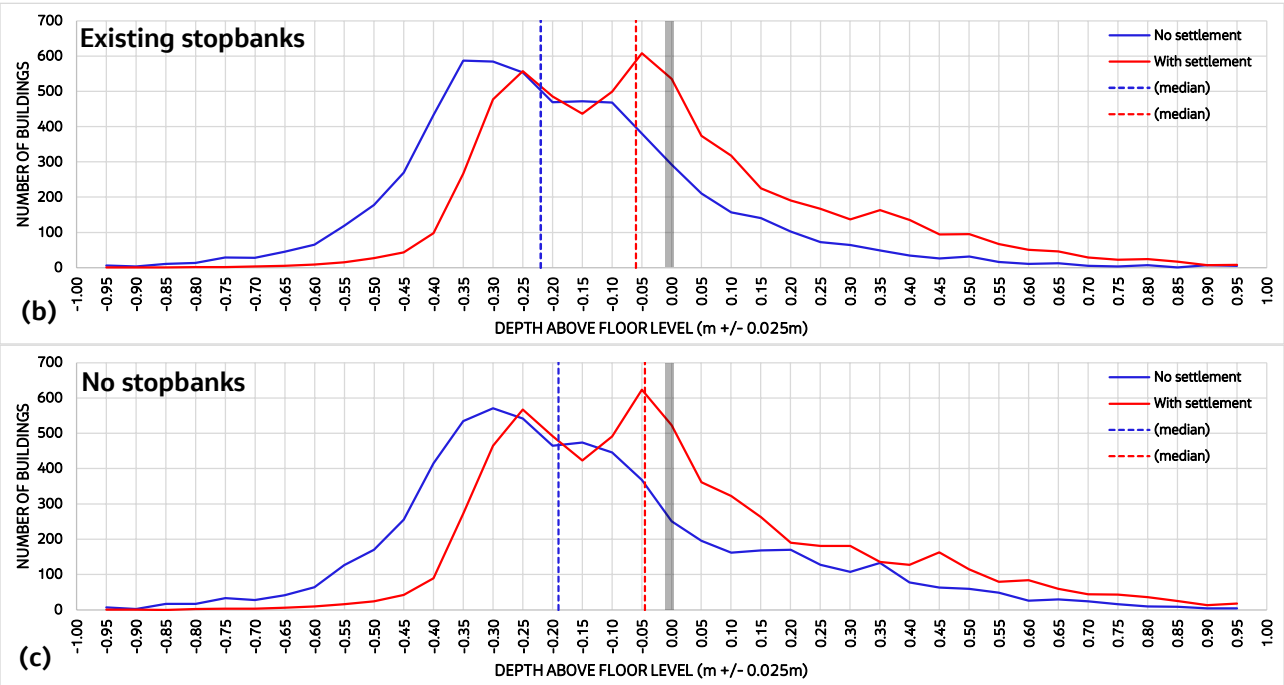

Figure 12. Distribution of flood depth above floor level of buildings for the 2% AEP in the +0.45 m SLR (+1.4°C) scenario (~2060) due to modelled liquefaction-induced settlement: (a) with proposed OARC stopbanks; (b) with existing stopbanks; (c) with no stopbanks.

2.6 Implications

2.6.1 Modelled flood hazards

Our review of the VLM data and flood model simulations of liquefaction-induced settlement indicate that:

- Ground settlement affects the depths of flooding more than the extent of flooding.
- Changes in the depth of pluvial flooding depends on the spatial variation of settlement.
- Median values of projected VLM to 2060 and 2100 without any seismic events (0.125 m and 0.157 m) are of a similar magnitude to the modelled liquefaction-induced settlement (0.118 m).
- Over the project area there is less variation in the projected VLM to 2060 and 2100 (interquartile range around +/- 10% of the mean) than in the modelled liquefaction-induced settlement (interquartile range around +/- 30% of the mean).
- The modelled liquefaction-induced settlement results in a relatively large increase in flood damages because flood levels are close to floor levels and so a relatively small increase in depth can result in a relatively large increase in above floor damages.

For the **proposed new OARC stopbanks:**

- We expect VLM to have less effect on the modelled flooding and flood damages in the project area than the other stopbank scenarios because:
    - In most of the modelled scenarios (up to 1.06 m SLR), flooding in the project area is purely due to direct rainfall. The flooding is therefore not significantly affected by the relative levels of the ground and the sea, or by SLR, due to the proposed pumping stations behind the stopbanks.
    - Modelling of liquefaction-induced settlement for this configuration of stopbanks shows that those reductions in ground level will increase flood damages, but this is mainly due to the non-uniform settlement of the ground which causes a redistribution of surface water resulting in deeper ponding at some properties and shallower ponding at others.
    - The current data suggests that projected changes in ground levels due to VLM are relatively uniform over the project area and we therefore expect the modelled flooding to be similar to that without VLM or settlement, provided the stopbank crest levels and pump station capacities include sufficient allowances for settlement.
- The modelled flooding, which excludes VLM, is therefore likely to be similar to flooding with VLM for scenarios up to 1.06 m SLR. However, given the data do indicate some spatial variations in VLM, overall damages from flooding are likely to be higher than those calculated with VLM.
- For the more extreme scenarios (over 1.06 m SLR), static storm tide levels will overtop the dune ridge along the shoreline more extensively. Overtopping by wave runup could occur at lower values of SLR but would result in less extensive inundation. VLM will reduce the crest levels of the dunes relative to sea level and increase the volume of overtopping. However, the amount of VLM is small relative to the uncertainty in SLR projections and potential future dune crest levels which will be subject to increased erosion with SLR. For these reasons the modelled scenarios are considered a reasonable indication of flooding under these more uncertain extreme scenarios.

For the **existing stopbanks** and **no stopbanks** configurations:

- We expect that, for a given future scenario, VLM will result in greater depths of flooding and flood damages in the project area than those modelled because:

  - Flooding along the main river corridor is mostly due to overflow from the river. The flooding in these areas is directly affected by the relative levels of the ground and the sea and by SLR.
  - VLM will therefore result in deeper flooding in these areas for a given sea level and larger damages to those we have modelled.

- Although the flooding in some parts of the project area is pluvial in nature and will not be affected by SLR, it is likely this forms a relatively small proportion of the damages.
- In interpreting the model results, the effects of VLM could therefore be considered as a change in the potential timing of the future climate scenarios. Figure 13 shows the modelled SLR values and the effect of the increased height of the sea above ground level due to VLM. This would mean the modelled future scenarios could occur 10 to 15 years earlier, depending on the scenario and whether earthquake events are included (due to the higher initial post-seismic VLM rate).
- Strictly, the change in potential timing of the scenarios should also be reflected in a change in the modelled increase in rainfall intensity – i.e., a lesser increase in rainfall should be applied due to the shorter period of climate change effects. However, the rate of increase in rainfall depth (which is estimated from temperature change) varies less with time than SLR. Figure 13 shows how the projected temperature increase for each modelled scenario would be around 0.5°C less than that adopted in the model scenarios. The ratio between change in rainfall depth and temperature change varies according to Annual Exceedance Probability and storm duration (Table 13 of MfE 2018[4]). For the modelled storm events, the average change in rainfall depth from the historic data is approximately 10% per degree of temperature change. Therefore, the potential over-estimate of rainfall depth in the modelled scenarios due to a change in timing would be only around 5% and we do not consider this likely to have a significant effect on the modelled flooding which in these stopbank configurations is dominated by tidally influenced water levels in the river.

In summary, we consider that the model results (without VLM) for the new OARC stopbanks in scenarios of SLR up to 1.06 m are likely to be similar to those including VLM. Flood damages are likely to be higher as a result of VLM depending on the actual spatial variation in VLM which is uncertain at present. For higher SLR scenarios the results provide a good indication of flooding under ongoing VLM but will tend to underestimate coastal flooding over the sand dune ridge along the shoreline. For the other modelled stopbank configurations (existing stopbanks and no stopbanks) we consider that allowing for VLM, the modelled flooding is representative of a lower value of SLR than that modelled – occurring around 10 to 15 years earlier than originally envisaged.

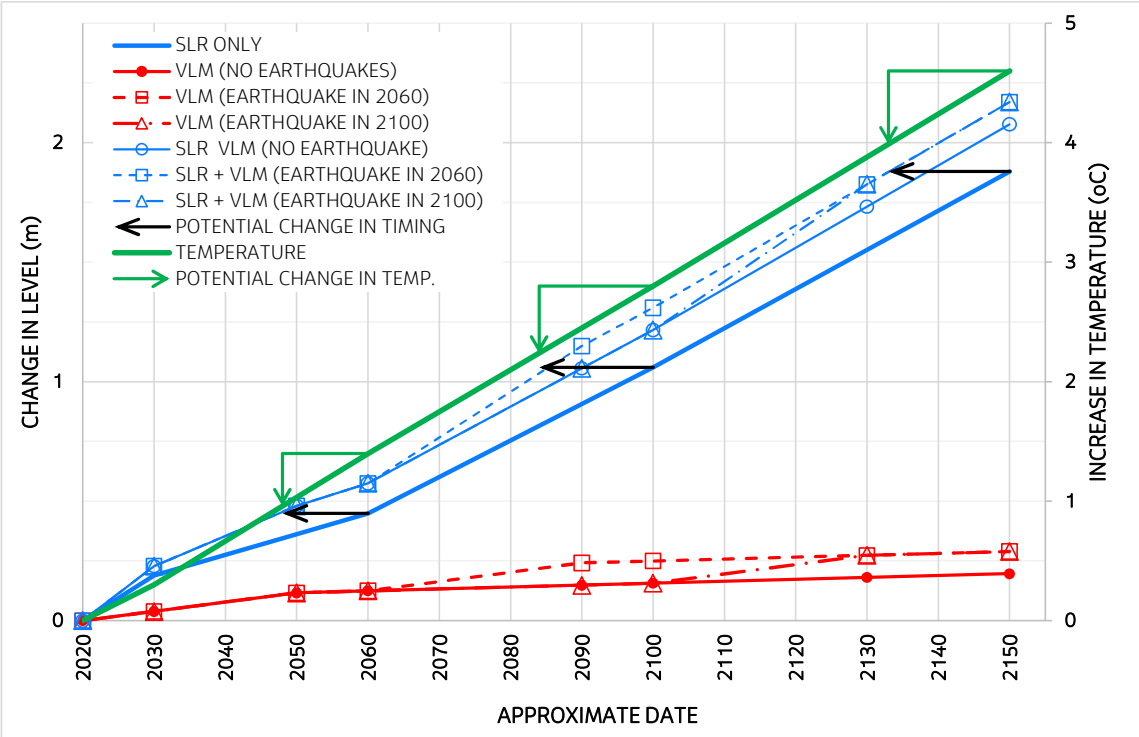

Figure 13. Approximate timing of SLR and temperature change in the modelled future scenarios, with and without VLM.

2.6.2 Other hazards

In Stage 3 of the project, we also consider the hazards of elevated groundwater levels, as measured by the depth to the water table below the ground surface (DTW) and of tsunami flooding.

In the project we use DTW data prepared by Aqualinc for each SLR scenario and a Project Response Indicator (PRI) for land use elements to assess when and where in the project area the potential need for a response to managing groundwater hazard is indicated. Groundwater levels are currently considered to be independent of VLM so that any reduction in ground surface level will reduce the depth to the water table. The DTW reduces with SLR but the change in DTW with SLR varies significantly over the project area. We therefore consider it better to interpret the effect of VLM as a reduction in DTW values for a given scenarios, as we have done for liquefaction-induced settlement, rather than a change in the value of SLR or timing of the scenario.

For the existing stopbanks and no stopbanks configurations, the tsunami modelling performed by NIWA indicates that flooding arises from overtopping the stopbanks (where present) as well as directly over the shoreline. In both these mechanisms the extent and depths of flooding depend on the height of the land relative to the sea. VLM will reduce the relative height of the land and so its effect on tsunami flooding for these configurations could also be interpreted as a change in timing of the scenarios as indicated in Figure 13. For the new OARC stopbanks, the degree to which tsunami flooding is affected by VLM will depend mainly on the estimated tsunami water levels relative to the design stopbank levels. If overtopping also occurs in this configuration so that the effect of VLM will be similar to that for the existing stopbanks.

In summary, the effect of VLM on groundwater is a reduction in the DTW data for each scenario and this will tend to increase the number of elements exceeding the PRIs. For tsunami flooding, the effect of VLM can be considered as reduction in SLR for the modelled scenarios or change in timing of the scenarios.

3. Sea Level Rise (SLR)

3.1 Current guidance

Current guidance on coastal hazards and climate change for Aotearoa New Zealand is provided in MfE 2024[6] which recommends future SLR values as provided in MfE 2022[5] and NZ SeaRise[1]. The 'medium confidence' projections of increments of SLR in decades, referenced to a 2005 baseline date, are reproduced in Table 2.

Table 2. MfE 2022 'medium confidence' projections of SLR in Aotearoa New Zealand for alternative Shared Socio-economic Pathways (SSPs)

Year	SSP1-2.6M	SSP2-4.5M	SSP3-7.0M	SSP5-8.5M	SSP5-8.5H+
2005	0	0	0	0	0
2020	0.06	0.06	0.06	0.06	0.09
2030	0.11	0.11	0.11	0.11	0.15
2040	0.15	0.16	0.16	0.18	0.23
2050	0.20	0.22	0.24	0.26	0.32
2060	0.24	0.28	0.31	0.34	0.43
2070	0.29	0.35	0.40	0.44	0.57
2080	0.34	0.42	0.50	0.56	0.72
2090	0.38	0.49	0.61	0.69	0.90
2100	0.44	0.57	0.73	0.83	1.09
2110	0.50	0.66	0.83	0.95	1.28
2120	0.55	0.74	0.95	1.08	1.47
2130	0.60	0.81	1.07	1.21	1.66
2140	0.64	0.89	1.19	1.34	1.84
2150	0.68	0.96	1.30	1.46	2.01

3.2 Comparison with SLR in modelled scenarios

The storm tide levels adopted for the flood modelling are referenced to mean sea level in approximately 2020, corresponding to the zero SLR scenario. In order to compare the MfE 2022 guidance with the SLR increments adopted for the Stage 3 modelling, we have referenced the sea level rise values in the MfE 2022 data to 2020 for three Shared Socio-economic Pathway (SSP) projections – SSP2-4.5M, SSP5-8.5M and SSP5-8.5H+ – as shown in Table 3, which also indicates the closest values to the modelled scenarios.

Table 3. MfE 2022 'medium confidence' projections of SLR referenced to 2020 with decadal values which encompass the modelled SLR values of 0.19 m, 0.45 m, 1.06 m and 1.88 m highlighted in yellow.

Year	SSP2-4.5M	SSP5-8.5M	SSP5-8.5H+
2020	0	0	0
2030	0.05	0.05	0.06
2040	0.10	0.12	0.14
2050	0.16	0.20	0.23
2060	0.22	0.28	0.34
2070	0.29	0.38	0.48
2080	0.36	0.50	0.63
2090	0.43	0.63	0.81
2100	0.51	0.77	1.00
2110	0.60	0.89	1.19
2120	0.68	1.02	1.38
2130	0.75	1.15	1.57
2140	0.83	1.28	1.75
2150	0.90	1.40	1.92

The potential timing of the modelled SLR increments of 0.19 m, 0.45 m, 1.06 m and 1.88 m based on the MfE 2022 projections are presented in Figure 14 together with the timing originally envisaged for these increments in Stage 2 of the Multi Hazards project. The effect of VLM on the timing of these scenarios, as described in Section 2.6 of this memorandum, is also shown.

The MfE 2022 guidance indicates the 0.19 m SLR scenario will occur one to two decades later than the Stage 2 estimate. However, with the additional effect of VLM the likely timeframes are similar. For the 0.45 m, 1.06 m and 1.88 m SLR scenario the estimated timeframes largely overlap. The effect of VLM in the 0.45 m SLR scenario could bring forward the date of this scenario by one or two years. The two higher SLR scenarios could occur one or two decades earlier due to VLM.

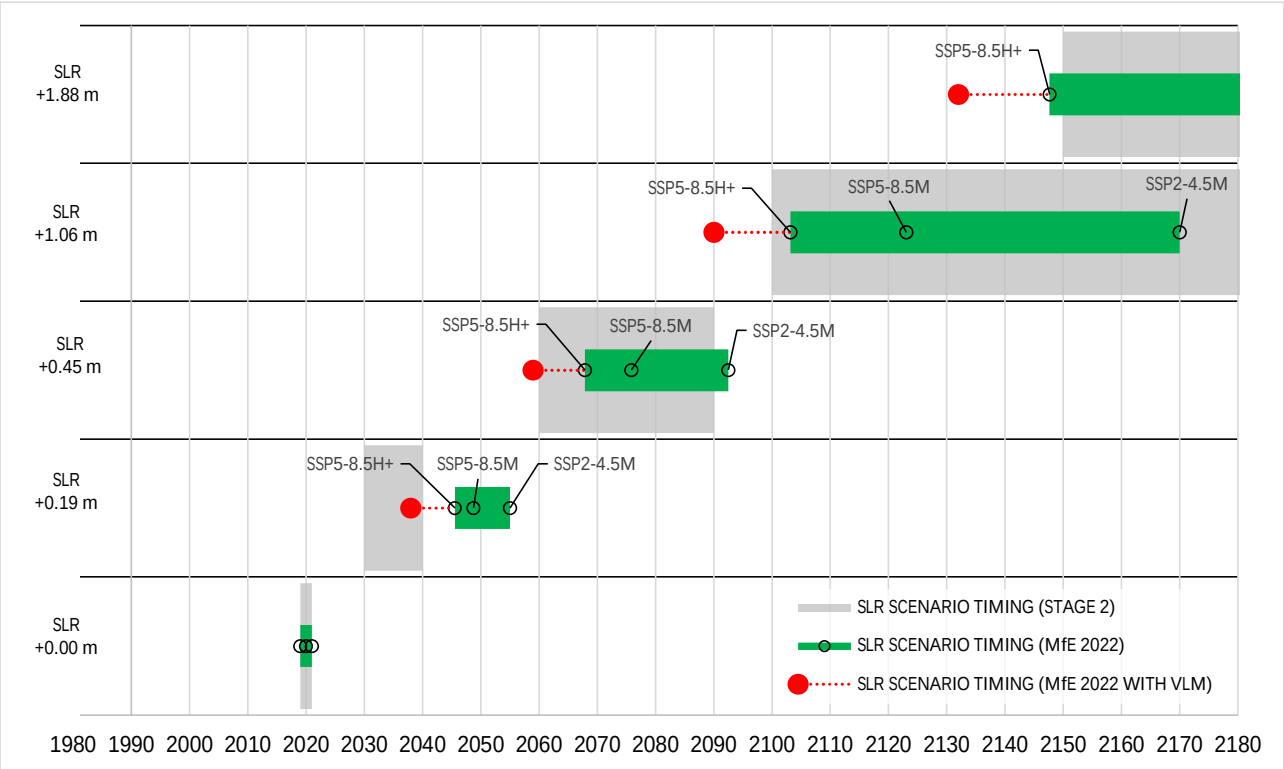

Figure 14. Approximate timing of SLR increments in modelled scenarios as originally envisaged in Stage 2 of the project and based on MfE 2022 guidance. The potential effect of VLM on the timing of SLR relative to ground level is also indicated for the SSP5-8.5H+ pathway (i.e., earliest projected timing).

3.3 Implications

Considering the latest guidance on SLR (MfE 2024), the timing of the modelled SLR scenarios is generally very similar to that estimated in Stage 2 of the Multi Hazards project. The 0.45 m SLR scenario would now be expected to occur one or two decades later but the potential effects of VLM would counter this change. **The flood model results can therefore be considered to largely occur within the originally reported timescales with some adjustments to take account of the effect of VLM.**

4. Summary of findings and suggested approach to addressing VLM in Multi Hazards

We have reviewed the latest data for VLM in the project area and the current guidance to SLR in Aotearoa New Zealand in relation to the future scenarios that have been simulated with the flood model in Stage 3 of the Multi Hazards project. We have used the results of model simulations which include the effects of liquefaction-induced settlement in a seismic event to understand more generally how flooding in the project area is affected by changes in land levels in each of the three stopbank arrangements modelled – proposed OARC stopbanks, existing stopbanks, and no stopbanks. From the data and the model results we have considered what the likely implications of ongoing and future VLM are for the results of the flood modelling completed in the Multi Hazards project.

The data represent the best available information for these processes but are subject to uncertainty.

- In terms of VLM, there is greater uncertainty in the current measurements of the rates of VLM within the OARC than other parts of the project area and general uncertainty in how VLM rates will change in the future.
- Projected SLR values are subject to uncertainty in terms of both the estimated magnitudes of change for a given climate change scenario (SSP) and the actual SSP which occurs.
- Liquefaction-induced settlement in an actual seismic event may vary to that modelled in terms of both magnitude and spatial distribution of settlement.

4.1 VLM

For the OARC stopbanks model, we expect the overall extents and general depths of flooding with VLM for scenarios of SLR up to 1.06 m to be similar to those modelled provided VLM is relatively uniform over the project area. This is because the new stopbanks and pumps largely exclude sources of flooding which are influenced by the relative levels of the ground and the sea. The results of flood modelling with liquefaction-induced settlement indicate that flood damages with VLM will likely to be somewhat higher than the values reported from the modelling since the changes in ground level will not be completely uniform. The change in damages will depend on the actual spatial variation in VLM, which is uncertain at present due to variable data quality over the project area, and its effect on flood depths at buildings. Additional modelling using more reliable VLM data would be needed to provide better estimates of these damages as well as a more detailed assessment of the effect of VLM on the exceedance of Project Response Indicators.

For the more extreme modelled scenarios (1.88 m SLR and 2.4 m SLR), the dune ridge along the shoreline to the project area is increasingly subject to overtopping by extreme tide levels and VLM will tend to increase the volume of overtopping. However, the VLM is small relative to the uncertainties in SLR projections and potential future dune crest levels which are expected to be subject to increased erosion with SLR.

For the baseline model with existing stopbanks and with no stopbanks, we expect flood depths and damages with VLM to increase more substantially from those modelled than for the proposed OARC stopbanks. This is because flooding from the river is a major source of hazard in the baseline modelling and this flooding is directly affected by the relative levels of the ground and the sea. For these stopbank configurations, the effects of VLM on the model outputs could be accounted for by changing the value of SLR or the potential date for the future climate scenarios which have been modelled. We estimate that the additional difference between ground levels and mean sea level due to VLM would mean the modelled future scenarios could be considered as occurring 10 to 15 years earlier than previously envisaged.

4.2 SLR

The timing of the modelled scenarios indicated by referring the adopted SLR values to the latest guidance is generally very similar to that envisaged in Stage 2 of the Multi Hazards project. The 0.45 m SLR scenario

could be expected to occur one or two decades later than originally stated but the potential effects of VLM could counter this change. The flood model results could therefore be considered to largely occur within the originally stated timescales with some adjustments to take account of the effect of VLM.

4.3 Suggested approach

The effect of VLM on flood and groundwater hazards in the project area needs to be considered in the Multi Hazards project, primarily when assessing the extent to which the OARC stopbanks may manage or be impacted by other hazards (Stage 3, Task 4) and in assessing the performance of the OARC Regeneration Plan (Stage 3, Task 5).

In terms of flood hazard, the effect of VLM could be assessed directly by producing new versions of the flood model incorporating projections of VLM and performing new simulations for all the future scenarios. This would entail producing a new version of the model for each future scenario since the amount of VLM and the changes in ground surface will increase in each scenario. A simpler approach to VLM is often adopted in flood modelling and other types of coastal hazard assessment by including VLM as an additional increase in the boundary sea level ('relative sea level rise') rather than a change in ground level. We do not consider this approach appropriate for the Multi Hazards project because:

- With the OARC stopbanks and pumps, flooding is largely disconnected from the sea and the spatial variation in ground settlement through VLM will have far more effect on the residual pluvial flood hazards than the relative levels of the ground and the sea.
- For the existing stopbanks and no stopbanks scenarios there are also parts of the project area where flooding is primarily determined by rainfall and is largely unaffected by the relative levels of the ground and the sea.
- The groundwater surfaces used in the flood model and for assessing groundwater hazards were developed for specific values of mean sea level and the effect of sea level rise is not uniform across the surface so that these surfaces cannot simply be uniformly raised by 'relative sea level rise'.

Producing new model versions and repeating simulations would be a lengthy task due to the nature of the model (three-way coupled surface flow, pipe network and river channels) and computational time needed. We understand that new VLM data is expected to become available[8] before such modelling can be completed which could limit the value of the new modelling.

As an alternative we suggest that:

i. In interpreting the model results for the OARC Scheme, recognize that VLM will likely result in a relatively small increase in flood damages for SLR up to 1.06 m and will introduce some additional uncertainty in the application of the Project Response Indicators for flooding, given that the modelled effects of liquefaction-induced settlement (which is a similar order of magnitude to VLM) on flood damages are likely greater than those resulting from VLM and the effect on flood depths are relatively small in comparison to the Project Response Indicator values.

ii. In terms of the Project Response Indicators for groundwater hazards, consider re-mapping using a ground surface adjusted for projected VLM in each scenario, as has already been done for liquefaction-induced settlement, to calculate revised depth to water surfaces on the proviso that the groundwater surface itself is not affected by VLM.

iii. For the flood damages in the baseline model scenarios, the potential order of increase in present value damages due to VLM are estimated through adjusting the timing of the modelled scenarios in the Annual Average Damages discounting calculations.

[8] pers. comm. T Simmons-Smith, Christchurch City Council

iv. The effect of VLM on tsunami flooding is broadly interpreted as a change in the timing of the scenario, subject to the findings of our assessment of the potential behavior of tsunami with the new OARC stopbanks.

v. Council consider undertaking limited sensitivity tests of the effects of VLM on flooding with the proposed OARC Scheme using the flood model, using a simplified approach to adjusting ground levels if possible, to confirm or otherwise the expected effects.

Items i. to iii. could be incorporated as additional minor tasks in Tasks 4 and 5 of the project. Item iv. could be undertaken as a separate activity as an addendum to the project.

4.4 Further considerations

In terms of the design of the new OARC stopbanks and pumpstations, the stopbanks have been modelled on the basis that the design crest levels will include sufficient allowance for any future settlement – VLM or liquefaction-induced settlement – in all the modelled scenarios and therefore this would need to be included in the design requirements if the modelled performance is to be achieved. Similarly, the new stormwater pumps have been modelled on the basis that the pump capacities (flow and head) are sufficient to lift the full flow reaching the pumpstation into the river in all the modelled scenarios and these requirements would also need to be included in the design.

In terms of adaptation planning, under implementation of the new OARC scheme, VLM is unlikely to change the needs for responding to increasing residual pluvial flood hazards provided the land movement is relatively uniform. If alternative flood management strategies were adopted, then VLM could bring forward the timing of responses needed to address fluvial and tidal flooding. In terms of groundwater hazards, VLM will tend to bring forward the timing of any responses needed to address these hazards, regardless of the flood management strategy.

Note: Subsequent to this memo additional scope was agreed to explicitly model VLM within the hydraulic modelling for selected future scenarios. The approach to the additional modelling is outlined in the final Stage 3 report and discussion of the results are incorporated throughout relevant sections of the stage 3 report.
The stage 3 report therefore now explicitly considers the impact of VLM as a hazard for selected future scenarios.

Appendix E. NIWA Land Drainage Recovery Programme: Tsunami Study (Feb 2018)

NIWA
Taihoro Nukurangi

Land Drainage Recovery Programme: Tsunami Study

Prepared for Jo Golden
Christchurch City Council

February 2018

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Executive summary

NIWA was commissioned by Christchurch City Council (CCC) to carry out a numerical modelling study of tsunami inundation in Christchurch caused by two tsunamis originating from distant sources. This study aims to aid the understanding of the tsunami hazard in the greater Christchurch area so that Christchurch City Council has a better understanding of the influence of tsunamis on flooding risk and of potential defence options. The results of this project will feed into the multi-hazard analysis being undertaken by the LDRP97 project team in preparing the floodplain management plan.

The selected tsunami sources were a 1:500-year return period event cause by a magnitude 9.28 earthquake and a 1:2500-year return period event caused by a magnitude 9.49 earthquake both at the Peru subduction zone. The simulations were completed for different sea-level rise scenarios (present day, 0.19 m, 0.41 m and 1.06 m) taking into account predicted shoreline changes predicted for 2065 and 2120. Note that the magnitude 9.49 scenario at current sea-level was produced in a previous study and not replicated here.

Both tsunami scenarios result in major inundation in Christchurch which, as expected, worsens with the higher sea-level scenarios. The inundation extent was similar for both tsunami scenarios but the inundation depth and flow velocities along the coastal strip were much larger for the worst-case tsunami (1:2,500-year scenario). The total inundation extent for the higher sea level rise scenario (1.06 m above present sea level) was 53 km^2 for the 1:500-year return period tsunami event, 75 per cent more than for the same tsunami occurring at present day sea level.

Such large tsunami events are expected to cause severe erosion of the coastal strip and at the mouth of the Waimakariri River and the Avon-Heathcote Estuary. Severe erosion can also be expected at the Avon Bridge Street bridge and the Heathcote Ferry Road bridge. This erosion could cause increased inundation by removing dunes and opening river and estuary mouths which is not taken into account in this modelling.

The results for areas specifically modelled in this study are considered more robust and should supersede previous interpretations.

1 Introduction

Christchurch is subject to a range of natural hazards and one of these is tsunami. Since the Canterbury Earthquake Sequence (CES), the direct effects of the earthquakes have caused changes that may exacerbate future natural hazards. The Land Drainage Recovery Plan seeks to understand the post-earthquake flood risk in the greater Christchurch area, including multi-hazards in the form of co-location, coincident or cascading hazards. Christchurch City Council (CCC) engaged a project team to investigate these multi-hazard risks and develop a floodplain management plan encompassing these. The project is split into three parts. Firstly, a gap analysis; secondly, studies aiming to fill those gaps; and finally, the development of the floodplain management plan. Tsunamis were identified as one of the areas where future research is need. Consequently, NIWA was commissioned by Christchurch City Council to model tsunami inundation in Christchurch City from two earthquake scenarios and consider various sea level rise scenarios.

This study aims to aid the understanding of the tsunami hazard in the greater Christchurch area so that Christchurch City Council has a better understanding of the influence of tsunamis on flooding risk and potential defence options. The results of this project will feed into the multi-hazard analysis being undertaken by the LDRP97 project team in preparing the floodplain management plan.

The first tsunami source scenario used was the same as that used by Lane et al. (2014, 2017) and involves a tsunami originating from a moment magnitude (M_w) 9.485 earthquake at the South Peru / North Chile Subduction Zone. This scenario was based on the findings of Power (2013), and represents a 1:2,500-year return period event; this is considered an extreme scenario. A less-extreme scenario was also considered based on previous work from Power (2013). The 1:500-year return period earthquake scenario was selected as the most realistic rupture mechanism from two scenarios of fault rupture mechanism presented in a progress report (Lane and Bosserrelle 2017).

A local tsunami source was initially considered. However, tsunami propagation simulation showed that the tsunami wave height at the coast was significantly smaller than for far-field scenarios. Results for local source scenarios were presented in a progress report (Lane and Bosserrelle 2017). For convenience these results are included as an appendix to this report. Subsequently, CCC decided that local source scenarios were not a priority, and to focus on the distant source tsunami scenarios.

This report presents the results for modelled tsunami inundation caused by these tsunami scenarios at different sea-level. Four sea-level scenarios were considered: current conditions, sea level rise for 2040 (0.19 m), 2065 (0.41 m) and 2120 (1.06 m) all based on the analysis of Tonkin & Taylor Ltd (2017). The modelling assumes the tsunami coincides with Mean High Water Spring tide (MHWS), which was taken to be 1.2 m above Lyttelton Vertical Datum 1937 (LVD37) as calculated in Bell (2011); consistent with the MHWS value used in previous modelling Lane et al. (2014, 2017). MHWS was set as the baseline water level for the modelling and represents the case where the largest wave arrives in conjunction with high tide for an average spring tide. Flow from the Avon, Heathcote and Waimakariri Rivers were included in the simulation to account for the tsunami wave propagation in the rivers.

Outputs of maximum inundation depth, maximum flow velocity and maximum shear-stress maps are presented as well as time series of water level, speed and shear-stress. Areas of interest include Avon-Heathcote Estuary, the Waimakariri River Mouth, Brookland Lagoon and bridges in the lower reaches of the rivers.

1.1 Use of this report

The distant source scenarios modelled have long estimated return periods (2,500 years and 500 years) and represent extreme scenarios. Information provided in this report may also be useful for strategic development and infrastructure planning as it may, when used with other hazard and risk information, highlight areas of higher vulnerability that are potentially unsuitable for future development. Maps of the inundation extents should not be used at scales finer than 1:25,000. The overview maps are intended as a guide only and should not be used for interpreting inundation.

The main purpose of this report is to provide the Council with a clearer understanding of the potential tsunami inundation extent and the effects of sea level rise on the Christchurch City region (from the Waimakariri River Mouth to Sumner Head). The information provided is intended to aid understanding of the tsunami for current conditions and sea level rise scenarios up to 2120 (1.06 m) including how tsunamis could impact the local estuaries and lagoons in terms of geomorphic changes, scouring and deposition and resulting long-term effects. Results are intended to inform the Land drainage recovery program (LDRP97).

1.2 Caveat

This report is based on state-of-the-art knowledge and modelling capabilities of tsunamis and tsunami inundation at the time of writing. While every effort was made to provide accurate information, there are many uncertainties involved including knowledge of potential tsunami sources, source characteristics, bathymetry and topography (see Section 2.5 of this report for details). In addition, while the hydrodynamic models capture much of the physics involved in tsunami propagation and inundation, they also include some simplifying assumptions, as with all models. The information provided in this report is of a technical nature and should be considered with the above limitations in mind.

2 Tsunami Inundation Modelling

2.1 Source model and initial conditions

Power (2013) provides a wave height at the Christchurch coast of 12.63 m for the 2,500-year return period tsunami at the 84th percentile confidence level[1]. The de-aggregation of this wave height identified South Peru / North Chile as a major source of the hazard and that an earthquake of M_w 9.485 was required to produce that wave height at the Christchurch coast (Power 2014). For consistency with previous work by Lane et al. (2014, 2017), this source and corresponding modelling approach is used to model the tsunami in this study. The overarching scenario was guided by the GNS Science tsunami database and uses source segments from Tang et al. (2010). In Lane et al. (2014) four earthquake rupture scenarios were modelled. All had the same moment magnitude (M_w), but differed in configurations of rupturing segments and corresponding displacements. For this report we model the largest of those four scenarios as was done in Lane et al. (2017).

This study also analyses the inundation from a 1:500-year return period tsunami at the 84th percentile confidence level also from the South Peru / North Chile region. Two tsunami waves were initially simulated both originating from a magnitude of M_w 9.28 earthquake occurring in the South Peru area. The fault segment involved in the earthquake were selected to produce the largest tsunami waves for Christchurch using a sensitivity analysis of the SIFT (Short-term Inundation Forecast for Tsunamis) database Gica et al. (2008). Both tsunami produced similar waves in Pegasus Bay offshore of Christchurch. Scenario B (Lane and Bosserelle 2017) was selected for inundation simulation as it was produced by the most realistic fault rupture mechanism.

The two tsunami scenarios show very dissimilar waves with the 1:500-year return period scenario showing only large long period waves whereas the 1:2500-year return period scenario is showing large short period wave riding on top of large long period waves.

2.2 Progress report - Decisions

In the progress report, initial tsunami propagation simulations (typically completed at a coarser resolution than inundation simulation) were used to decide which scenarios and parameters to focus on in this study.

Far-field tsunami were modelled from sources across the Pacific Ocean to the edge of the inundation grid. De-aggregation results from the New Zealand Probabilistic Tsunami Hazard Assessment (Power 2013, Power 2014) were used to identify a representative source fault rupture, and (Okada 1985) was used to create the initial surface deformation. Higher resolution modelling of two of these scenarios was approved for further investigation.

Digital elevation models were developed for the new representative beach topography (in Appendix A) under the two most extreme sea level rise scenarios for 2065 (0.41 m) and 2120 (1.06 m) using the results from the Christchurch Coastal Hazards Assessment ((Tonkin & Taylor Ltd 2017).

[1] In probabilistic tsunami hazard assessment, the 84th percentile confidence level refers to the confidence level (or uncertainty) regarding the water level due to the contributions of different fault sources and uncertainty in the parameters of those sources (see Power 2013 for further details).

Four local tsunamis caused by fault rupture in Pegasus Bay and North Canterbury (two single faults and two multi-faults where one fault rupture triggers rupture in a neighbouring fault) were modelled. Faults were taken from an update of the National Seismic Hazard Model and used to create the initial surface deformation. CCC subsequently decided these scenarios were not a priority for this study. These results are reproduced in Appendix B for convenience.

2.3 Inundation modelling and grid

The tsunami modelling is undertaken using the Basilisk model, a partial differential equation solver based on adaptive grids that has been used for tsunami modelling in a range of situations (Popinet 2011, Popinet 2012, Lee et al. 2015, Lane and Bosserrelle 2017).

The Basilisk model (Popinet 2015), a successor to Gerris (Popinet 2011, Popinet 2012), was used to model the inundation together with the river flow. Both Gerris and Basilisk have been used for tsunamis (Popinet 2011, Popinet 2012) and flood inundation (Bind and Smart 2010, Smart 2017) which is why Basilisk, the more recent of the two, was chosen for this modelling. A feature of Basilisk and Gerris is that these models use an adaptive grid where the spatial resolution varies throughout the duration of the simulation, with the grid resolution automatically increasing in areas of interest as defined by Popinet (2012), while lower resolution is maintained elsewhere, improving computational efficiency.

The model grid was confined to Christchurch and Kaiapoi, extending from Taylors Mistake in the south to The Pines in the north. The model grid was rotated by 13.8˚ counter-clockwise so that the edge of the grid was approximately parallel with the shoreline (Figure 2-2). The model was forced with the incoming wave height at its outer edge taken from the previous modelling. The grid is square in shape with the length of a side of the grid being 27 km. The resolution of the model was adapted to optimise the number of model cells while maintaining high accuracy for the water level, flow speed and river channels with the finest resolution of the grid at 13.2 m. The adaptive resolution of the model is illustrated with a snapshot of the final resolution used for the 1:500-year return period tsunami simulation for present day mean sea level in Figure 2-3.

The inundation model for the Christchurch region (between the Waimakariri River and Sumner Head) was developed using topography from Environment Canterbury LiDAR and bathymetry of the rivers, estuary and ocean developed by NIWA. Although results are only required for the south of the Waimakariri River, the modelling extended further north ensuring that the results were not affected by the boundary. Flow was included in the Avon, Heathcote and Waimakariri rivers. Stop-banks along the Waimakariri and Avon rivers and the Sumner sea-wall were resolved.

The same LiDAR data obtained from Environment Canterbury as used for the previous modelling (Lane et al. 2017) was used for the land area. For the Avon and Heathcote rivers bathymetry developed post-earthquake for Environment Canterbury (Measures and Bind 2013) was used. Environment Canterbury provided bathymetry for the lower reaches of the Waimakariri River (the lowest 3 km) but this was not comprehensive enough for the purposes of this modelling. We were also able to obtain cross-sections that were used to reconstruct river bathymetry further upstream. Details of this reconstruction technique are provided in Lane et al. (2017). For the more extreme sea level rise scenarios (2065 SLR 0.41, 20100 SLR 1.06m) we used the revised dune topographies documented in Appendix A.

Stop-bank crest levels were provided for the Waimakariri and Avon stop-banks and the Sumner seawall for previous projects (Lane and Arnold 2013, Lane et al. 2014, Kohout et al. 2015, Lane et al.

2017). In order to ensure that these features were resolved within Basilisk's adaptive refinement, the cells containing these features were refined to the highest level while other regions were allowed to adaptively refine according to details of the flow and whether they were inundated or not. Figure 2-1 shows the stop-banks specifically modelled in this way and the bathymetry from 0 to 10 m above LVD37.

Following Lane et al. (2017) the rivers were initialised with flows of 1.0, 1.7, and 60 m^3/s for the Heathcote, Avon (Cameron 1992, Orchard and Measures 2016) and Waimakariri rivers respectively. The black dots in Figure 2-1 indicate where this flow entered the rivers. The model was allowed to run for 1 day of model time to allow the rivers to fill up with water and reach a steady state. During this time the outer boundary was also gradually raised from LVD37 up to 1.2 m above LVD37. This gave us a baseline height of 1.2 m above LVD37 (i.e., MHWS) without resulting in ponding of low lying regions of Christchurch that are below 1.2 m above LVD37 but are not connected to the sea. After 24 hours simulation time, a steady state river flow and sea level was reached and the tsunami forcing was initiated.

The model boundary forcing for the 1:2,500-year return period tsunami was extracted from far-field propagation of the tsunami across the Pacific Ocean, modelled using Gerris (Popinet 2003, Popinet 2011) in Lane et al. (2014). We did not repeat this modelling but used the same input conditions taken from it for ocean boundary conditions (the height and timing of the approaching tsunami waves) driving the inundation modelling in this report. The boundary forcing for the 1:500-year return period tsunami was extracted from far-field simulations produced using the ComMIT interface (Titov et al. 2011).

The inundation model was used to simulate a 1:500-year tsunami under current sea level and sea level rise scenarios for 2040 (0.19 m), 2065 (0.41 m) and 2120 (1.06 m) and a 1:2,500-year tsunami (i.e., the maximum credible tsunami) under sea level rise scenarios for 2040 (0.19m), 2065 (0.41m) and 2120 (1.06 m). Results from these simulations (maps of maximum and integrated values of shear stress and time series at selected locations (see Figure 2-4 and Figure 2-5)) were used in a qualitative assessment of potential tsunami-induced changes to the geomorphology of the Avon-Heathcote Estuary and Waimakariri River mouths, as well as likely locations of scour and deposition by the tsunami in the estuary, Brookland Lagoon and the lower river reaches.

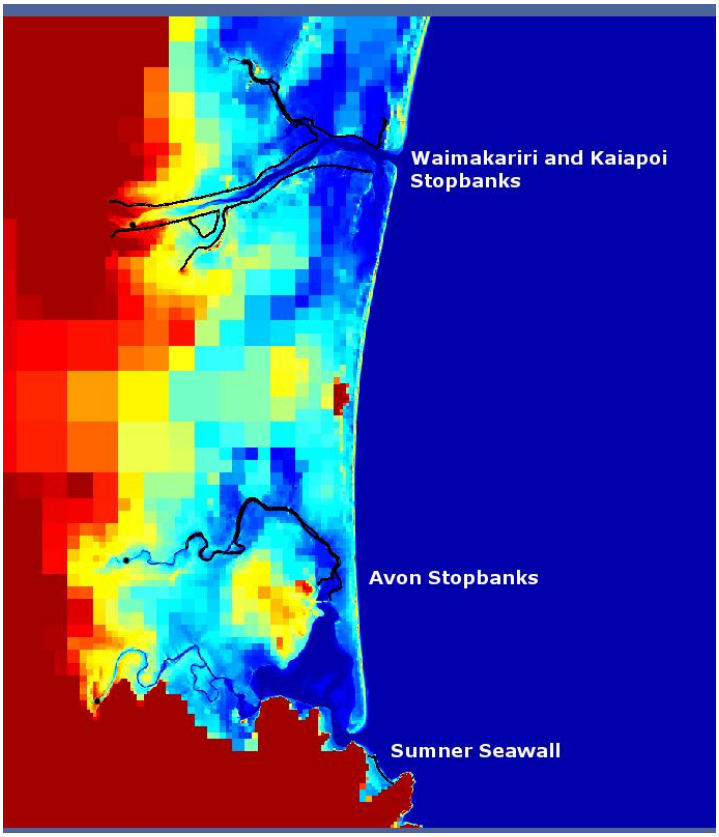

Figure 2-1: Stop-banks modelled in this scenario. The black lines show where stop-banks for the Waimakariri, Kaiapoi and Avon rivers are specified as well as the Sumner seawall. Black dots indicate where water was added to create flow down the rivers. The background shows the topography. Dark blue indicates topography and bathymetry below LVD37, dark red is topography greater than 10 m above LVD37. The adaptive grid can be seen in the different resolution of the topography (in some places where inundation does not reach the grid is very blocky but it is highly refined in other places). This grid has been rotated 13.8˚ clockwise from north so that the beach is approximately parallel with the edge of the grid.

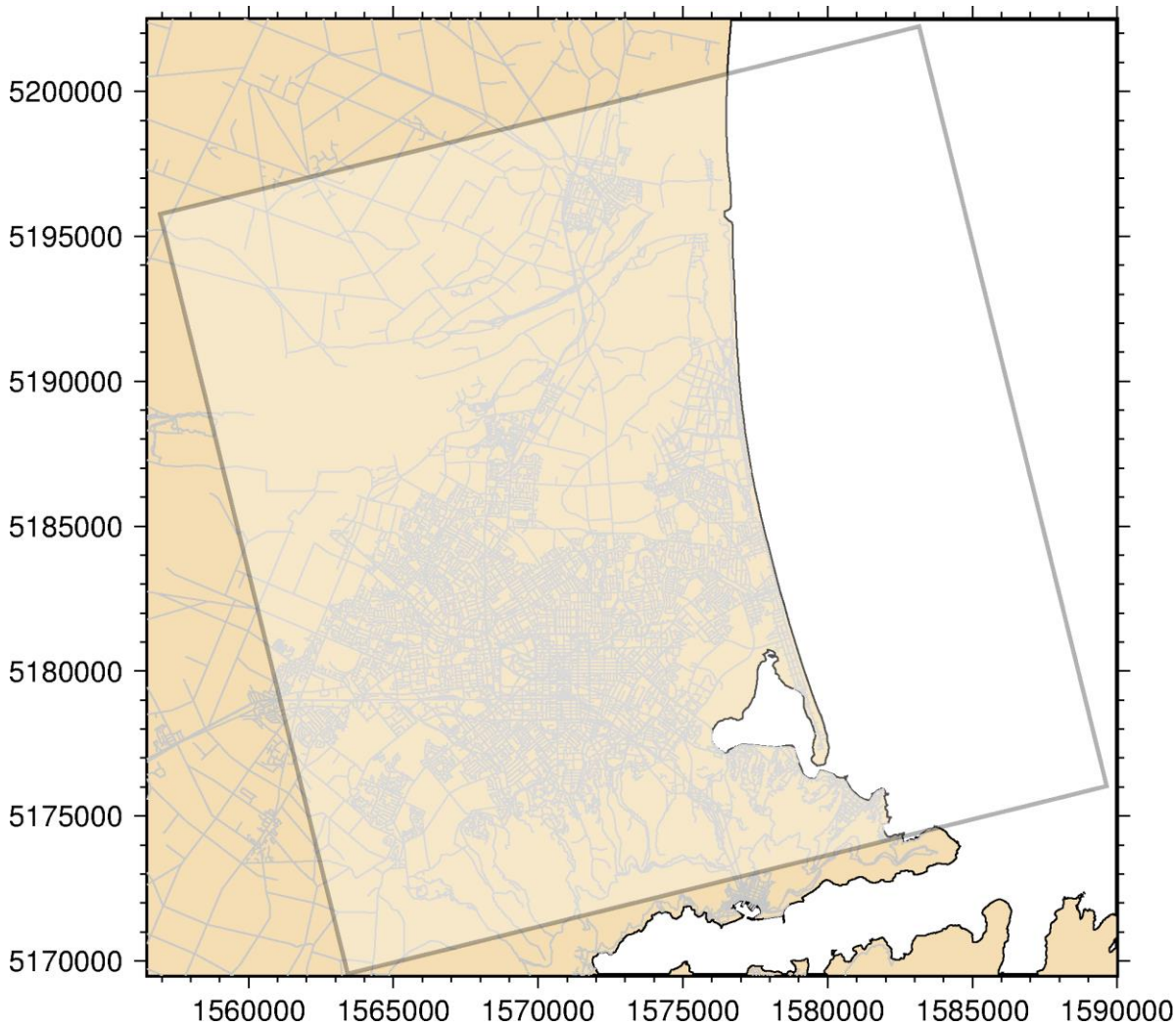

Figure 2-2: Model extent (white box) and location. The model uses an adaptive mesh that is 27 Km wide and is rotated by 13.8 degrees (counter clockwise from the east) to be approximately parallel with the shore.

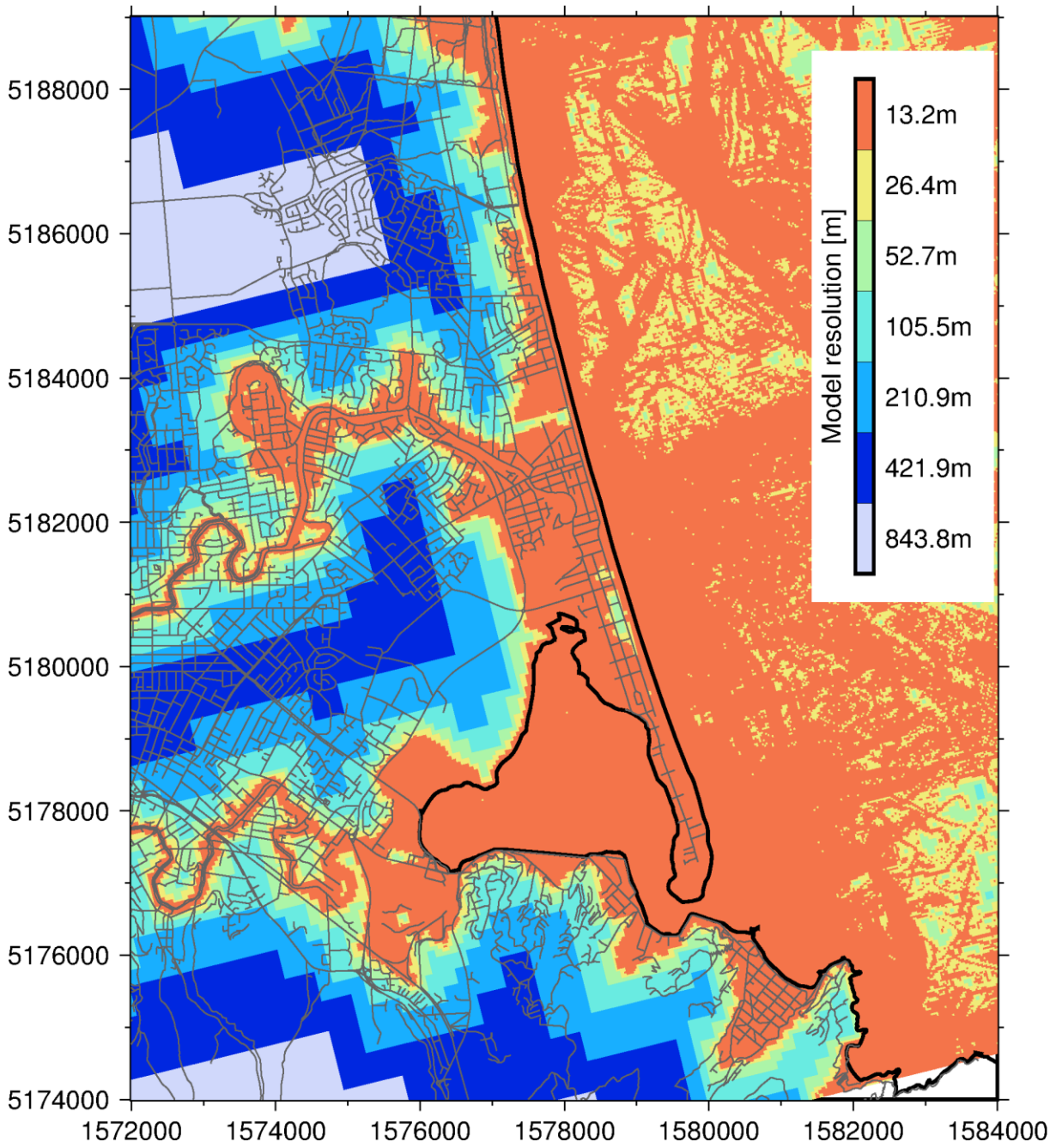

Figure 2-3: Snapshot of model resolution (shading) at the end of inundation for the 1:500-year return period at present mean sea level. The thick black line is the shoreline and the grey lines are roads. Note that higher resolutions occur in the inundated area and resolution gradually decreases on the dry land.

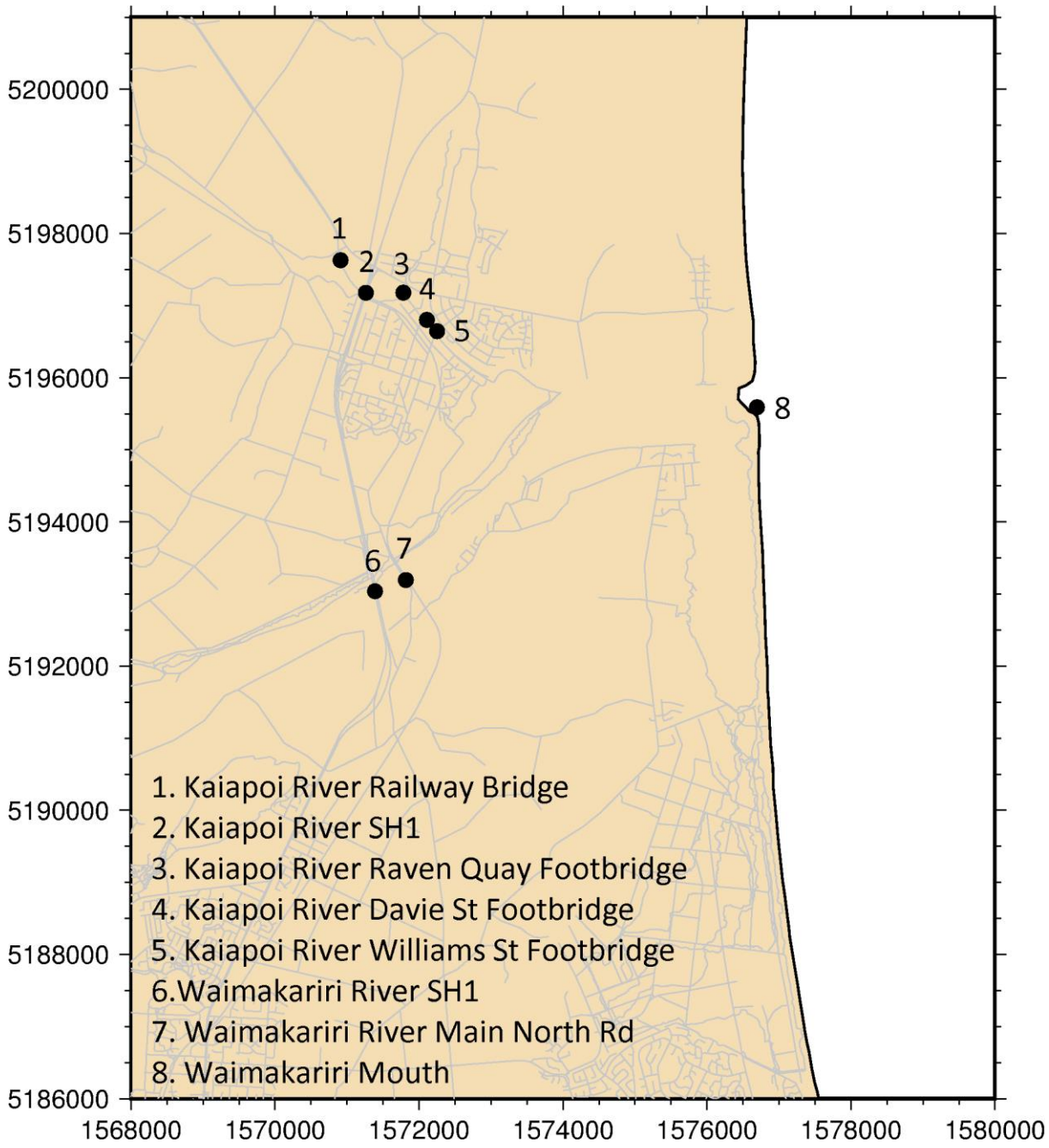

Figure 2-4: Bridge locations for the Northern Section.

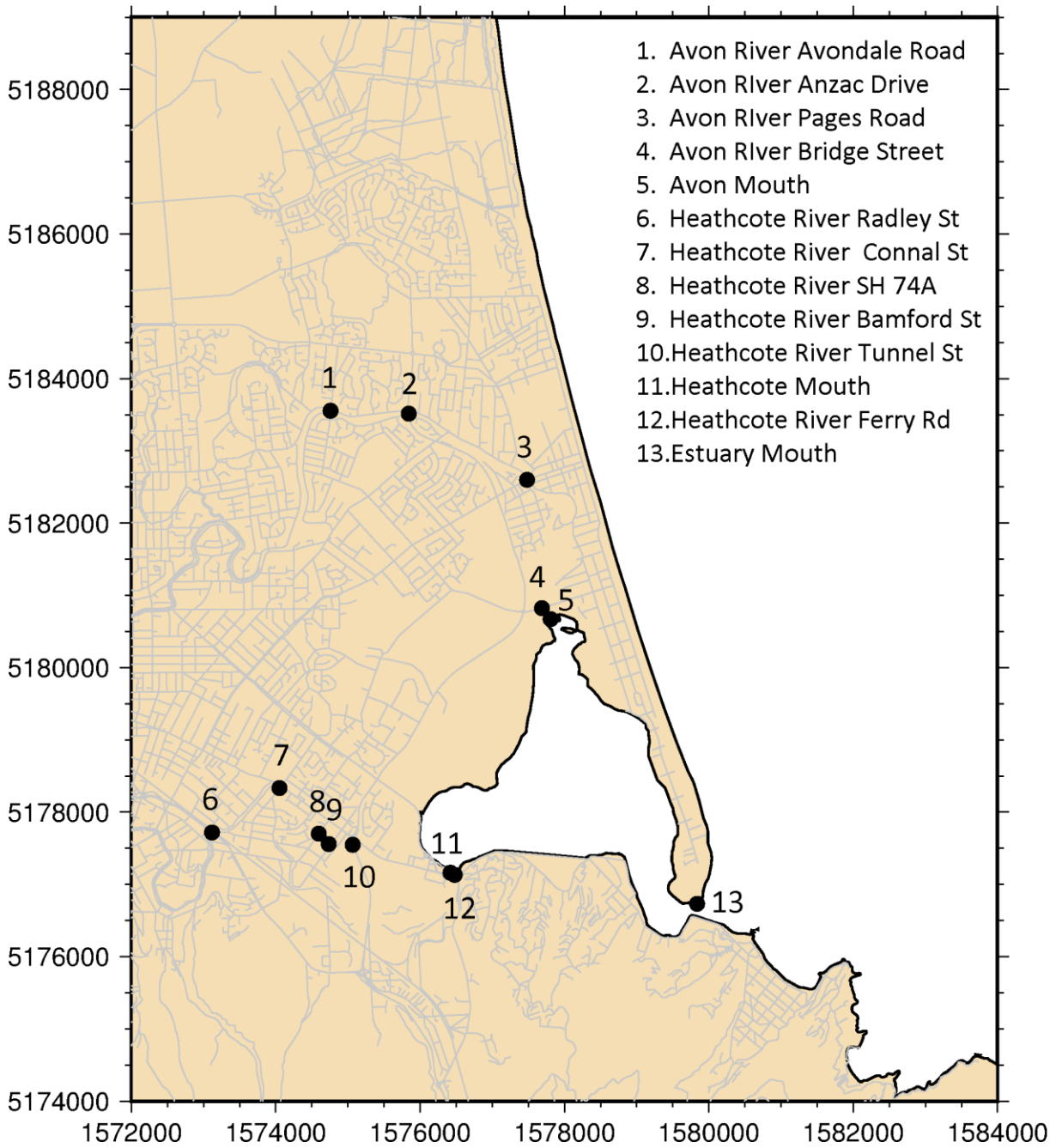

Figure 2-5: Bridge locations for the Southern Section.

2.4 Model outputs

The outputs listed below were produced using the numerical models:

A. Detailed spatial data depicting the maximum inundation depth and extent, maximum flow speed, and maximum shear stress for the specified sea levels for each scenario. The modelling covered Christchurch City from Godley Head in the south, to the Waimakariri River Mouth in the north.

a. 1:500-year far-field tsunami under current sea level and sea-level rise for 2040 (0.19 m), 2065 (0.41 m) and 2120 (1.06 m).

b. 1:2,500-year far-field tsunami (i.e., maximum credible tsunami) under sea level rise for 2040 (0.19 m), 2065 (0.41 m) and 2120 (1.06 m).

B. Qualitative assessments of the likely geomorphic changes of the river mouths and scour and deposition within the regions of interest:

- the mouth of the Avon-Heathcote Estuary
- the mouth of the Waimakariri River,
- bridge locations in the lower reaches of the rivers.

These outputs describe the propagation and magnitude of the tsunami arriving at the Christchurch coastline and the inundation at the locations of interest. The maps are presented and discussed in this report are all in NZTM coordinate system. Detailed spatial data (in digital ArcGIS format) is provided to CCC in addition to this report.

2.5 Uncertainties

Inherent uncertainties associated with the tsunami modelling stem from the bathymetric resolution of the grid used, the fault rupture scenarios used, the numerical equations and the solver used for the modelling. These uncertainties are described in more detail below.

The quality of the topographic data and the bathymetric data in inshore waters strongly influences the simulation of inundation. For this modelling, we used available DEM data for the land topography and near-shore bathymetry in the vicinity of Christchurch, but in order to capture some of the more complex small-scale processes in harbours and embayed areas, higher resolution data is required. Known topographic uncertainties associated with the DEM used for this study include the bathymetry of the Waimakariri River. Also, in order to resolve the Waimakariri and Avon stop-banks and Sumner seawall, we refined cells in these regions to the highest resolution and then set their elevation to the specified stop-bank and seawall crest levels. Given that the finest resolution is 13.2 m, this means that the stop-banks and seawalls were modelled as having at least that width. In the case of the Sumner seawall, this is wider than the actual sea wall. This resolution also limits how well the dunes can be resolved.

Other uncertainties in the modelling study include the gridded representation of a continuous coastline (grid-stepping), which can deform the shape of bays and estuaries, and the effects of building and land features on form drag. The latter could substantially modify the onshore propagation of tsunamis. Improving the drag representation remains a goal of current research. Eradication of the other errors is constrained by limitations of data quality and the practicalities of grid resolution. Models always represent an approximation of reality.

Model uncertainty can be quantified by running multiple simulations with small variations in key parameters, an approach known as ensemble prediction or sensitivity analysis. Such an approach provides an envelope of predicted solutions, rather than single "worst-case" or "scenario-type" predictions, on which to base emergency response procedures. However, running many simulations increases the computational and research costs, and, in any event, model forecasts can never be certain because our knowledge of all the geophysical processes involved in tsunami generation, propagation and inundation remains incomplete.

Quantitative calibration of the tsunami inundation model against real measurements is difficult due to the uncertain nature of tsunami impact data from New Zealand and the consequent difficulty in identifying events from the past. Nevertheless, the Gerris and Basilisk models have been continuously validated against standard analytical test cases (e.g., Popinet 2003, Popinet 2011, Popinet 2012, Popinet 2015).

3 Model results

3.1 Water level at the main bridges.

Tsunami wave propagating along river channels can cause severe damage to infrastructure far upstream. The maximum elevation of tsunami waves at each of the main bridges in the lower reaches of the Waimakariri, Avon and Heathcote rivers is presented in Table 3-1 and Table 3-2. Elevation of the underside of the bridge decks (LVD37) are also presented (where the value is known) and the modelled tsunami heights above LVD37 at each location.

Tsunami waves reached the highest levels at the Waimakariri River SH1 bridge (Figure 3-1 and Figure 3-2). For most scenarios the tsunami waves did not reach bridge deck (where elevation is known) except for the Heathcote River Bamford Street bridge (Figure 3-3 – Figure 3-6) where the bridge deck elevation is reached by the tsunami wave for all the scenarios. For the 1:500-year return period at the predicted sea level of 2120 (1.06m), the tsunami level reaches within less than 1 m of the bridge deck for the Avon River Pages Road bridge (Figure 3-7 – Figure 3-10), the Avon River Avondale Road bridge (Figure 3-11 and Figure 3-12), the Heathcote River Ferry Road Bridge (Figure 3-13 and Figure 3-14) and the Heathcote River Tunnel Road bridge (Figure 3-15 and Figure 3-16). This would make these bridges more vulnerable to debris transported by the tsunami waves.

For some of the bridges (e.g., Waimakariri River SH1, Heathcote River Ferry Road) the maximum water level reached with the 1:500-year return period event exceeds the level reached by the 1:2,500-year return period event. While this may appear counter-intuitive, this is the result of the higher frequency waves from the 1:2,500-year scenario losing a large amount of energy while propagating along the river channels. The 1:500-year scenarios do not include such high frequency waves. This highlights the potential differences in impacts caused by different tsunami scenarios.

Table 3-1: Bridges on Waimakariri, Avon and Heathcote rivers with heights above LVD37 and modelled maximum tsunami height at those locations for the 1:500-year return period scenario.

Bridge	Bridge underside deck level above LVD37 (m)	1:500-year return period Tsunami height above LVD37 (m)			
		Current Sea Level	2040 Sea Level 0.19 m Rise	2065 Sea Level 0.41 m Rise	2120 Sea Level 1.06 m Rise
Waimakariri River Main North Rd	7.8	3.96	4.17	4.39	4.90
Waimakariri River SH1		4.02	4.20	4.43	4.95
Avon River Bridge Street	6.2	2.66	2.83	3.12	3.72
Avon River Pages Road	4.2	2.57	2.77	3.02	3.71
Avon River Anzac Drive	4.2	2.09	2.21	2.39	2.84
Avon River Avondale Road	3.8	1.99	2.08	2.23	2.82
Heathcote River Ferry Road	4.6	2.57	2.77	2.96	3.57
Heathcote River Tunnel Road	4.3	2.51	2.65	2.84	3.55
Heathcote River Bamford Street	2.1	2.51	2.66	2.83	3.55
Heathcote River SH 74A		2.50	2.65	2.81	3.50
Heathcote River Connal Street		2.38	2.53	2.69	3.21
Heathcote River Radley Street		2.38	2.54	2.70	3.20

Table 3-2: Bridges on Waimakariri, Avon and Heathcote rivers with heights above LVD37 and modelled maximum tsunami height at those locations for the 1:2,500-year return period scenario.

Bridge	Bridge underside deck level above LVD37 (m)	1:2,500-year return period Tsunami height above LVD37 (m)		
		2040 Sea Level 0.19 m Rise	2065 Sea Level 0.41 m Rise	2120 Sea Level 1.06 m Rise
Waimakariri River Main North Rd	7.8	3.85	4.04	4.65
Waimakariri River SH1		3.86	4.07	4.70
Avon River Bridge Street	6.2	3.12	3.34	3.90
Avon River Pages Road	4.2	2.97	3.22	3.96
Avon River Anzac Drive	4.2	2.28	2.40	2.93
Avon River Avondale Road	3.8	2.19	2.31	2.9
Heathcote River Ferry Road	4.6	2.82	2.98	3.49
Heathcote River Tunnel Road	4.3	2.66	2.81	3.41
Heathcote River Bamford Street	2.1	2.66	2.81	3.40
Heathcote River SH 74A		2.65	2.80	3.37
Heathcote River Connal Street		2.60	2.75	3.15
Heathcote River Radley Street		2.60	2.76	3.16

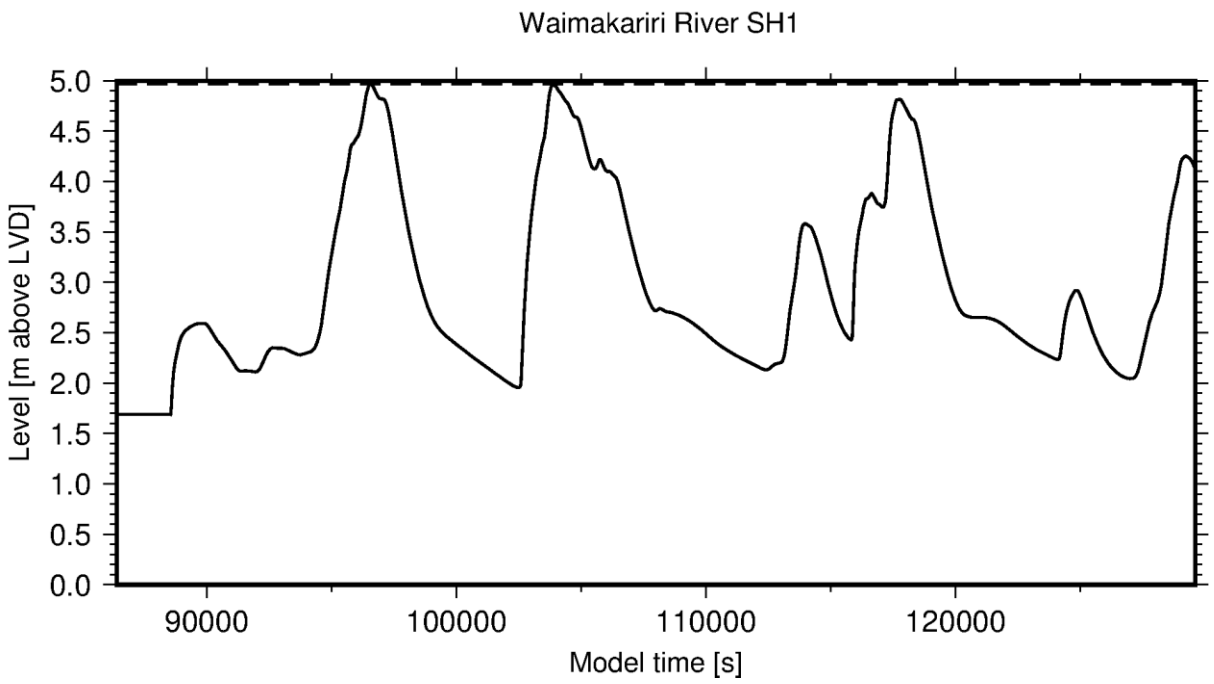

Figure 3-1: Tsunami height timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Waimakariri River SH1 bridge.

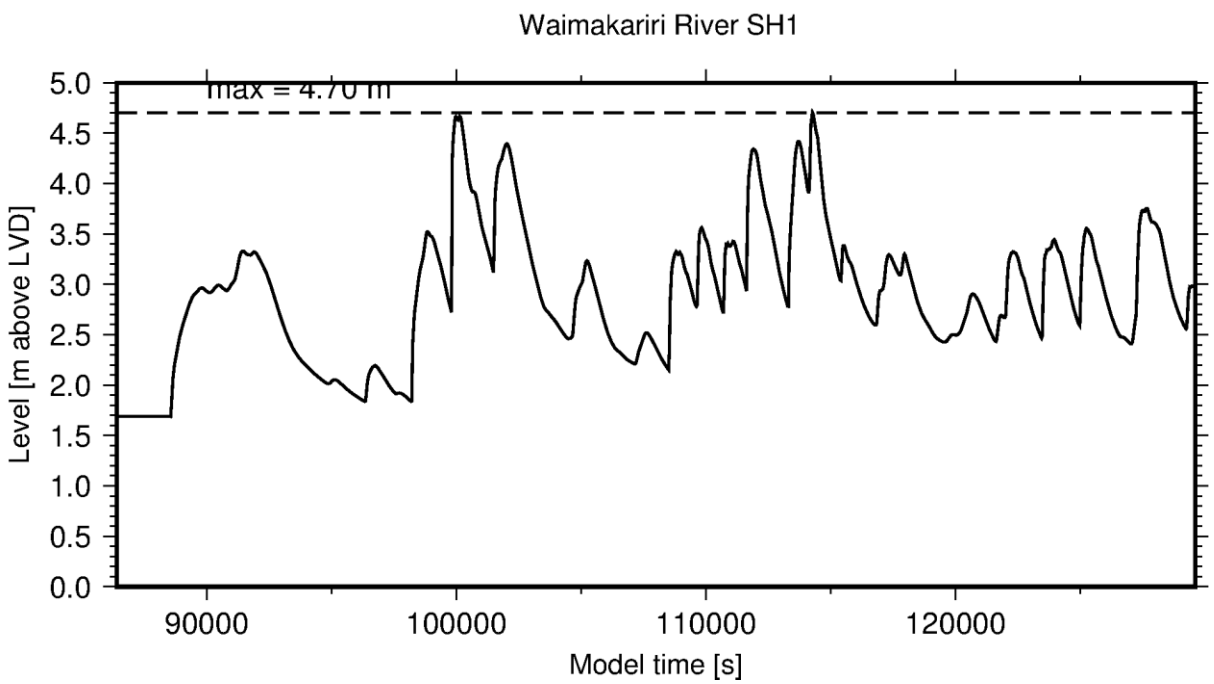

Figure 3-2: Tsunami height timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Waimakariri River SH1 bridge.

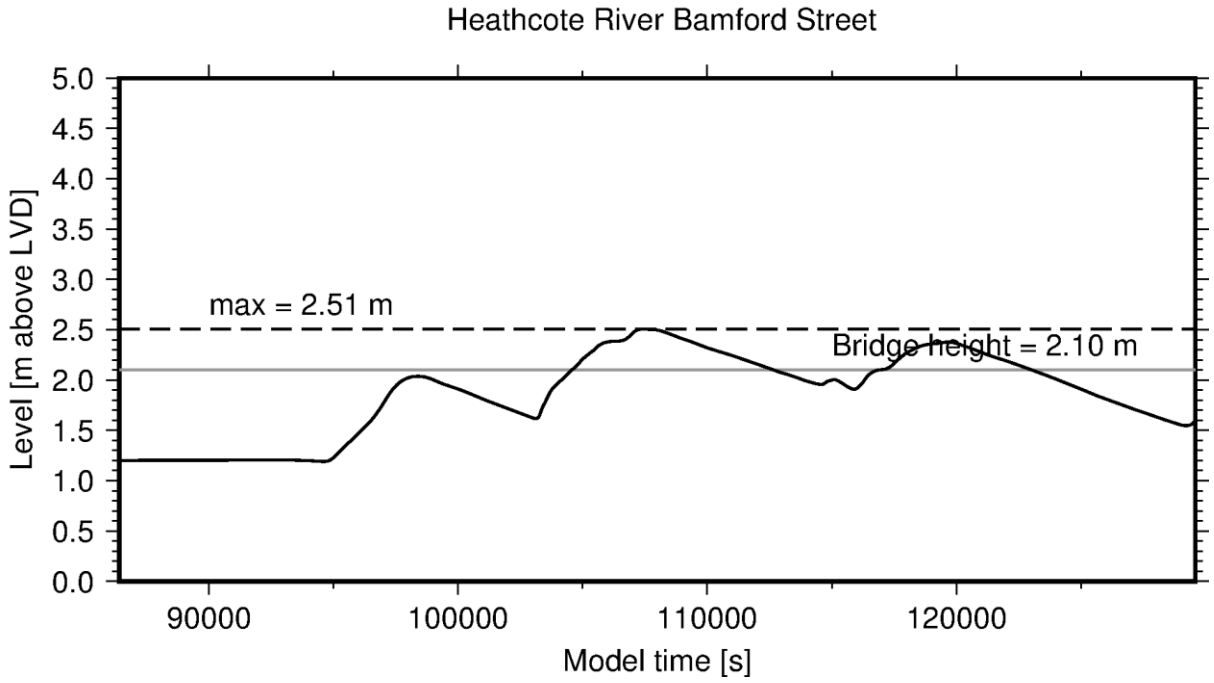

Figure 3-3: Tsunami height timeseries for 1:500-year return period - Current Sea Level at Heathcote River Bamford Street.

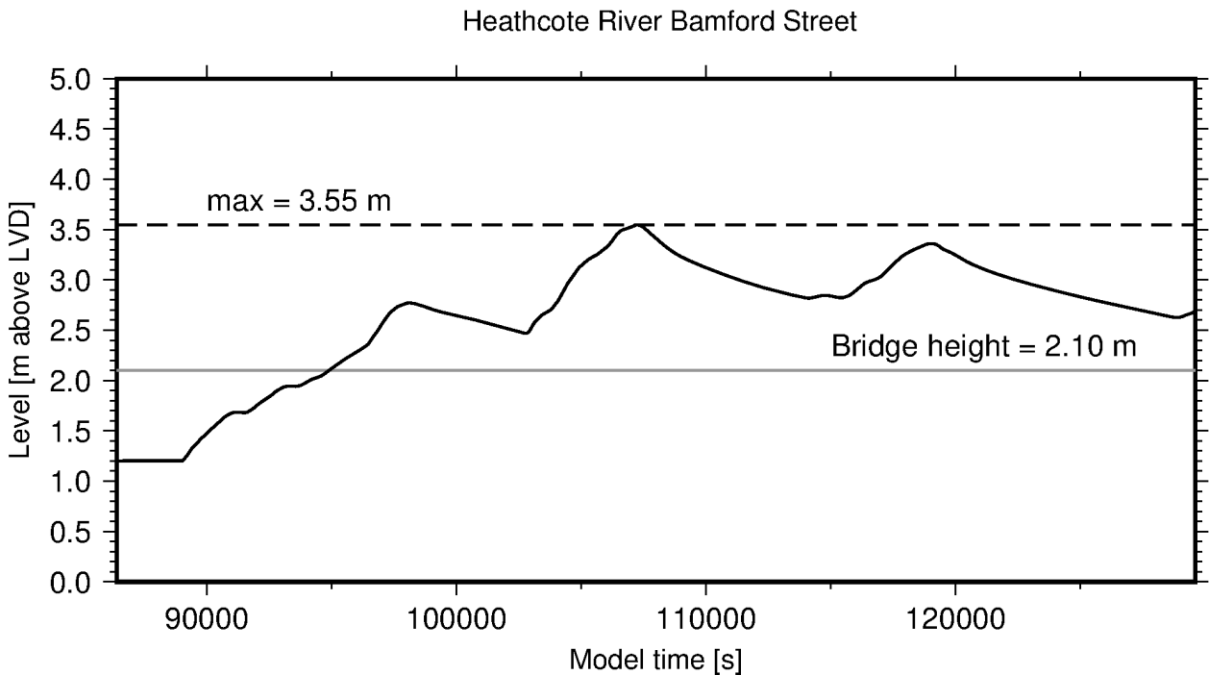

Figure 3-4: Tsunami height timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Heathcote River Bamford Street.

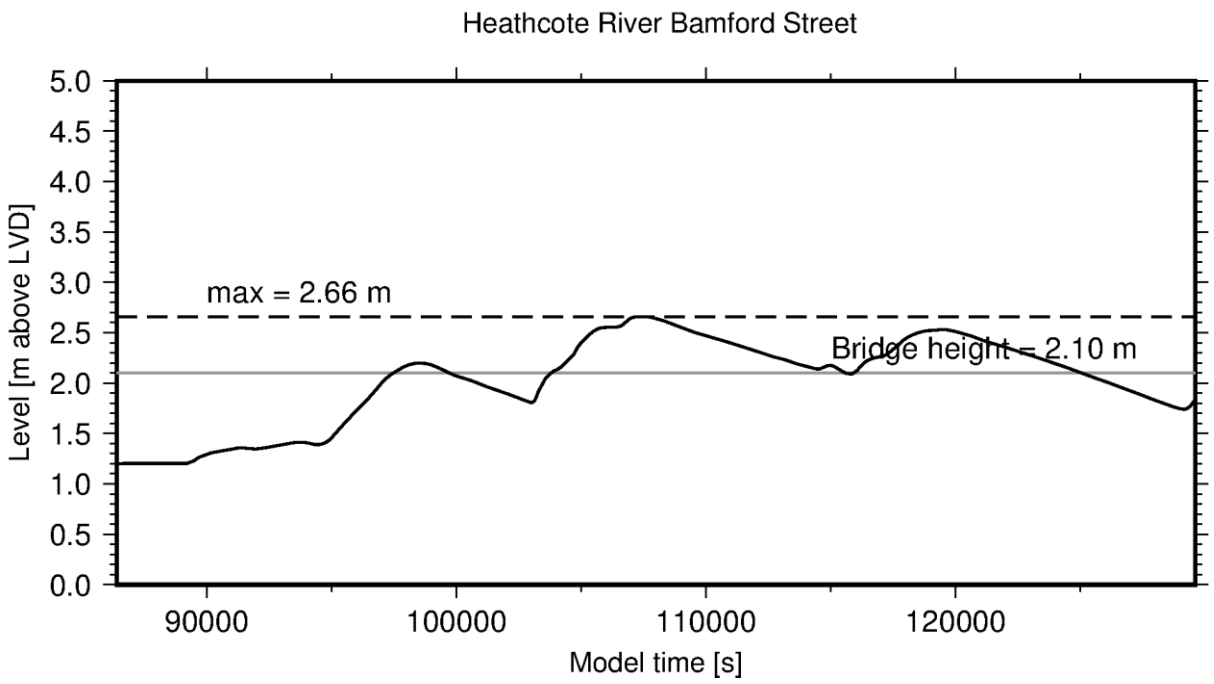

Figure 3-5: Tsunami height timeseries for 1:2,500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise at Heathcote River Bamford Street.

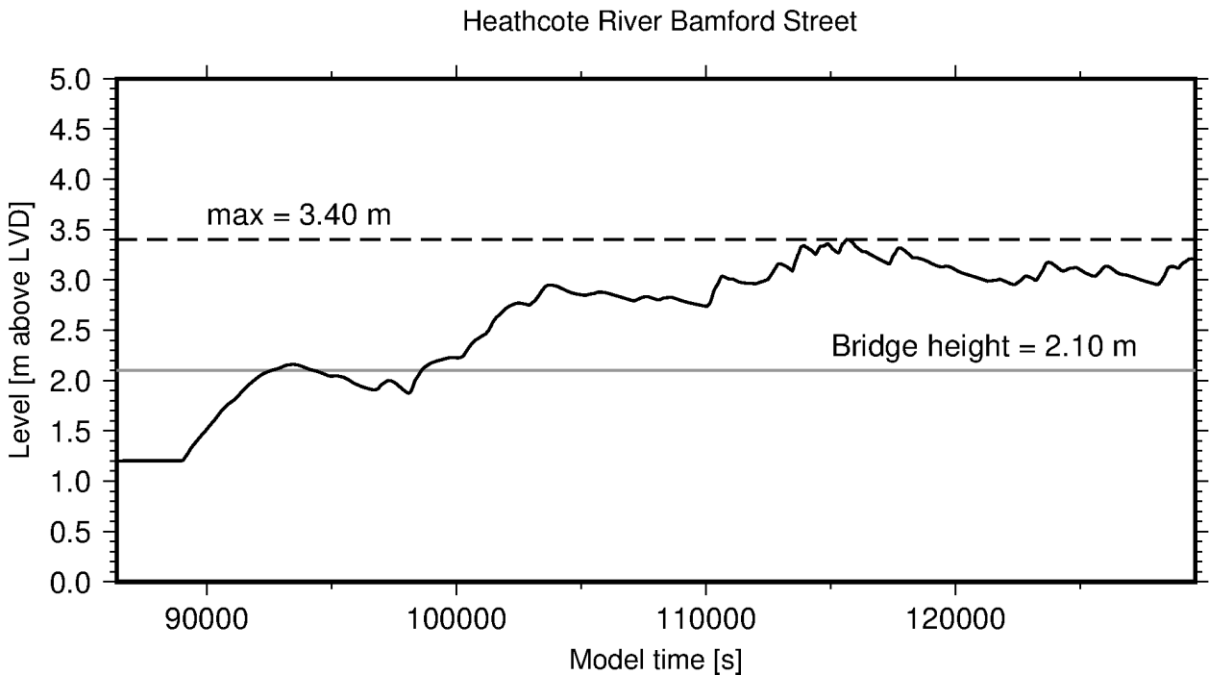

Figure 3-6: Tsunami height timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Heathcote River Bamford Street.

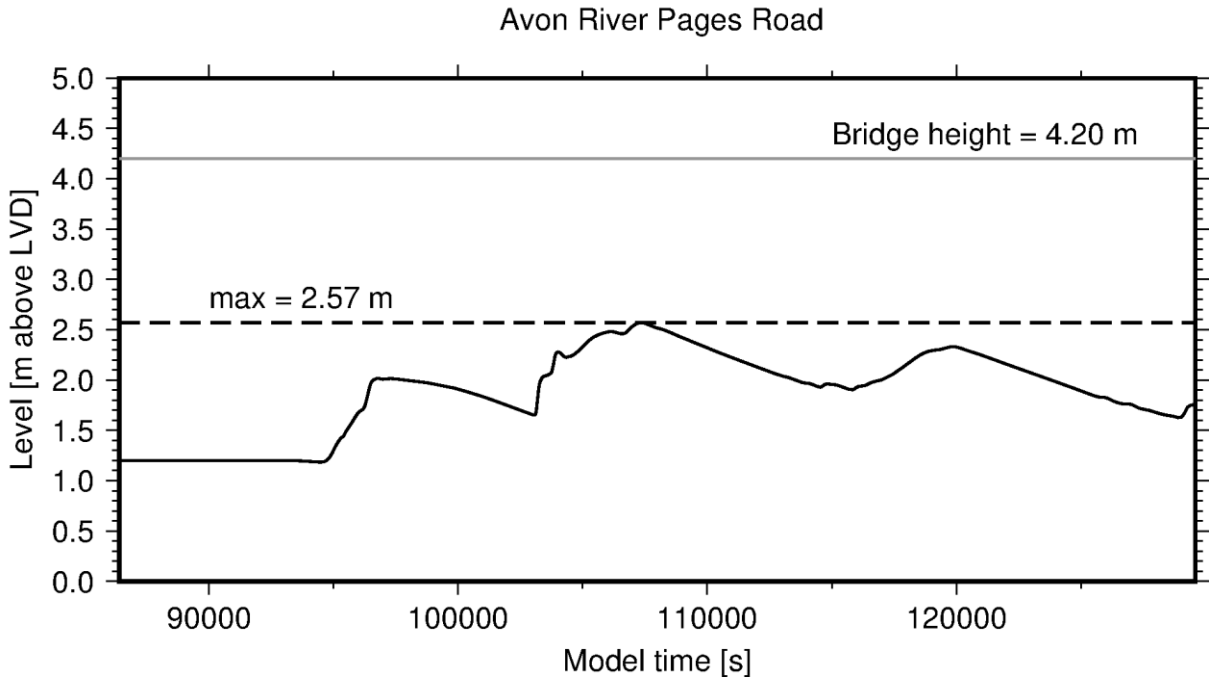

Figure 3-7: Tsunami height timeseries for 1:500-year return period - Current Sea Level at Avon River Pages Road.

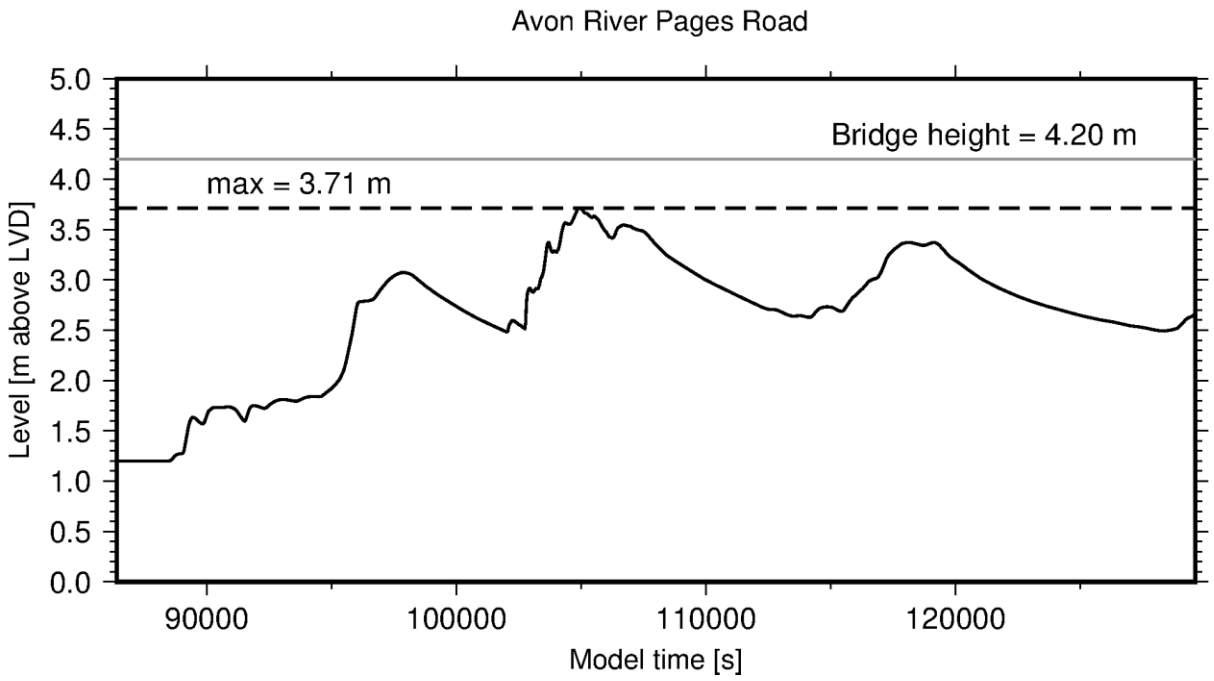

Figure 3-8: Tsunami height timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Avon River Pages Road.

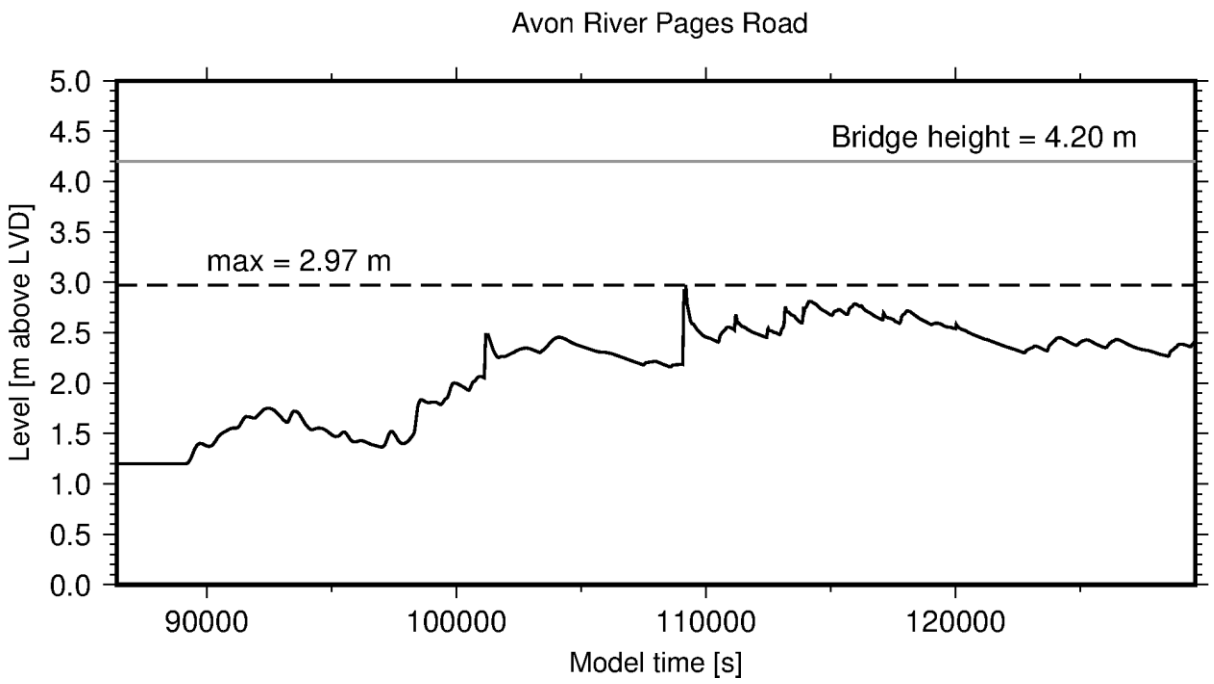

Figure 3-9: Tsunami height timeseries for 1:2,500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise at Avon River Pages Road.

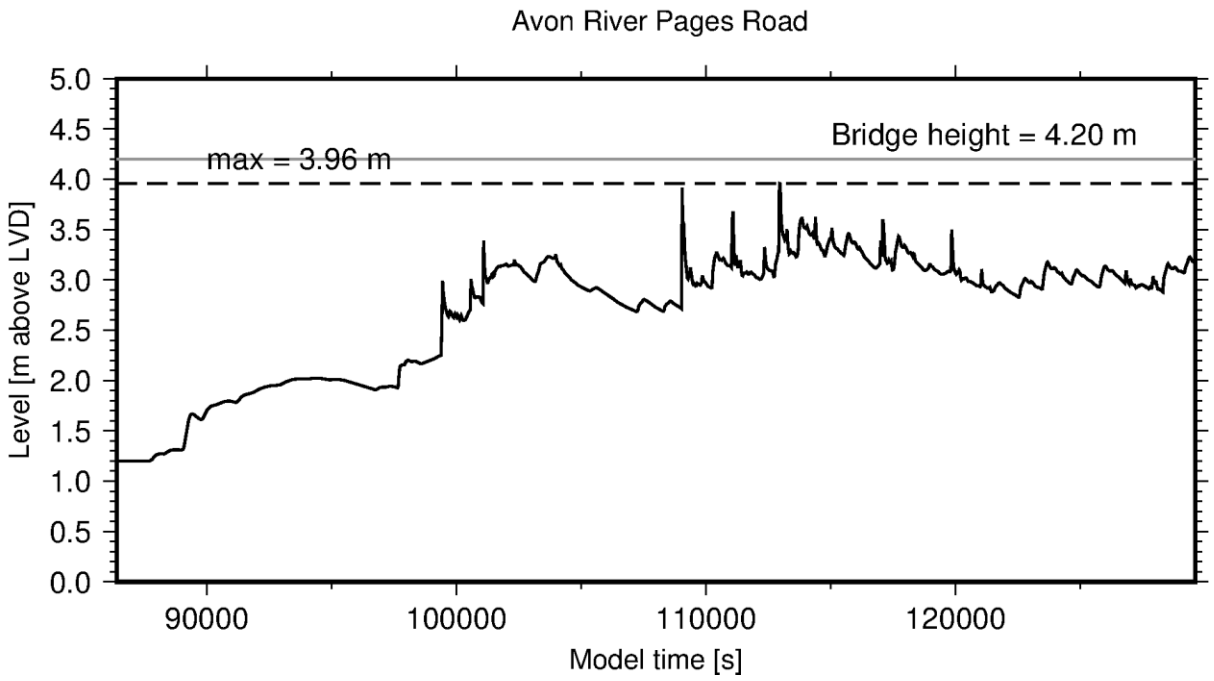

Figure 3-10: Tsunami height timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Avon River Pages Road.

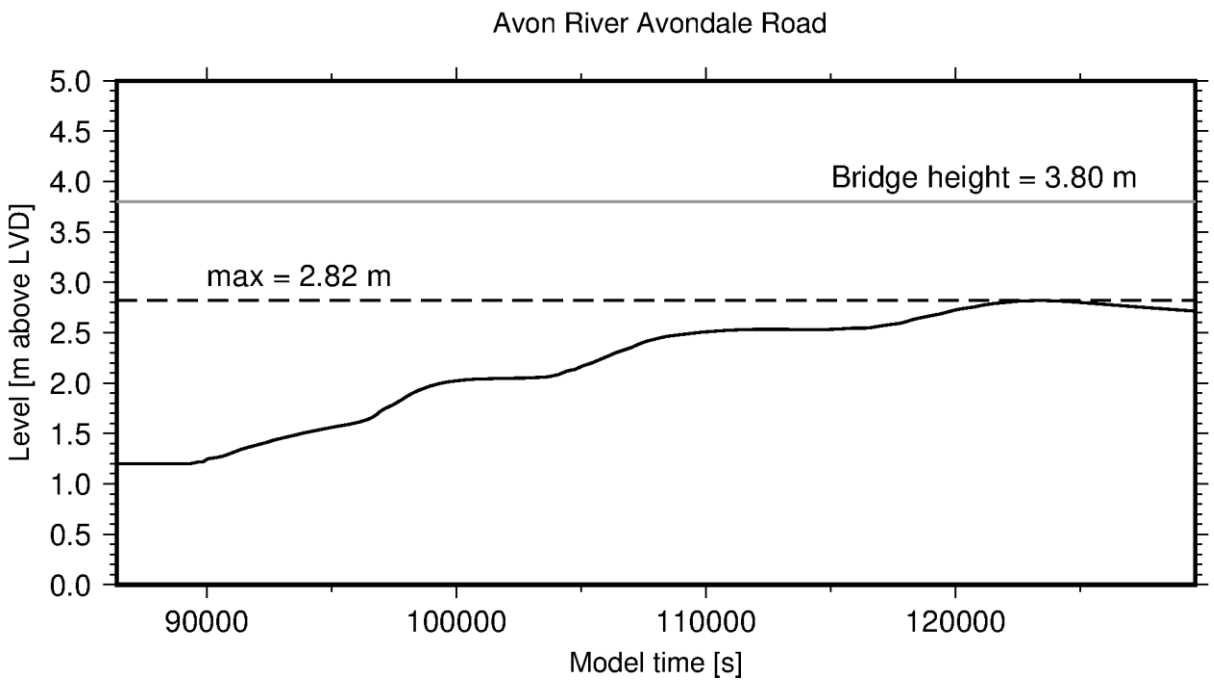

Figure 3-11: Tsunami height timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Avon River Avondale Road bridge.

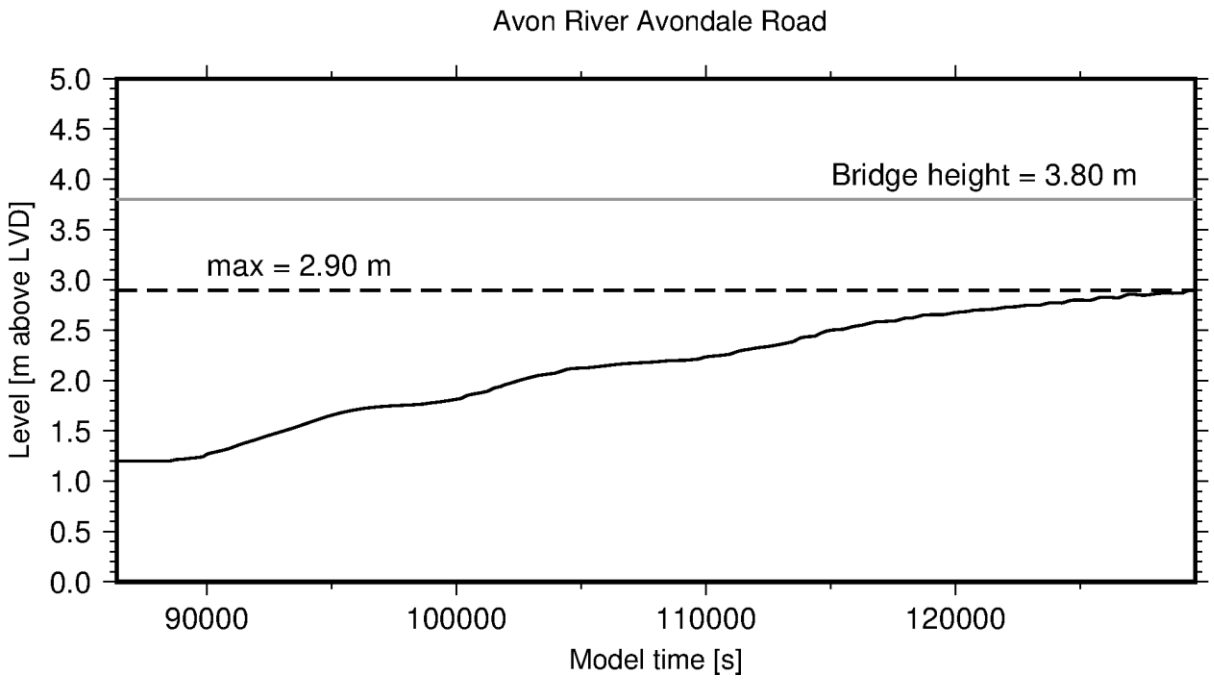

Figure 3-12: Tsunami height timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Avon River Avondale Road bridge.

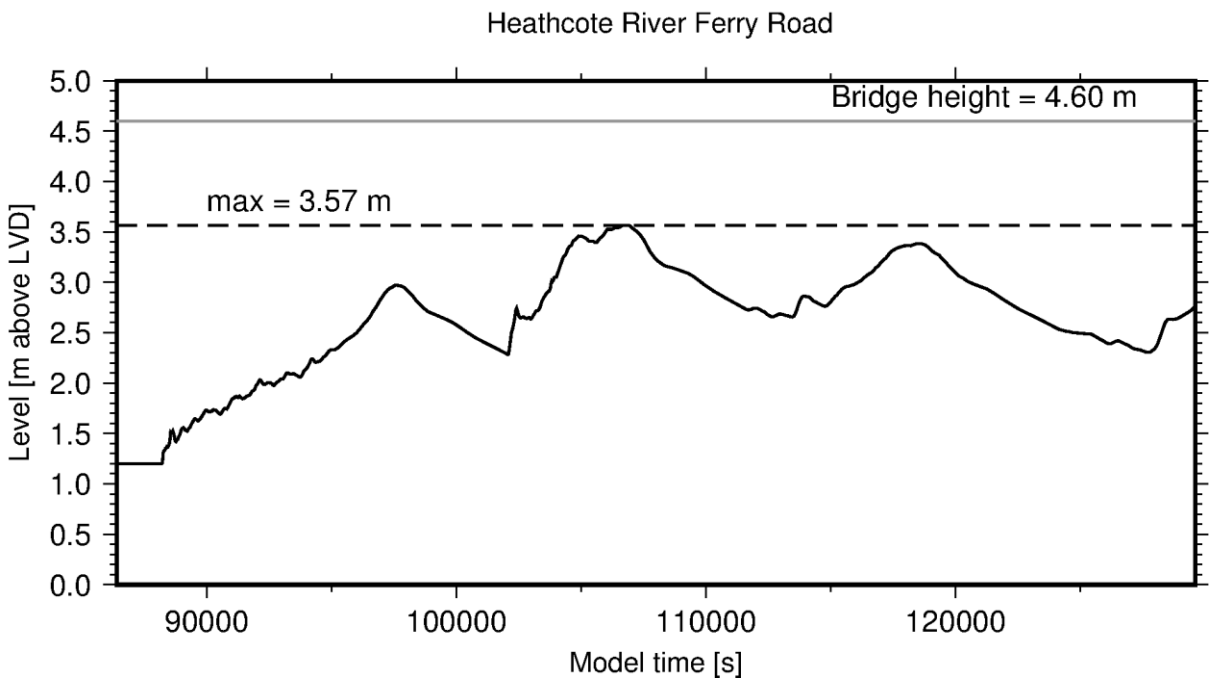

Figure 3-13: Tsunami height timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Heathcote River Ferry Road bridge.

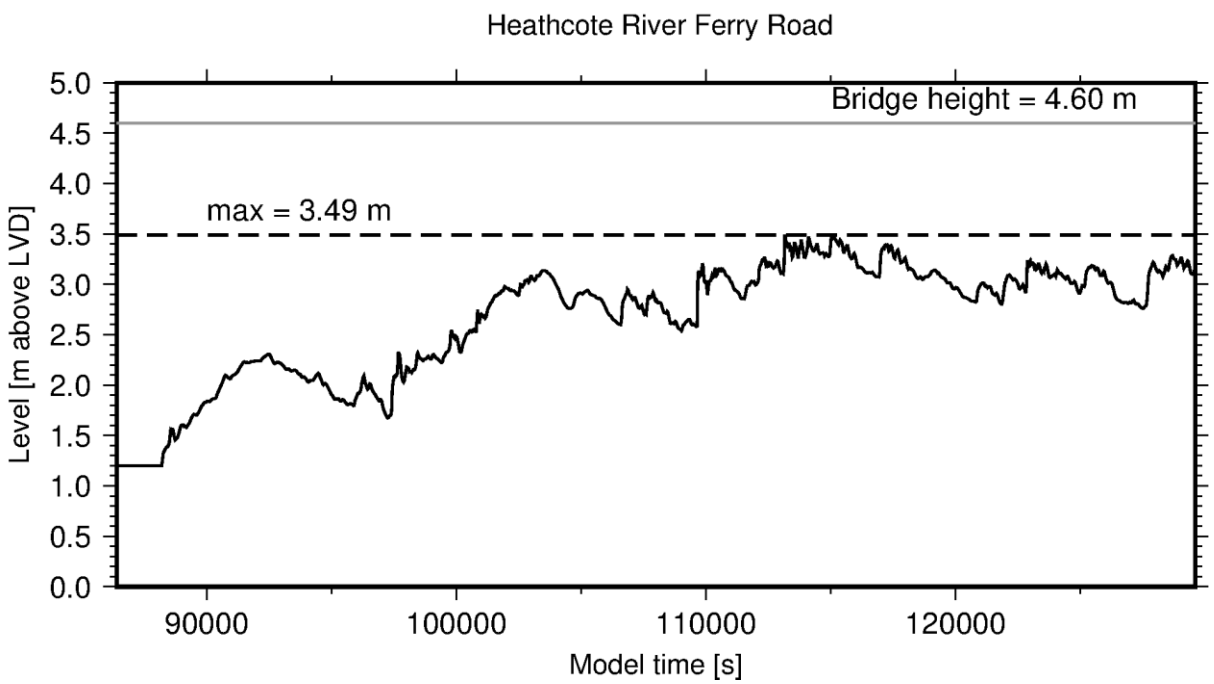

Figure 3-14: Tsunami height timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Heathcote River Ferry Road bridge.

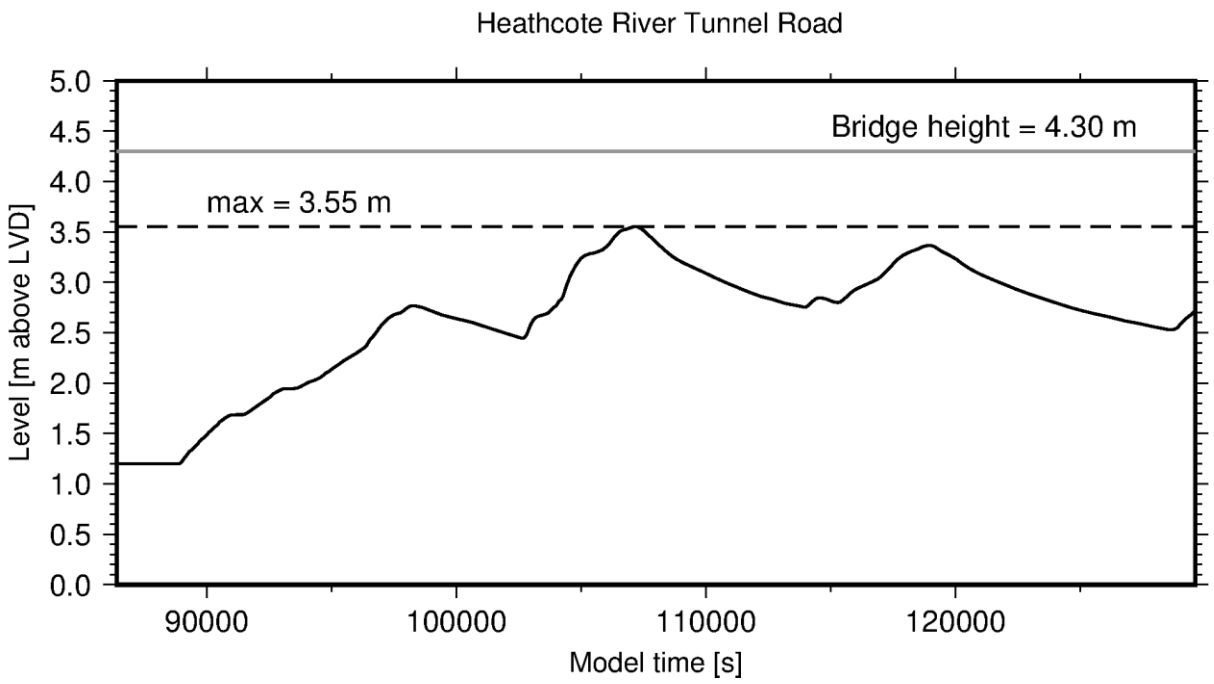

Figure 3-15: Tsunami height timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Heathcote River Tunnel Road bridge.

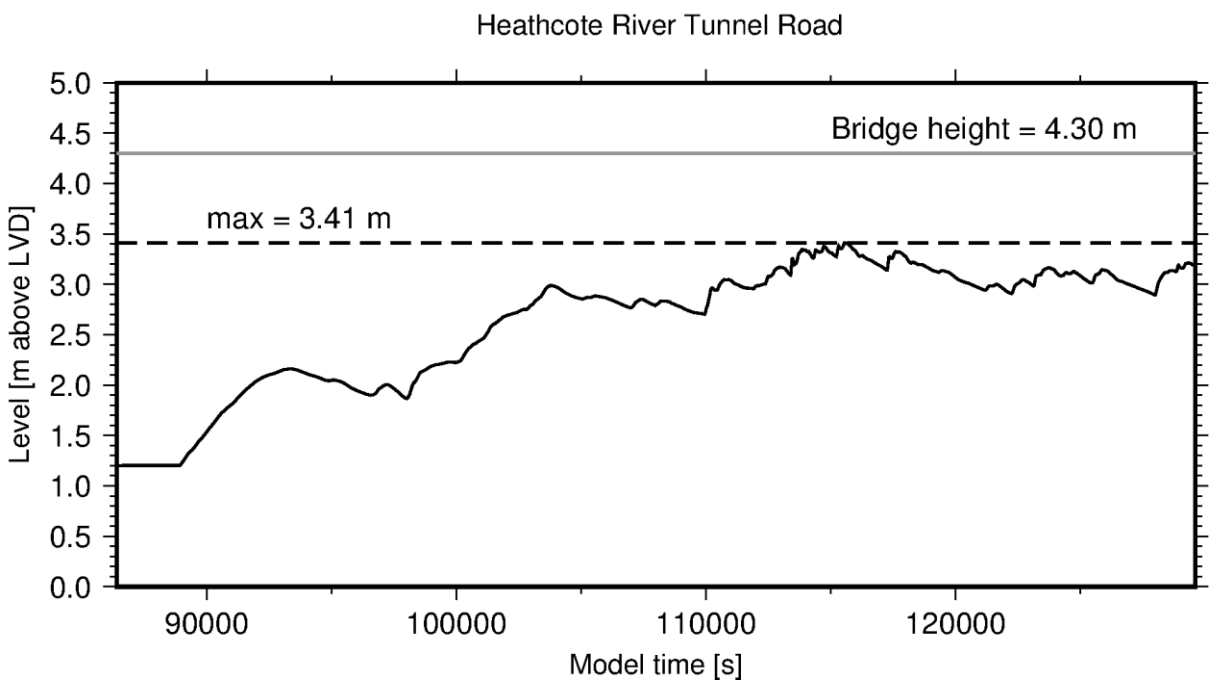

Figure 3-16: Tsunami height timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Heathcote River Tunnel Road bridge.

3.2 Maximum inundation, speed and shear stress.

3.2.1 1:500-year return period tsunami - Current Sea Level

The inundation extent for the 1:500-year return period tsunami at current mean sea-level covers an area of 30 km^2 and reaches a maximum depth of 14 m in the Waimakariri River bed (i.e., 14 m above the Waimakariri River normal water level). The main inundation locations on the northern side of the area of interest are the flood plain of the Brooklands Lagoon and the Styx River floodplain (Figure 3-17). In this area the high flow speed (>2 m/s) is constrained to the Waimakariri River Channel, the Kaiapoi River channel, Brooklands Lagoon and the Waimakariri River Mouth (Figure 3-18). On the southern side of the area of interest, inundation for the 1:500-year tsunami occurs in the floodplain of the Avon River, near the mouth of the Heathcote River, on the low-lying area along the Avon-Heathcote Estuary (e.g., South Shore) and near low lying "breaches" in the dunes near the New Brighton pier, and the Waimairi Beach surf club (North New Brighton) (Figure 3-19). Extremely high flow velocities are predicted in the estuary mouth (8 m/s) and the Waimakariri River Mouth (7 m/s). High velocities are predicted near the dune breaches (New Brighton Pier, North New Brighton surf club, South Sumner) (3-4 m/s) and near the main bridges where the flow is constricted (Avon River Bridge Street bridge, 3.2 m/s, and Heathcote River Ferry Road bridge, 2.7 m/s) (Figure 3-20).

The high velocities predicted in the model would entrain large quantities of sediment and radically modify the topography and bathymetry from what was used in the model. This could affect later inundation but is not captured in the modelling.

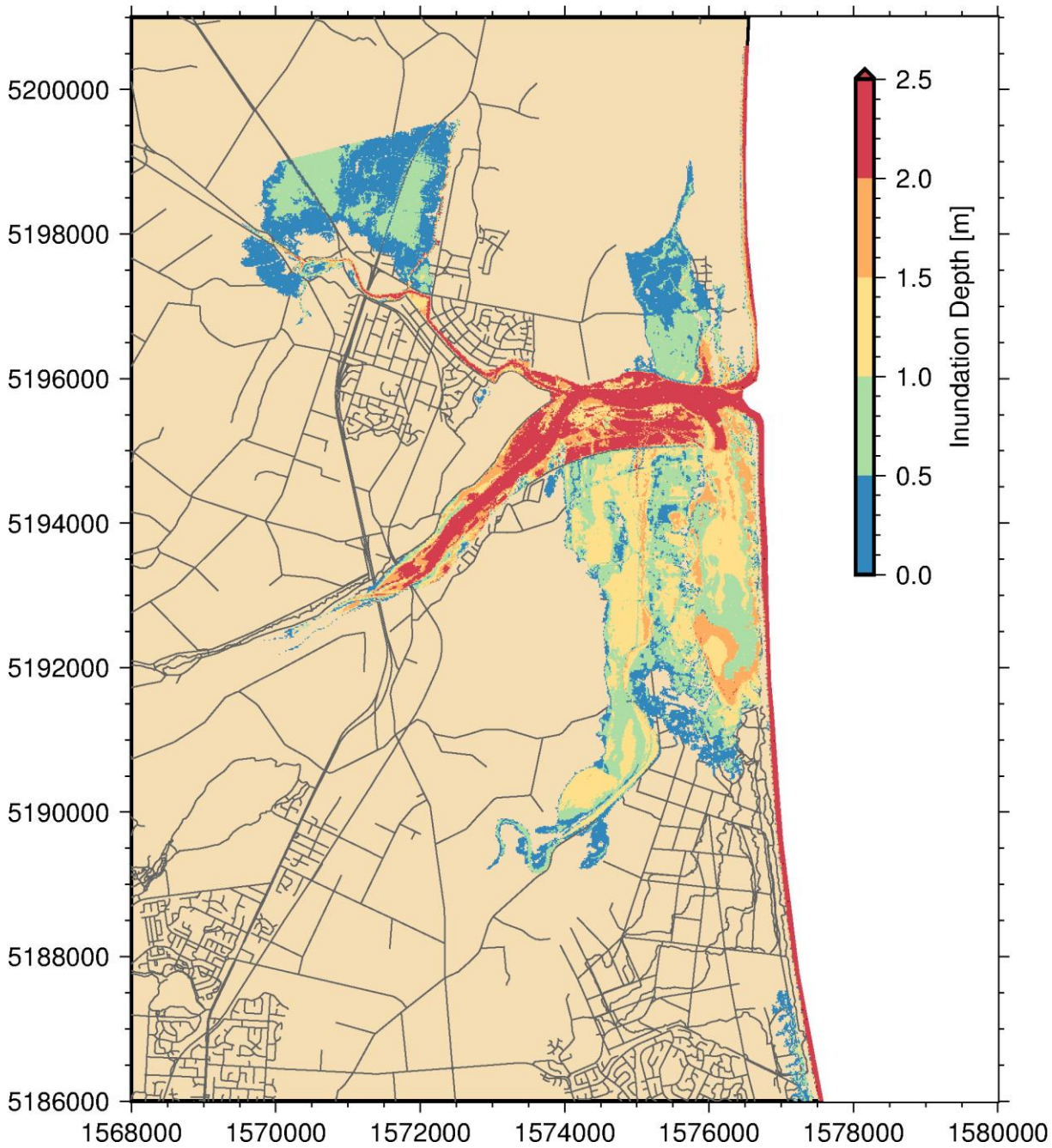

Figure 3-17: Maximum inundation depth (i.e., height above ground) for 1:500-year return period event Current Sea Level - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

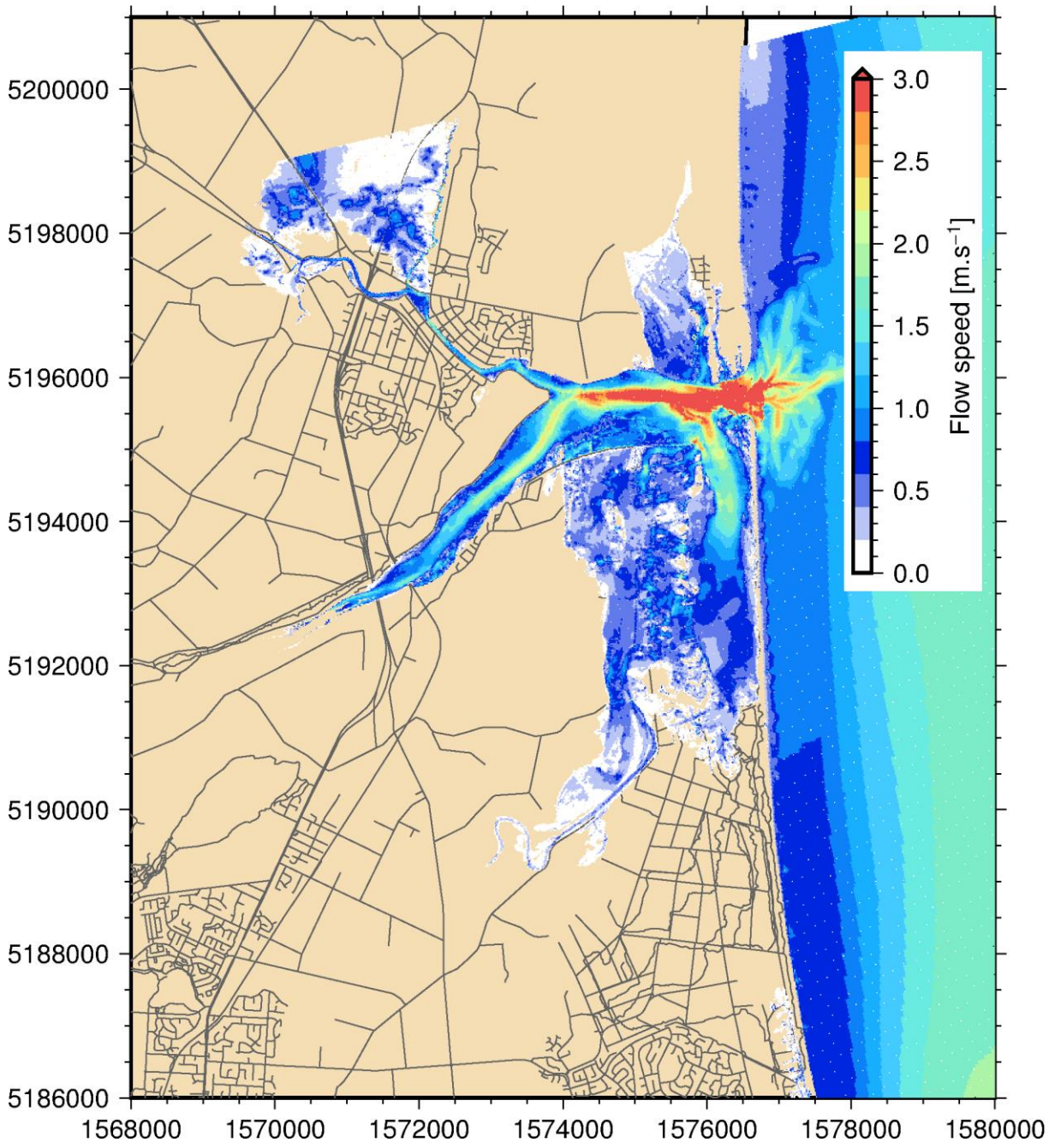

Figure 3-18: Maximum flow velocity for 1:500-year return period event Current Sea Level - Northern Section.

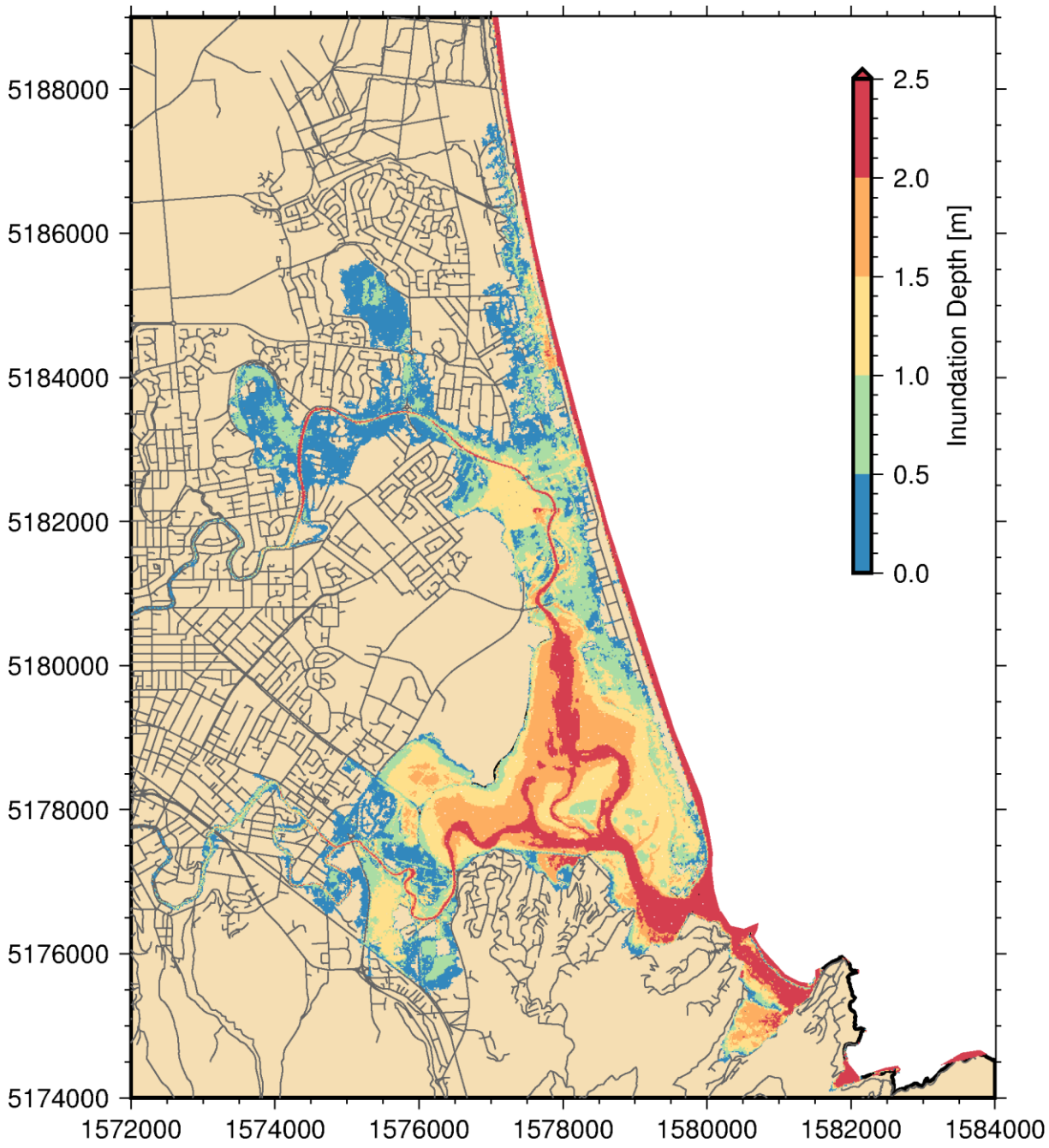

Figure 3-19: Maximum inundation depth (i.e., height above ground) for 1:500-year return period event Current Sea Level - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

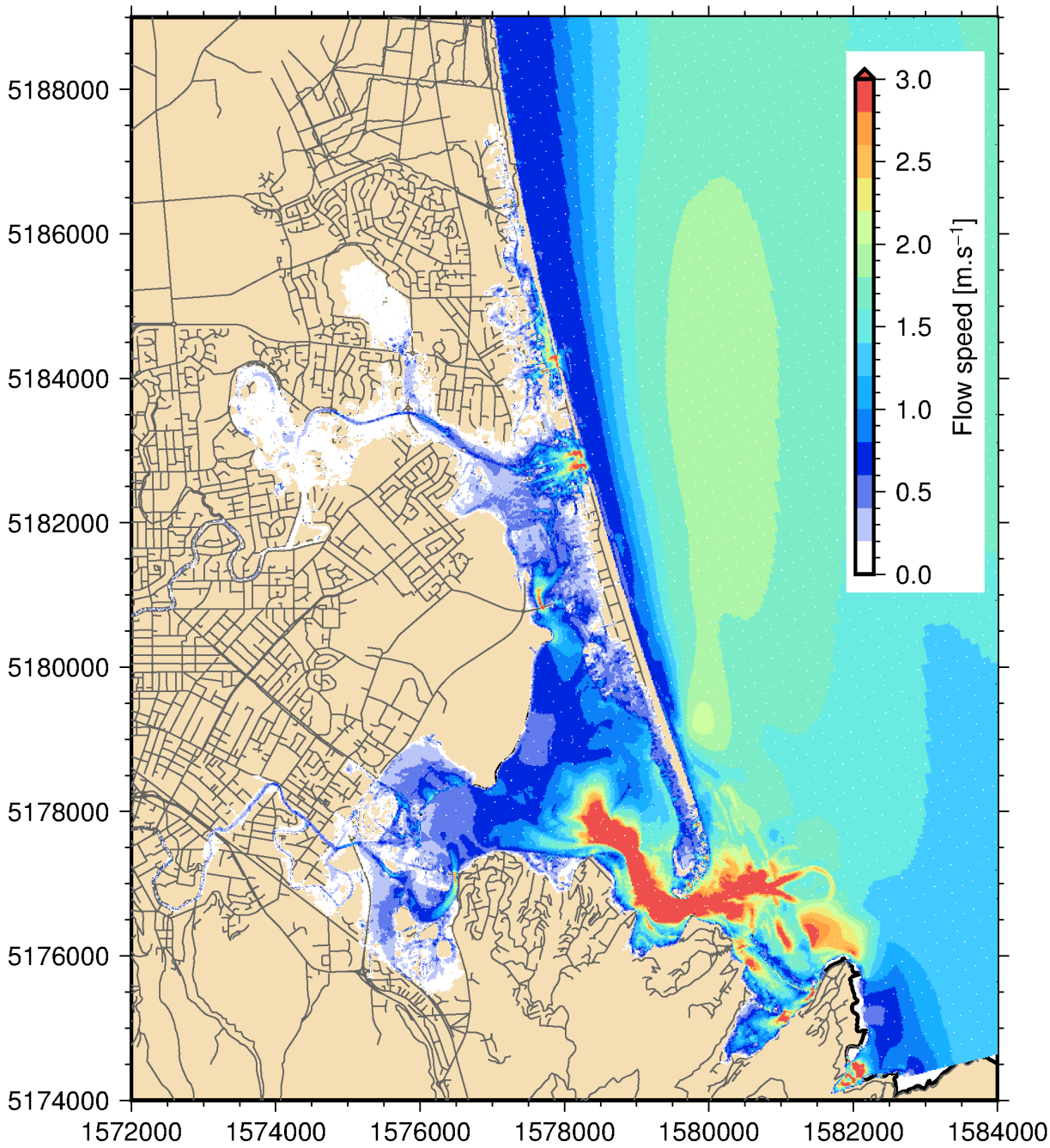

Figure 3-20: Maximum flow velocity for 1:500-year return period event Current Sea Level - Southern Section.

3.2.2 1:500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise

For the 1:500-year return period tsunami at 0.19 m above present mean sea-level (2040 scenario), the inundation covers an area of 35 km^2 and reaches a maximum depth of 14 m. The inundation naturally extends further than the scenario with present day sea level (Figure 3-21 and Figure 3-23). Flow velocity patterns are similar to the present day sea-level and similar flow speeds are observed at the main bridges (Figure 3-22 and Figure 3-24).

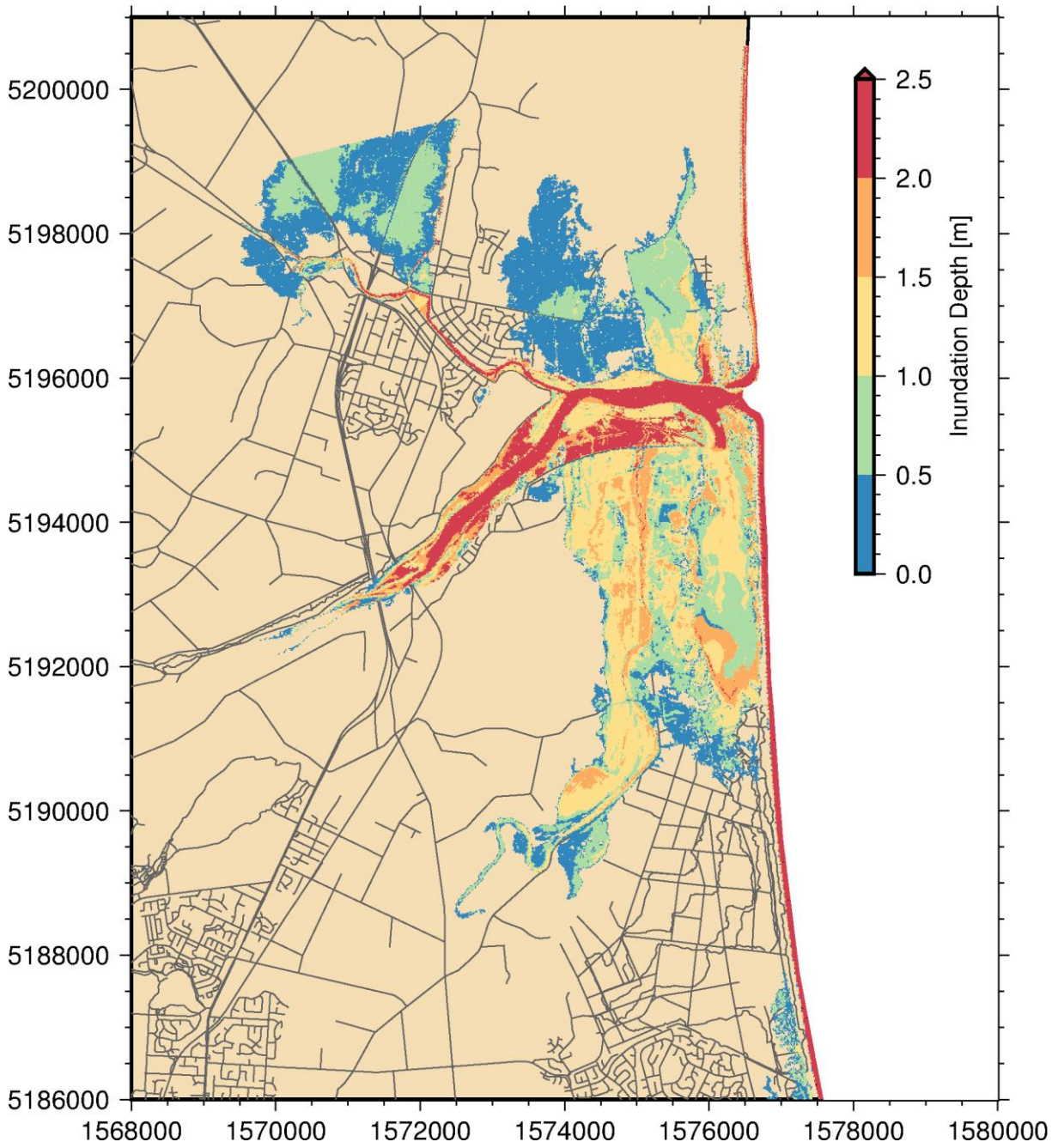

Figure 3-21: Maximum inundation depth (i.e., height above ground) for 1:500-year return period event 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

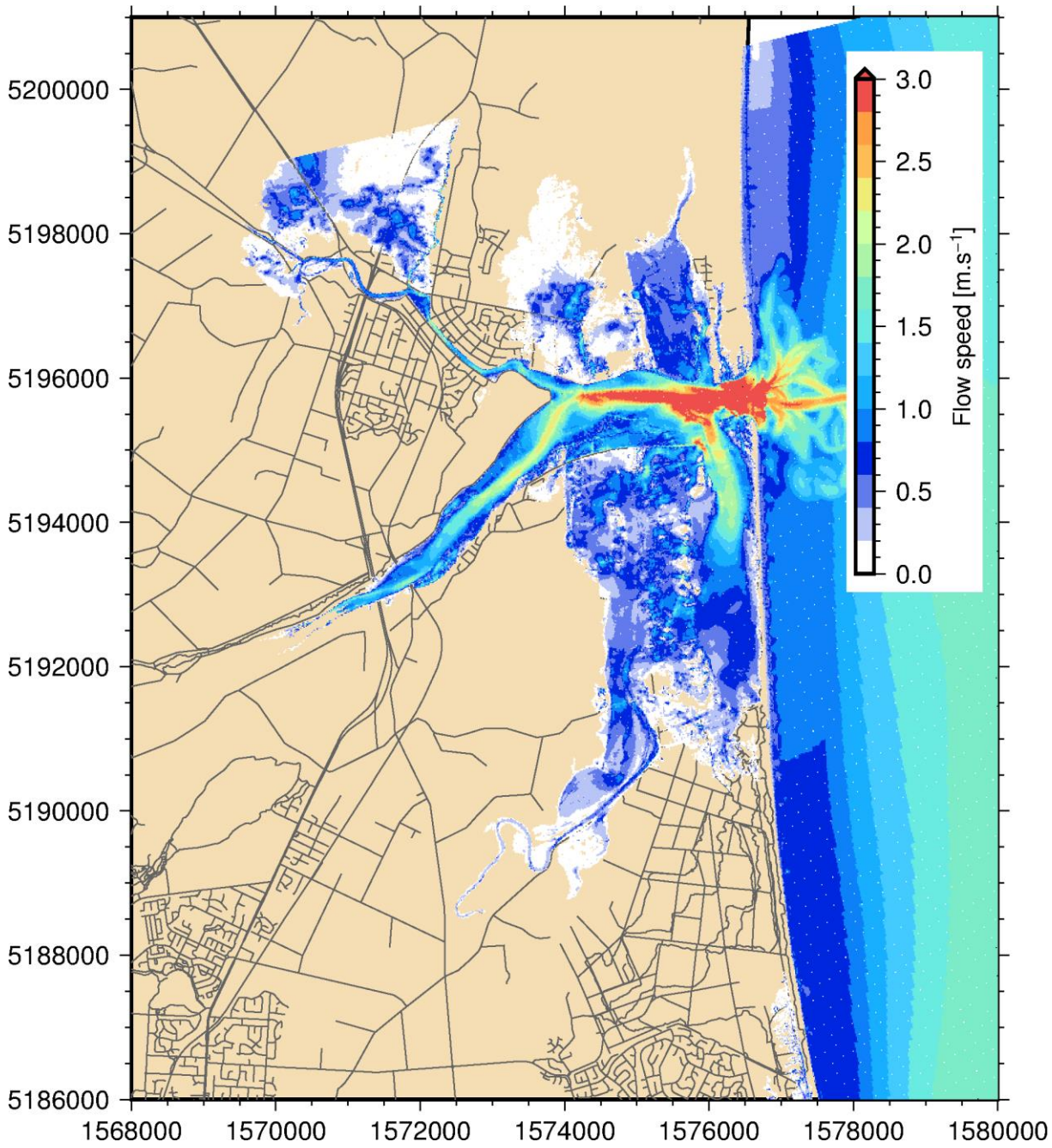

Figure 3-22: Maximum flow velocity for 1:500-year return period event 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Northern Section.

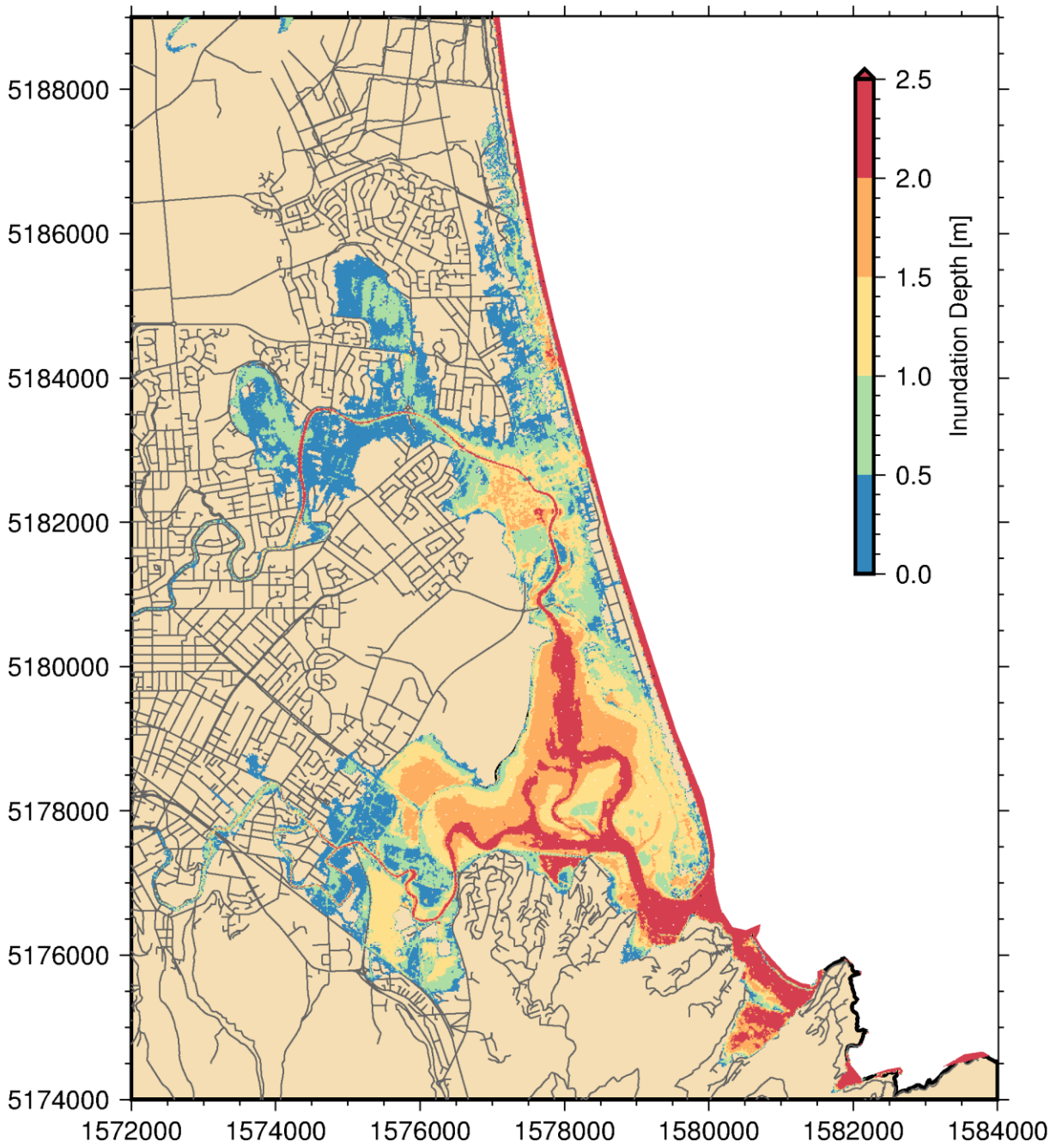

Figure 3-23: Maximum inundation depth (i.e., height above ground) for 1:500-year return period event 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

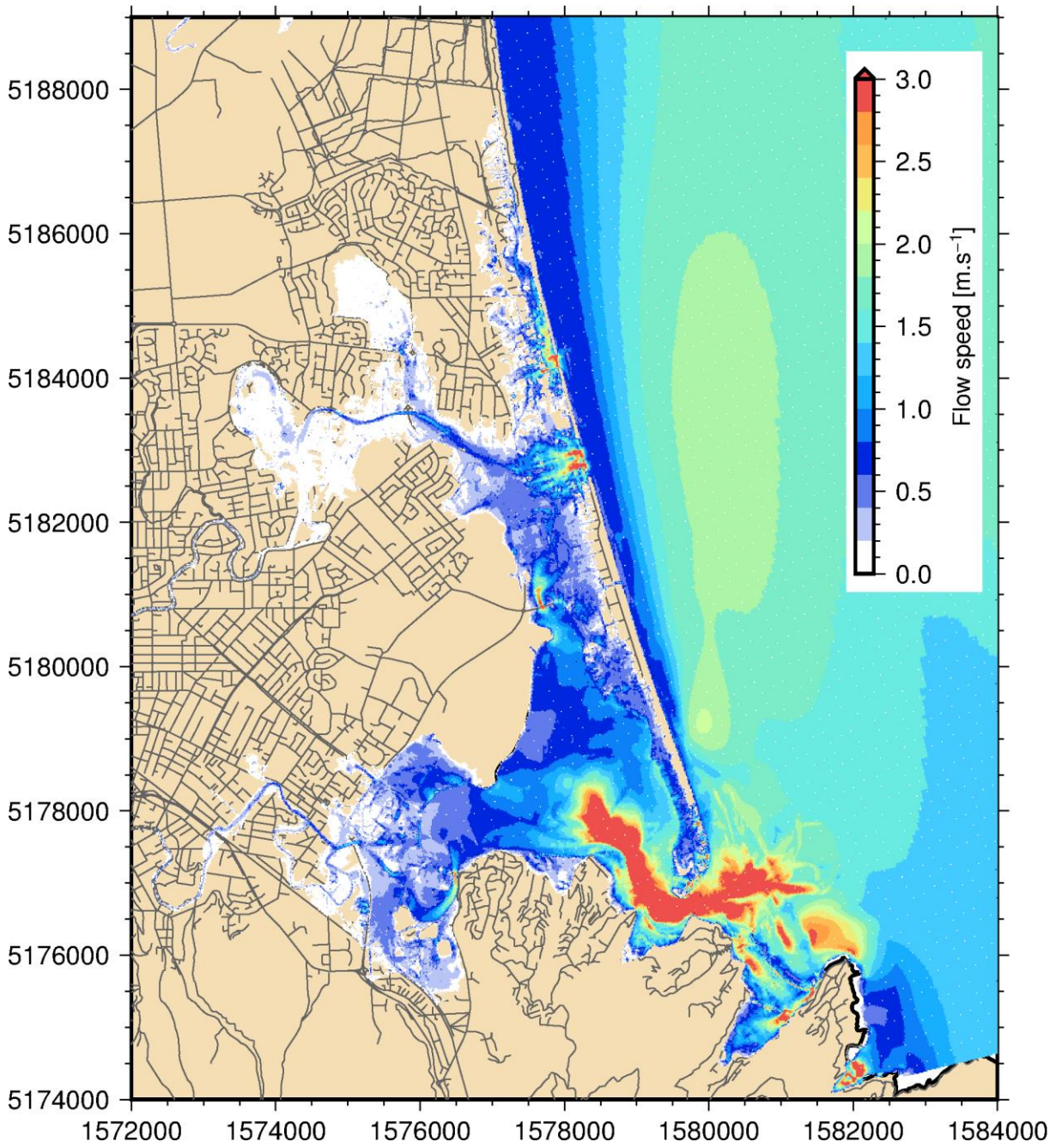

Figure 3-24: Maximum flow velocity for 1:500-year return period event 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Southern Section.

3.2.3 1:500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise

Inundation extent for the 1:500-year return period tsunami at 0.41 m sea-level rise (Figure 3-25 and Figure 3-27) covers an area of 39 km^2 and reaches a maximum depth of 13.5 m. Overall the flow patterns are similar (Figure 3-26 and Figure 3-28), however, more water can overtop the dunes near the New Brighton Pier than in the scenarios presented above and in the dune "breach" the flow speed exceed 4 m/s.

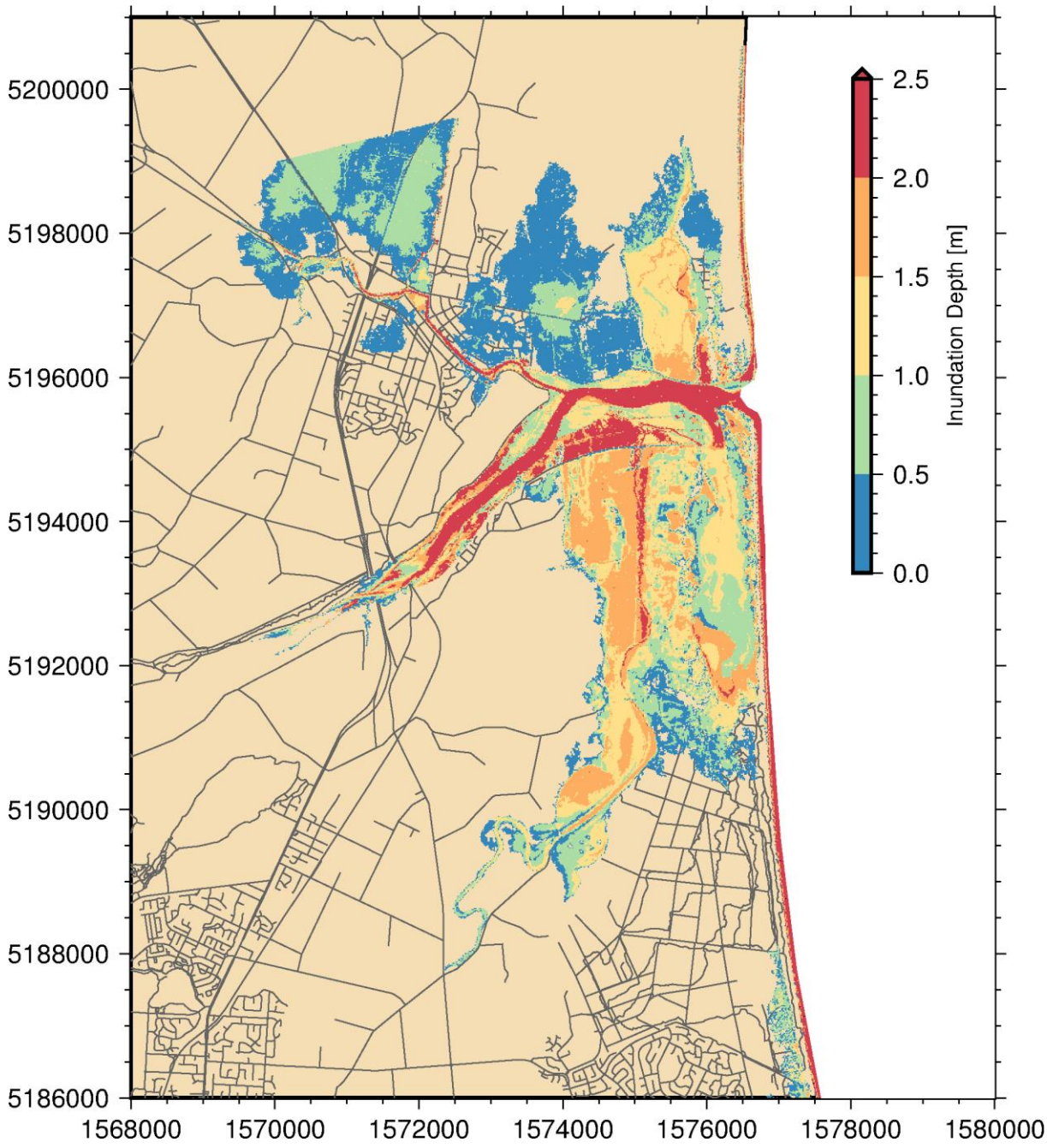

Figure 3-25: Maximum inundation depth (i.e., height above ground) for 1:500-year return period 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

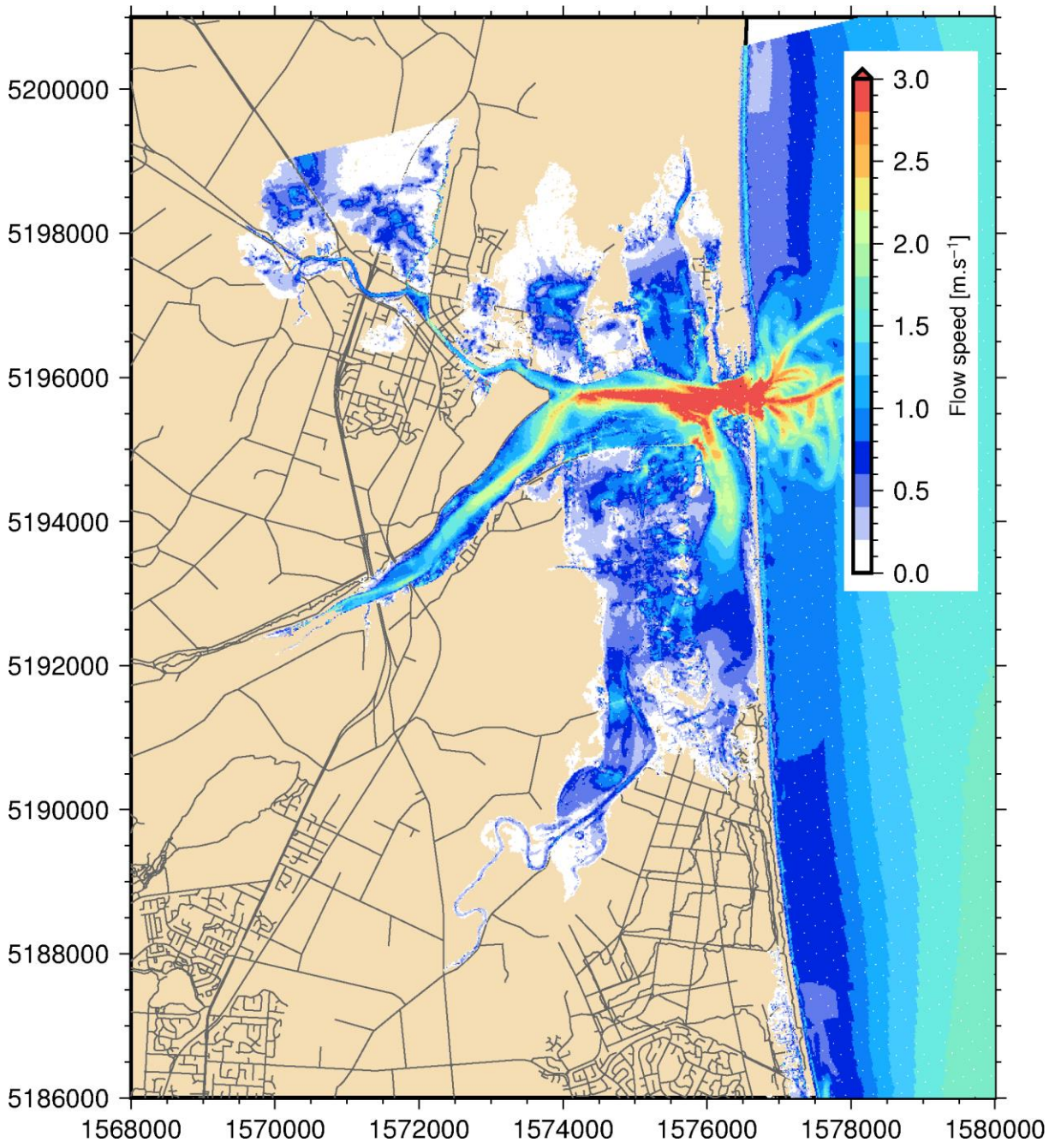

Figure 3-26: Maximum flow velocity for 1:500-year return period event 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Northern Section.

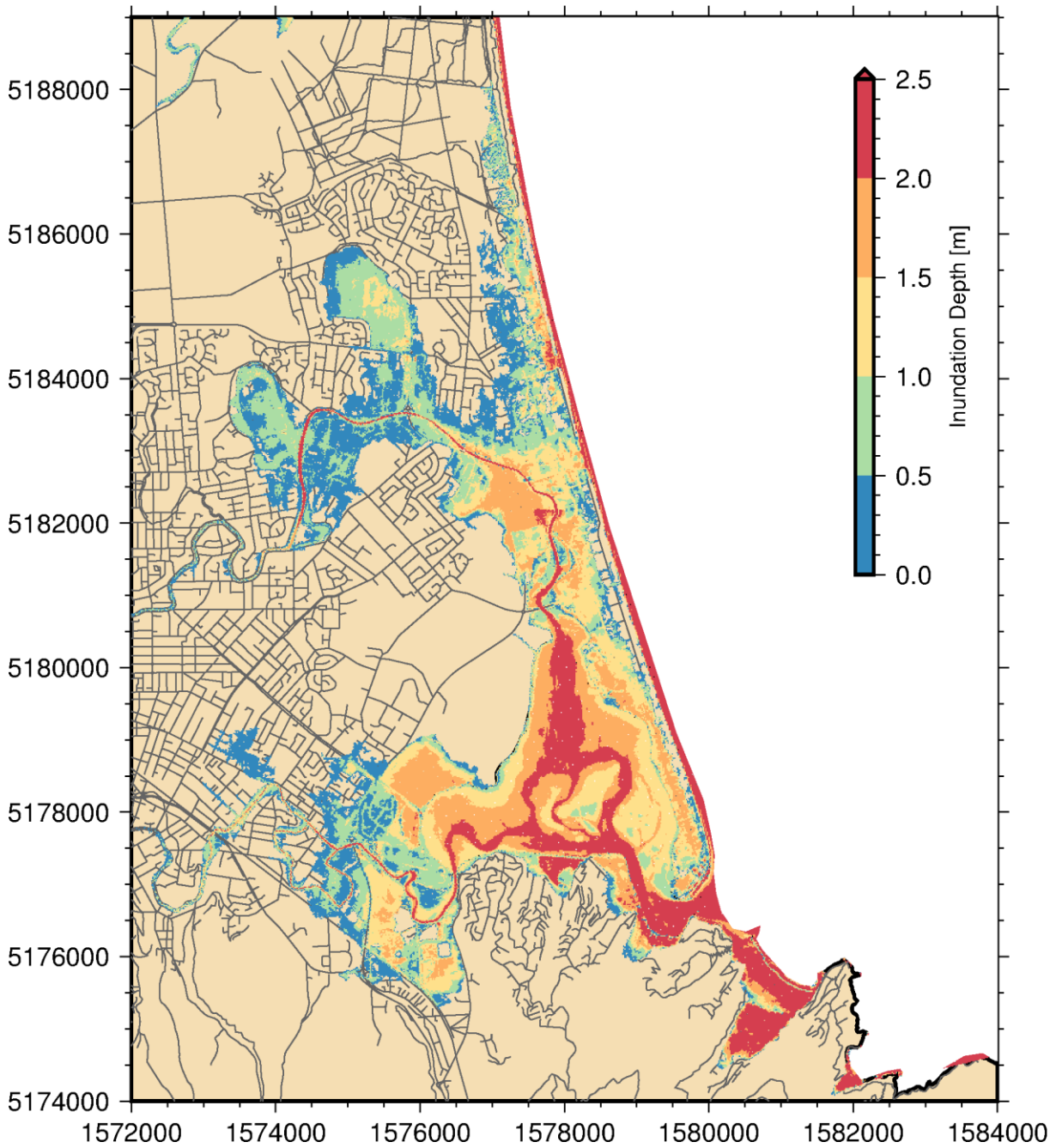

Figure 3-27: Maximum inundation depth (i.e., height above ground) for 1:500-year return period 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

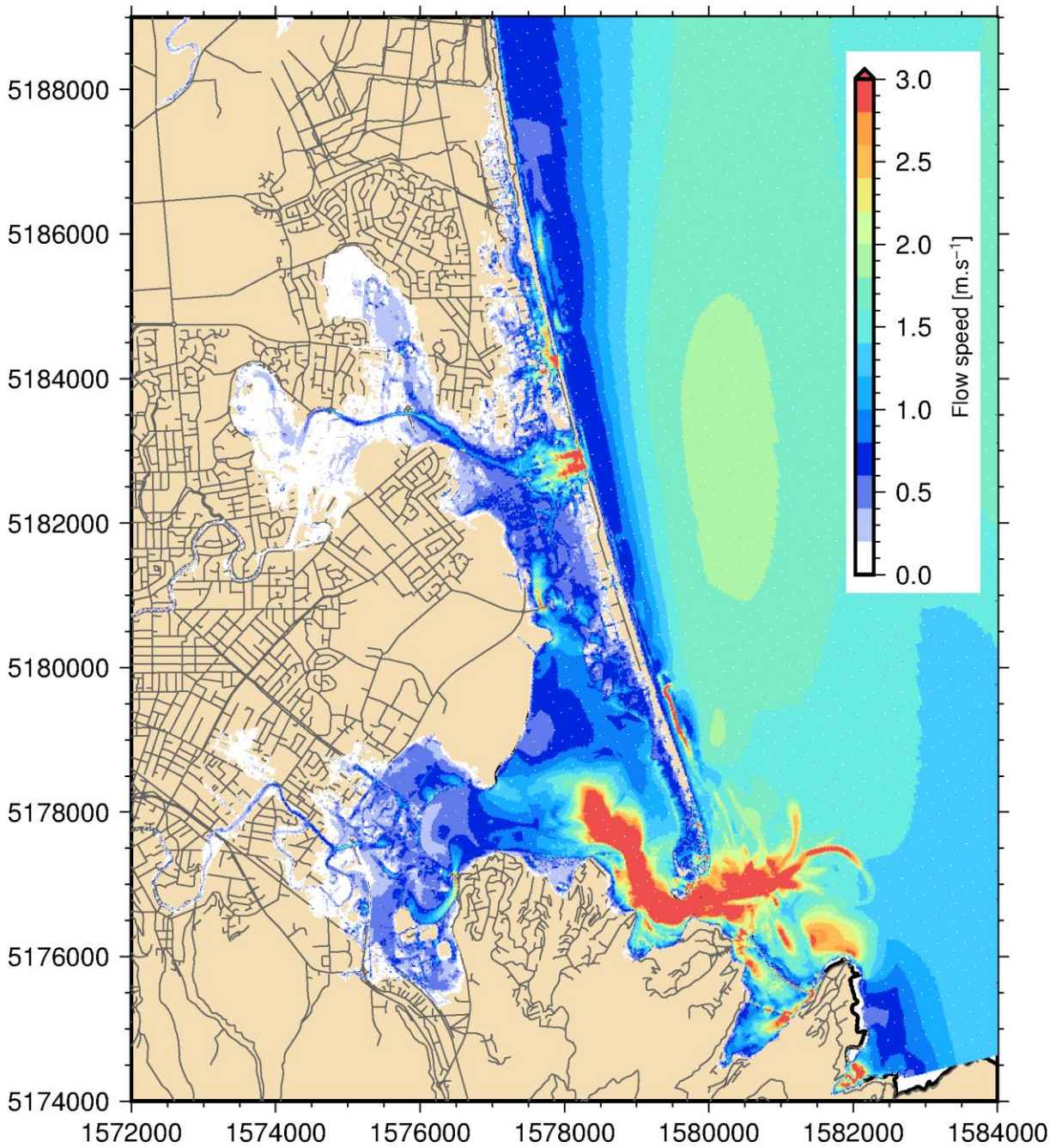

Figure 3-28: Maximum flow velocity for 1:500-year return period event 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Southern Section.

3.2.4 1:500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise

Inundation extent for the 1:500-year return period tsunami at 1.06 m sea-level rise covers an area of 53 km^2 and reaches a maximum depth of 13.0 m (Figure 3-29 and Figure 3-31). The dunes on the coastal strip are overtopped at numerous locations causing nearly continuous inundation of the dune backshore. Flow velocity does not increase at the main bridges but increases in the flooded area (e.g., South New Brighton, over the Sumner sea-wall) (Figure 3-30 and Figure 3-32). This overtopping

would likely breach the dunes and could cause increased inundation but this is not captured in this model.

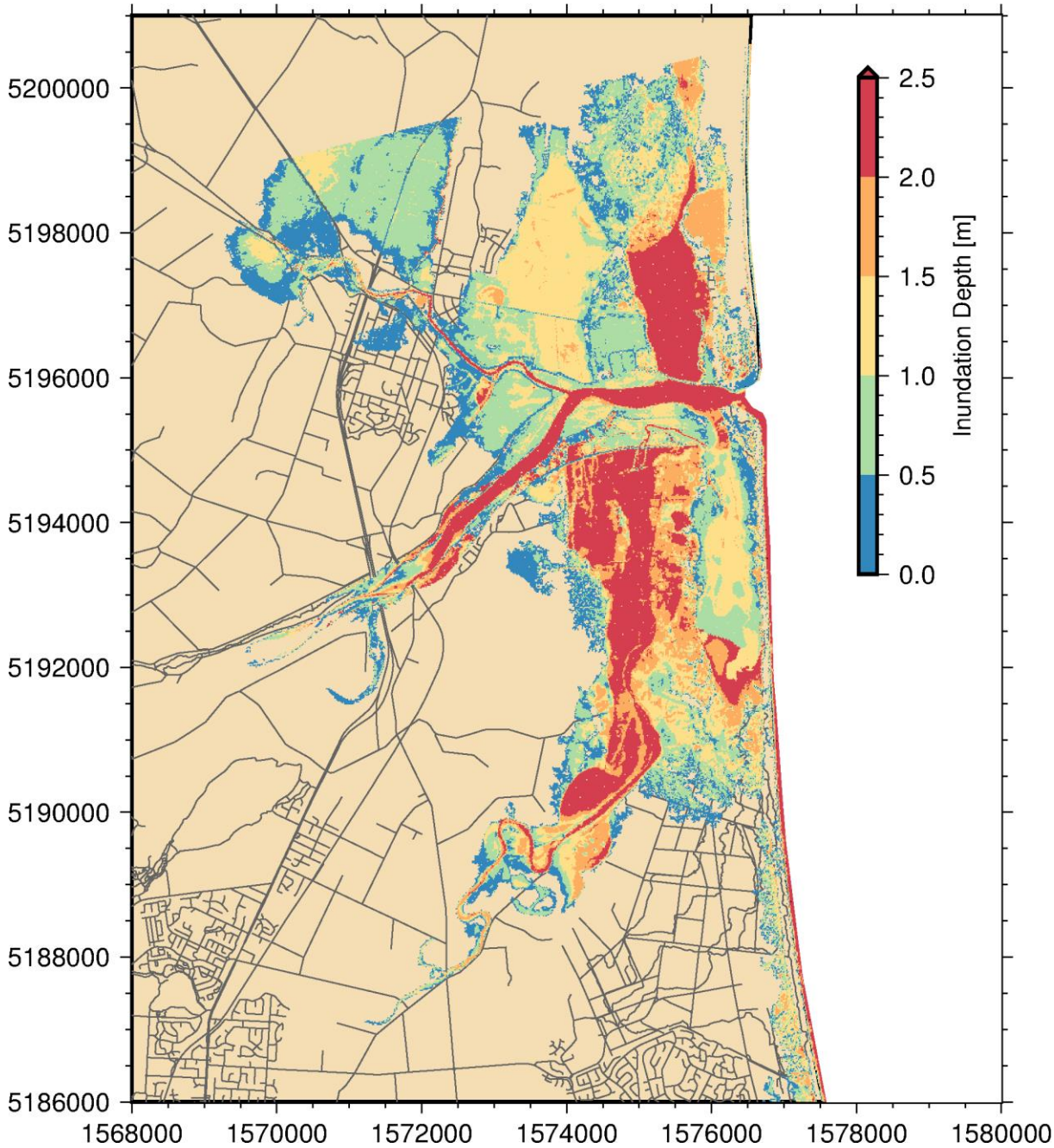

Figure 3-29: Maximum inundation depth (i.e., height above ground) for 1:500-year return period event 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

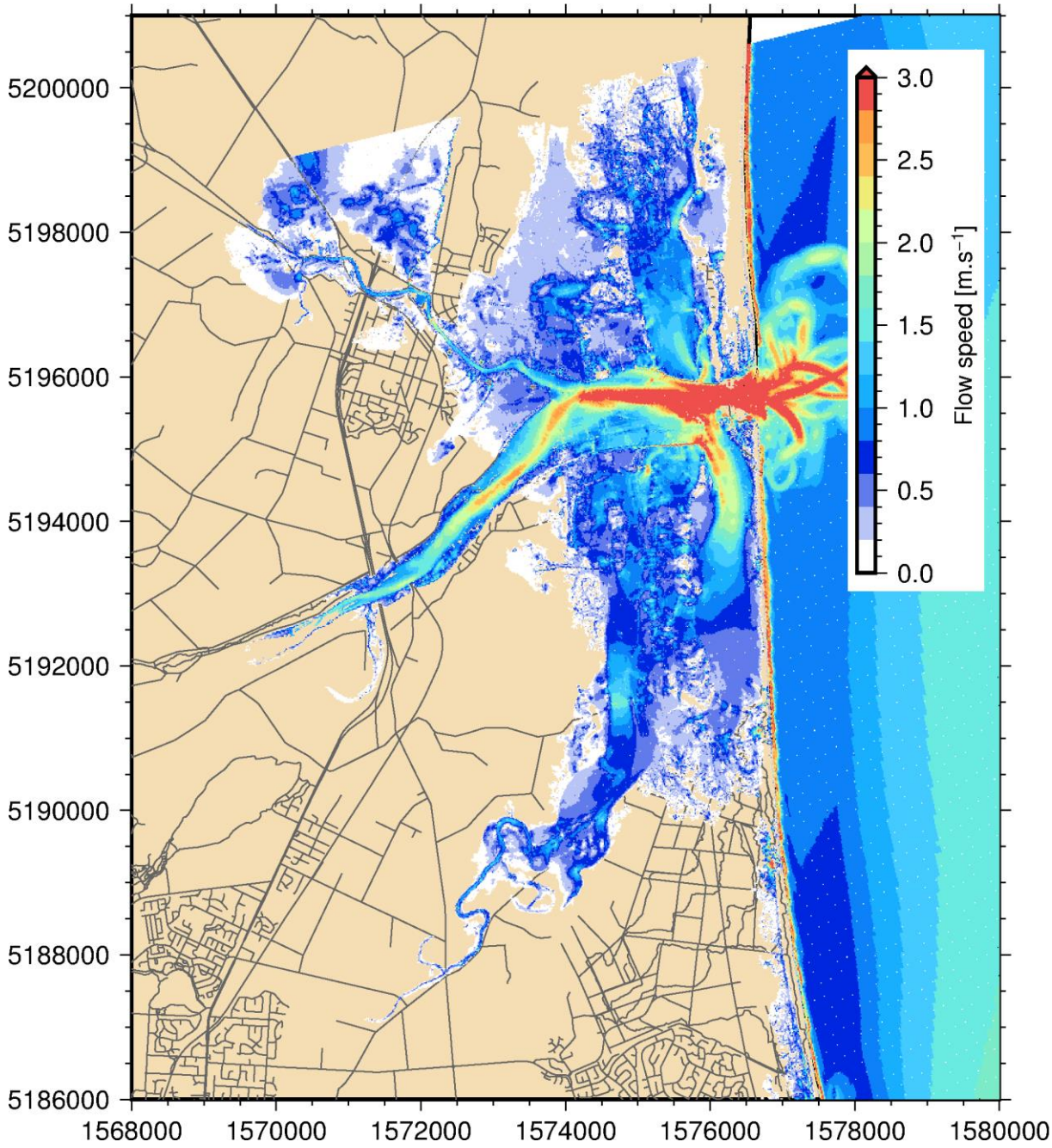

Figure 3-30: Maximum flow velocity for 1:500-year return period event 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Northern Section.

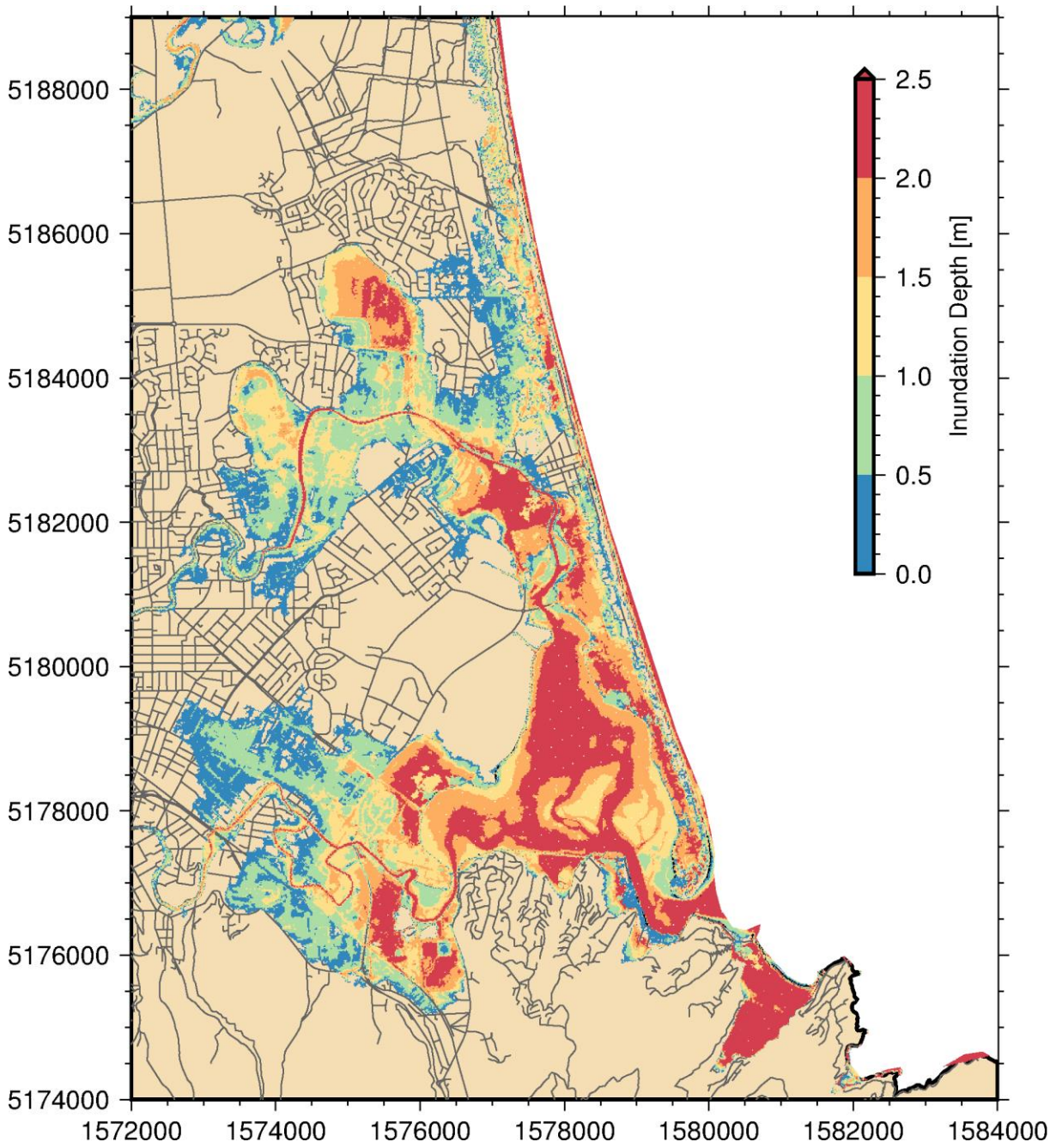

Figure 3-31: Maximum inundation depth (i.e., height above ground) for 1:500-year return period event 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

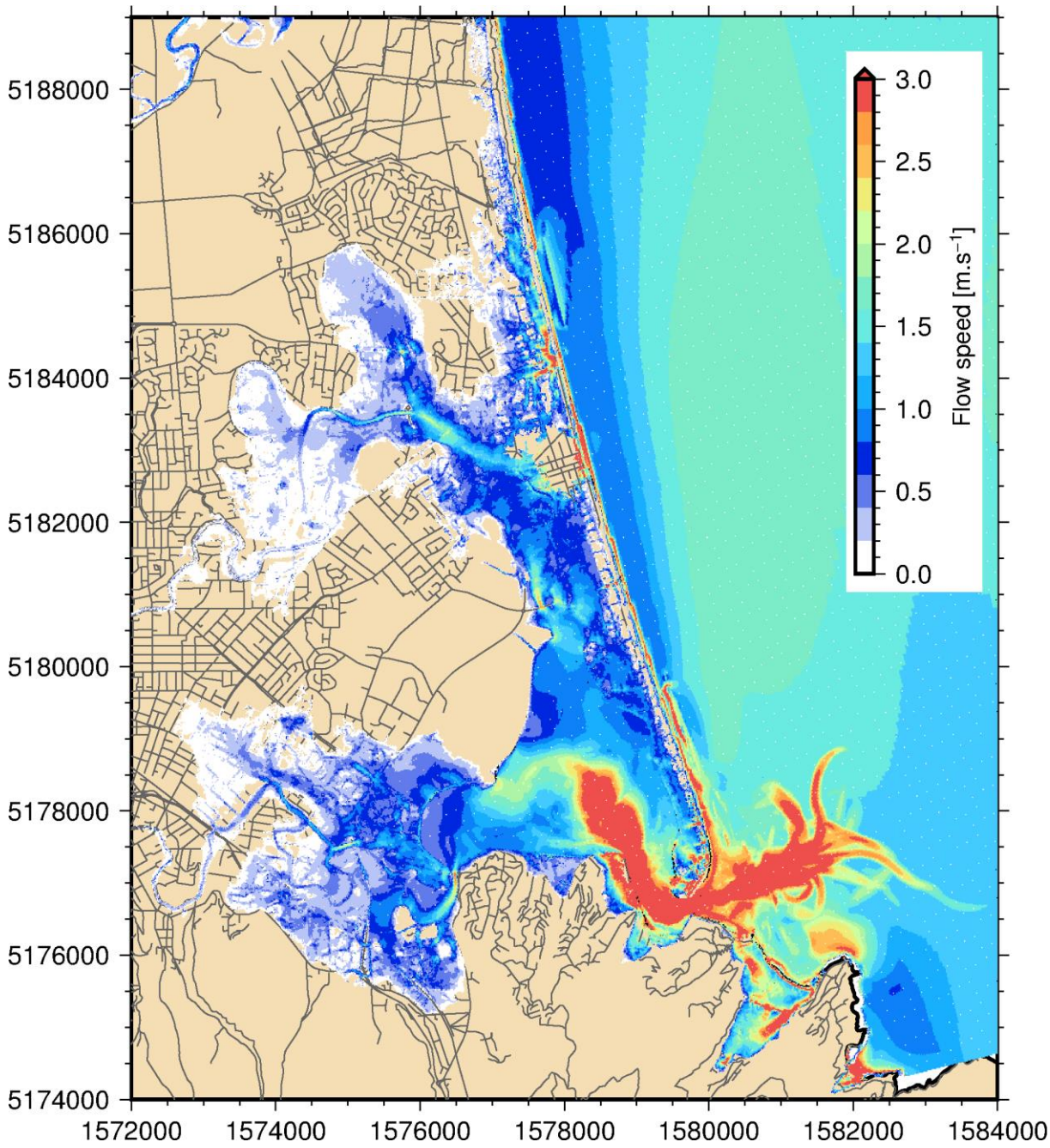

Figure 3-32: Maximum flow velocity for 1:500-year return period event 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Southern Section.

3.2.5 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise

Inundation extent for the 1:2500-year return period tsunami at 0.19 m sea-level rise covers an area of 42 km^2 and reaches a maximum depth of 15.0 m in the Waimakariri River bed. The inundation extent is comparable to the 1:500-year return period at 0.19 m sea-level but the higher inundation depth especially in the coastal strip. In this scenario the dunes along coastal strip are consistently overtopped by the tsunami waves leading to major inundation on the low-lying area of the backshore (Figure 3-33 and Figure 3-35). This overtopping would likely breach the dunes and could cause

increased inundation but this is not captured in this model. The simulated flow velocity over the dunes is also much faster than in the 1:500-year return period scenario exceeding 10 m/s at the Avon-Heathcote Estuary mouth and over the dunes in New Brighton (Figure 3-34 and Figure 3-36).

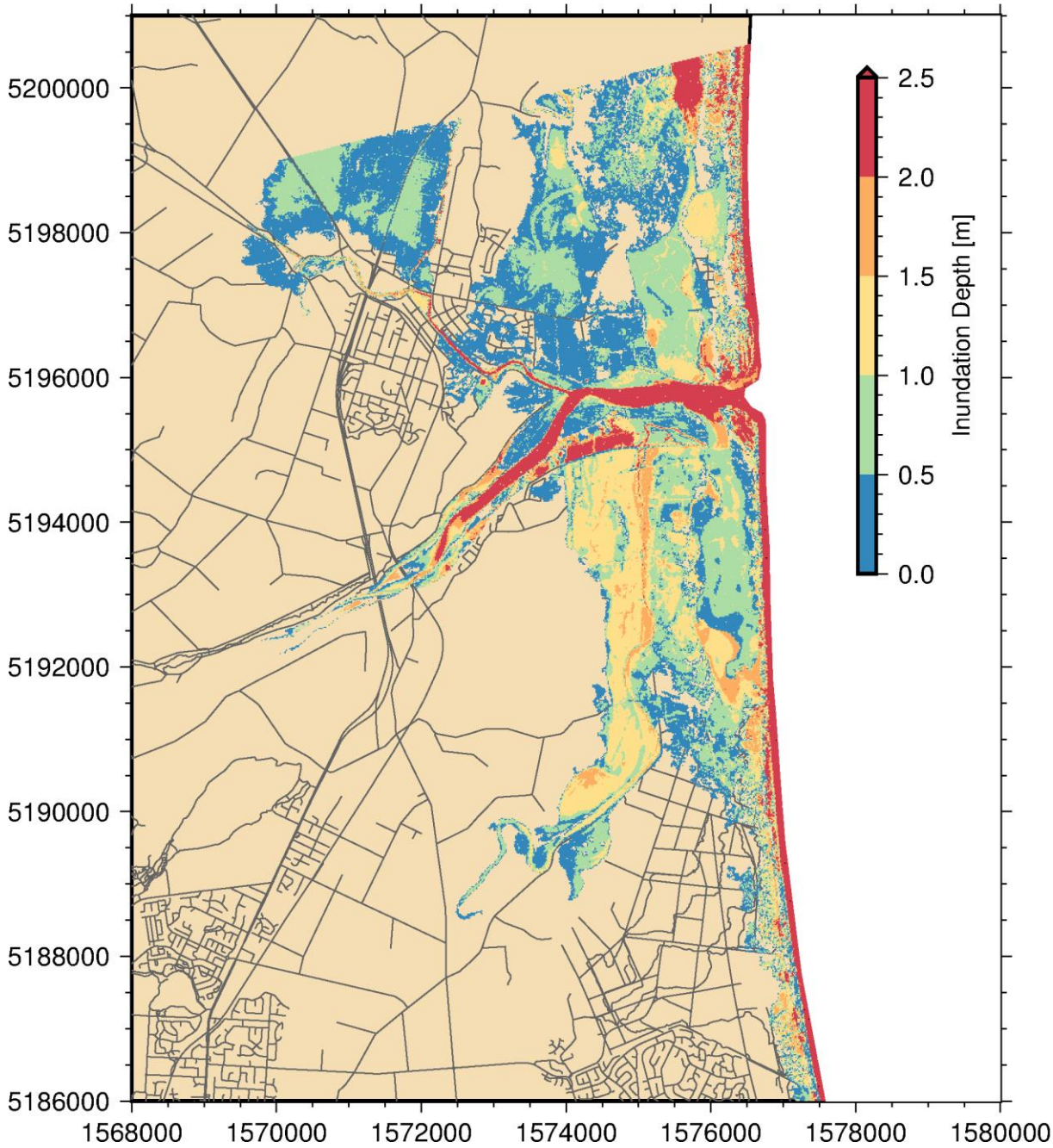

Figure 3-33: Maximum inundation depth (i.e., height above ground) for 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

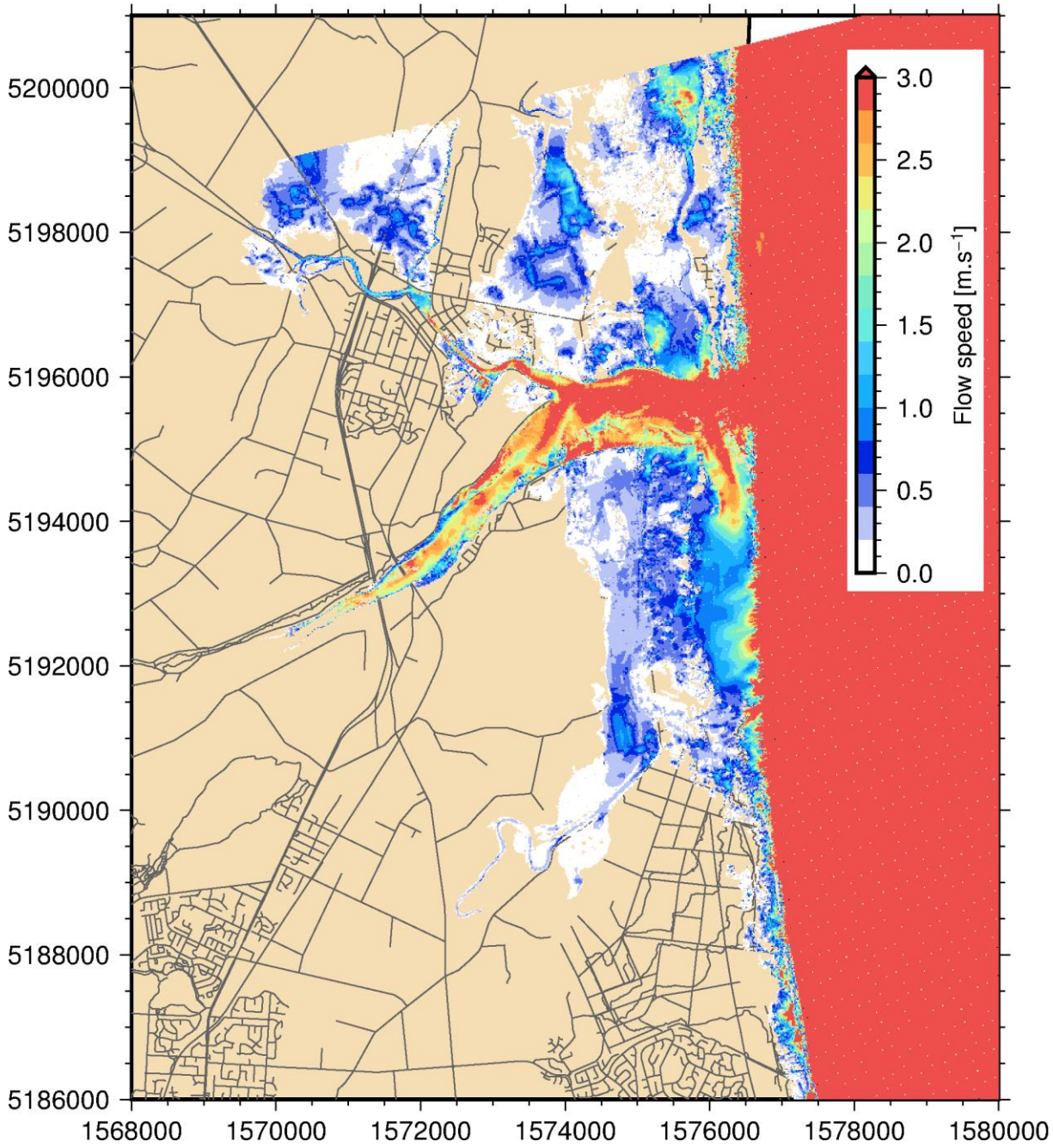

Figure 3-34: Maximum flow velocity for 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Northern Section.

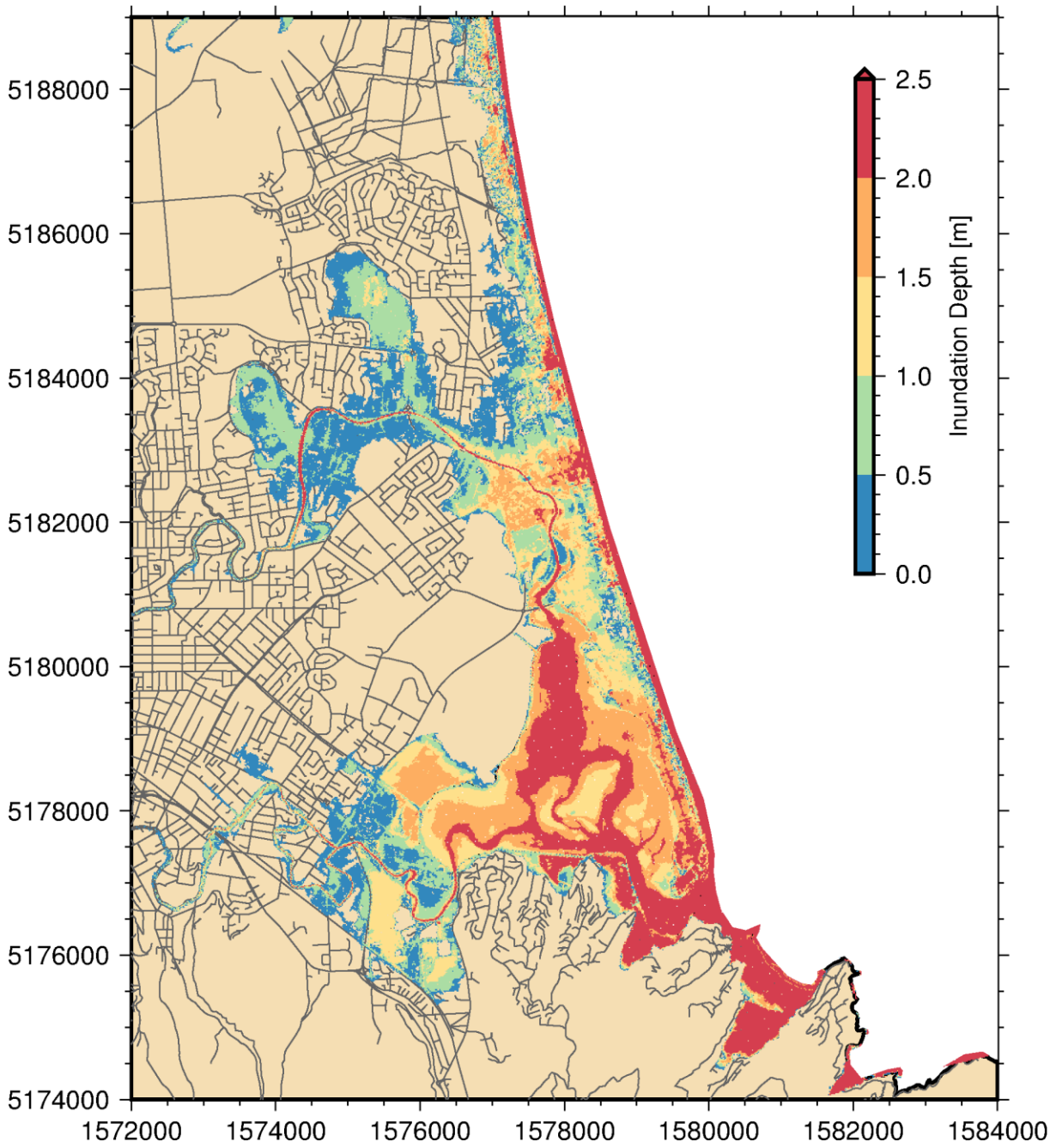

Figure 3-35: Maximum inundation depth (i.e., height above ground) for 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

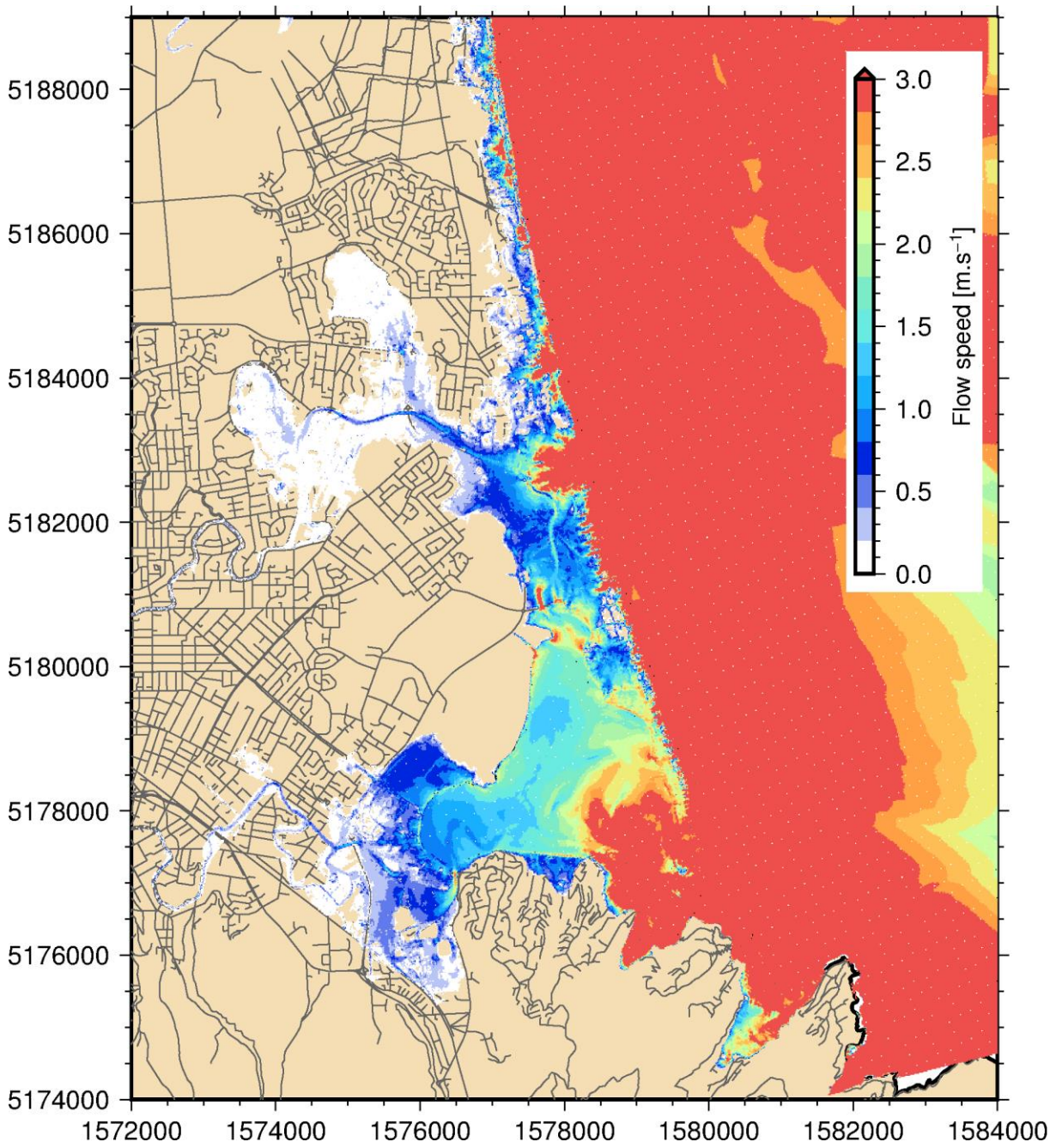

Figure 3-36: Maximum flow velocity for 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Southern Section.

3.2.6 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise

Inundation extent for the 1:2500-year return period tsunami at 0.41 m sea-level rise covers an area of 37 km^2 and reaches a maximum depth of 14.6 m in the Waimakariri River bed. The tsunami waves in this scenario is slightly diverted southward compared with the scenario at 0.19 m sea-level rise causing less inundation on the north of the Waimakariri River. In the rest of the model area the inundation is slightly larger (Figure 3-37 and Figure 3-39). As with the previous sea level scenario, the dunes along coastal strip are consistently overtopped by the tsunami waves lead to major inundation

on the low-lying area of the coastal strip with velocity exceeding 10 m/s where the dunes are overtopped (Figure 3-38 and Figure 3-40). This overtopping would likely breach the dunes and could cause increased inundation but this is not captured in this model.

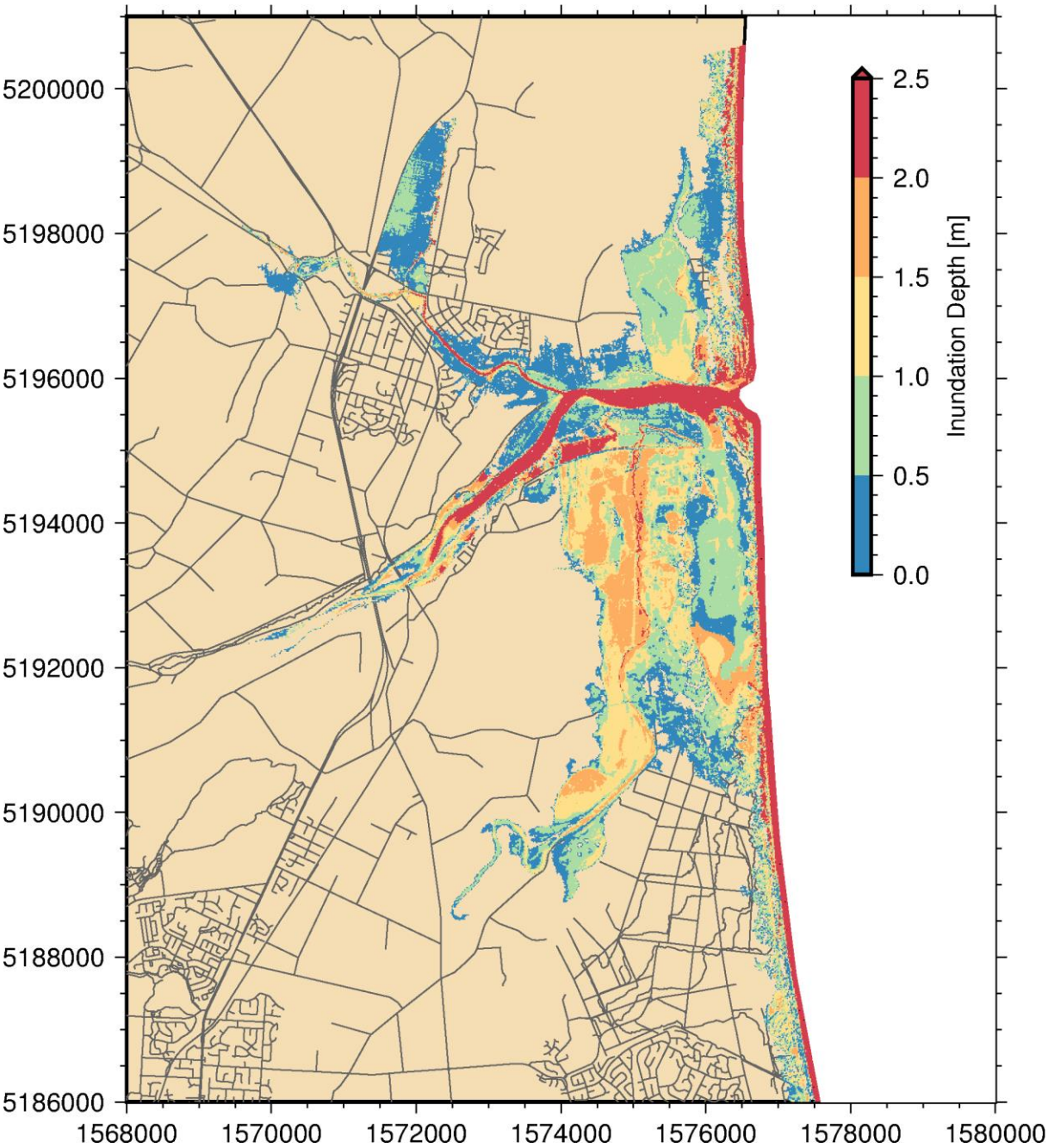

Figure 3-37: Maximum inundation depth (i.e., height above ground) for 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

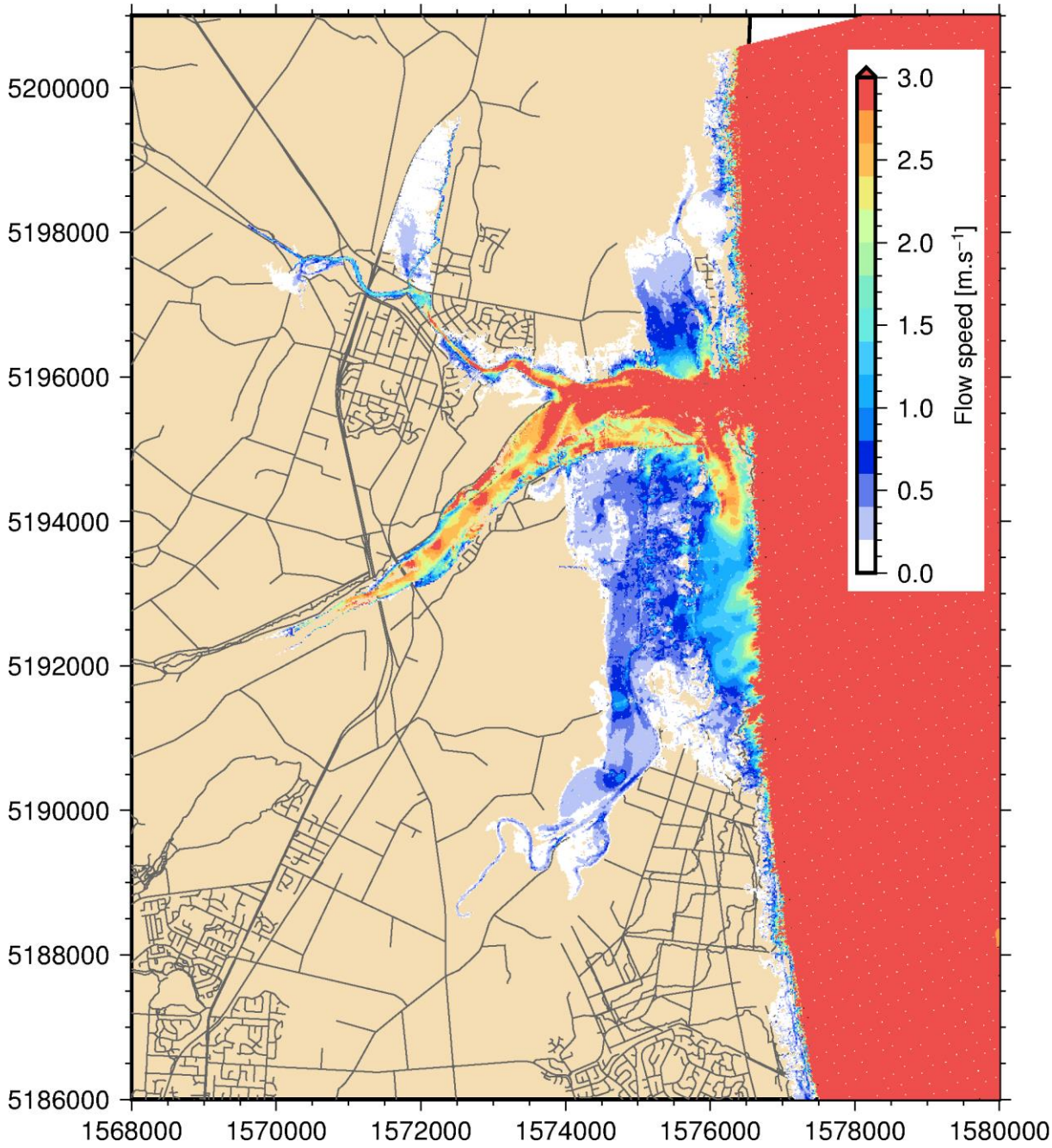

Figure 3-38: Maximum flow velocity for 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Northern Section.

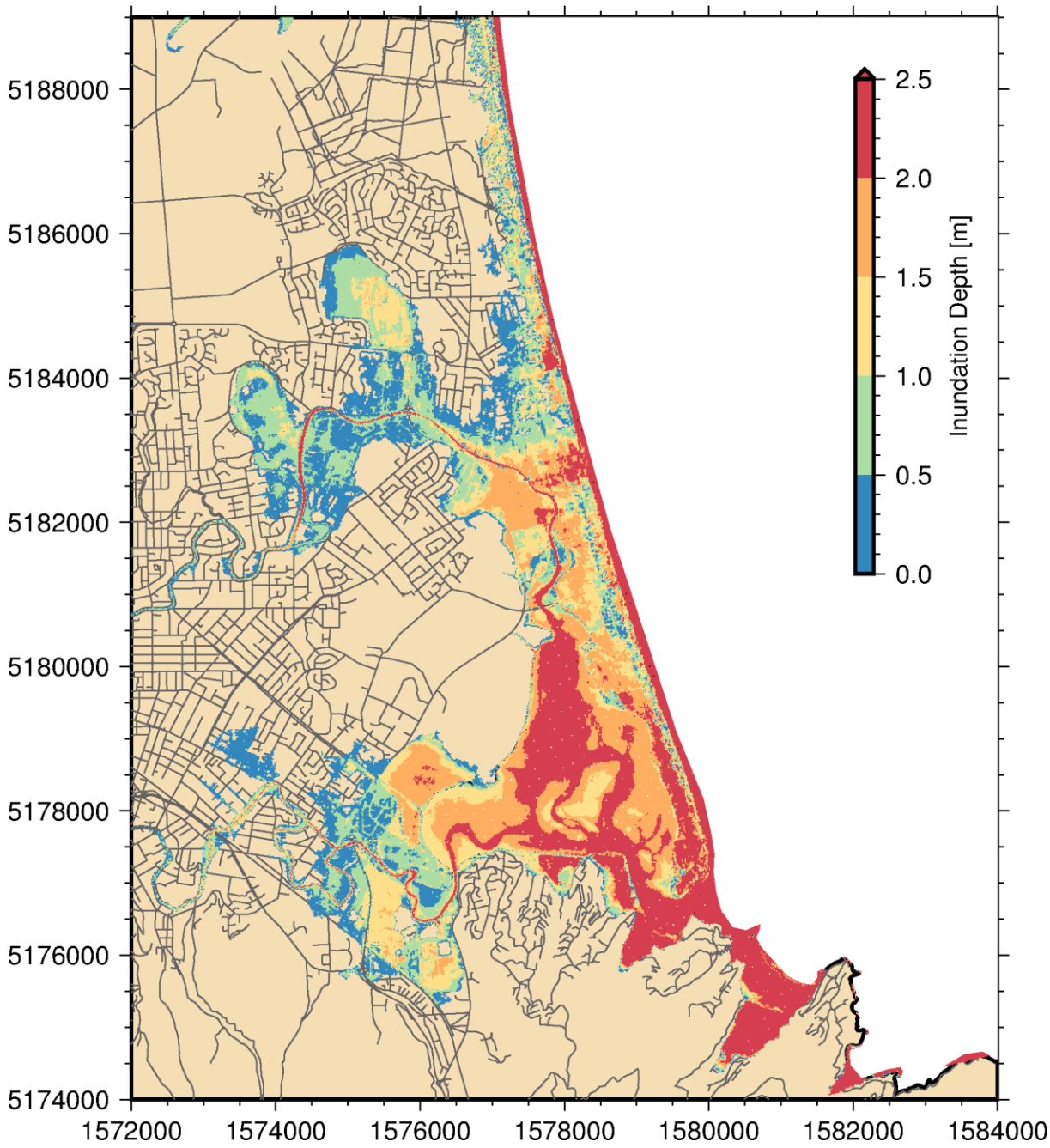

Figure 3-39: Maximum inundation depth (i.e., height above ground) for 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

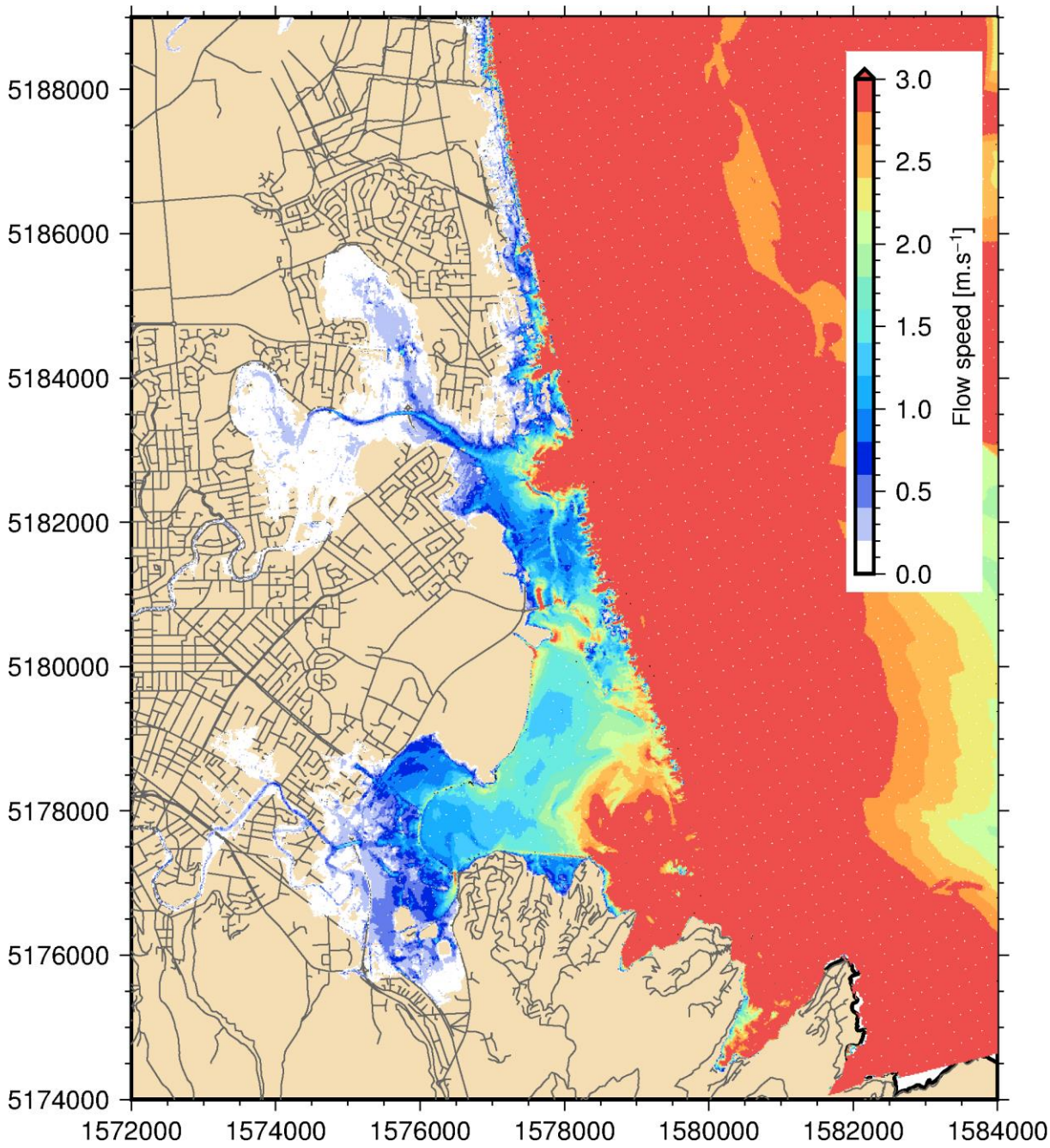

Figure 3-40: Maximum flow velocity for 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Southern Section.

3.2.7 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise

Inundation extent for the 1:2500-year return period tsunami at 1.06 m sea-level rise covers an area of 55 km^2 and reaches a maximum depth of 13.8 m in the Waimakariri River bed. As expected this scenario shows the worst inundation and largest flow velocities. However, the inundation extent is only slightly larger than the 1:500-year scenario at the 1.06 m sea level rise but with significantly larger maximum inundation depth and flow velocity (for the 1:2500-year return period scenario), especially along the coastal strip. The inundation reaches as far as the Waltham suburb on the Heathcote River and the Avonside suburb on the Avon River and covers the entire coastal strip (Figure 3-41 and Figure 3-43). Simulated flow velocities in the Avon-Heathcote Estuary exceed 12 m/s

near the entrance and 8 m/s where the dunes are overtopped (Figure 3-42 and Figure 3-44). This overtopping would likely breach the dunes and could cause increased inundation but this is not captured in this model.

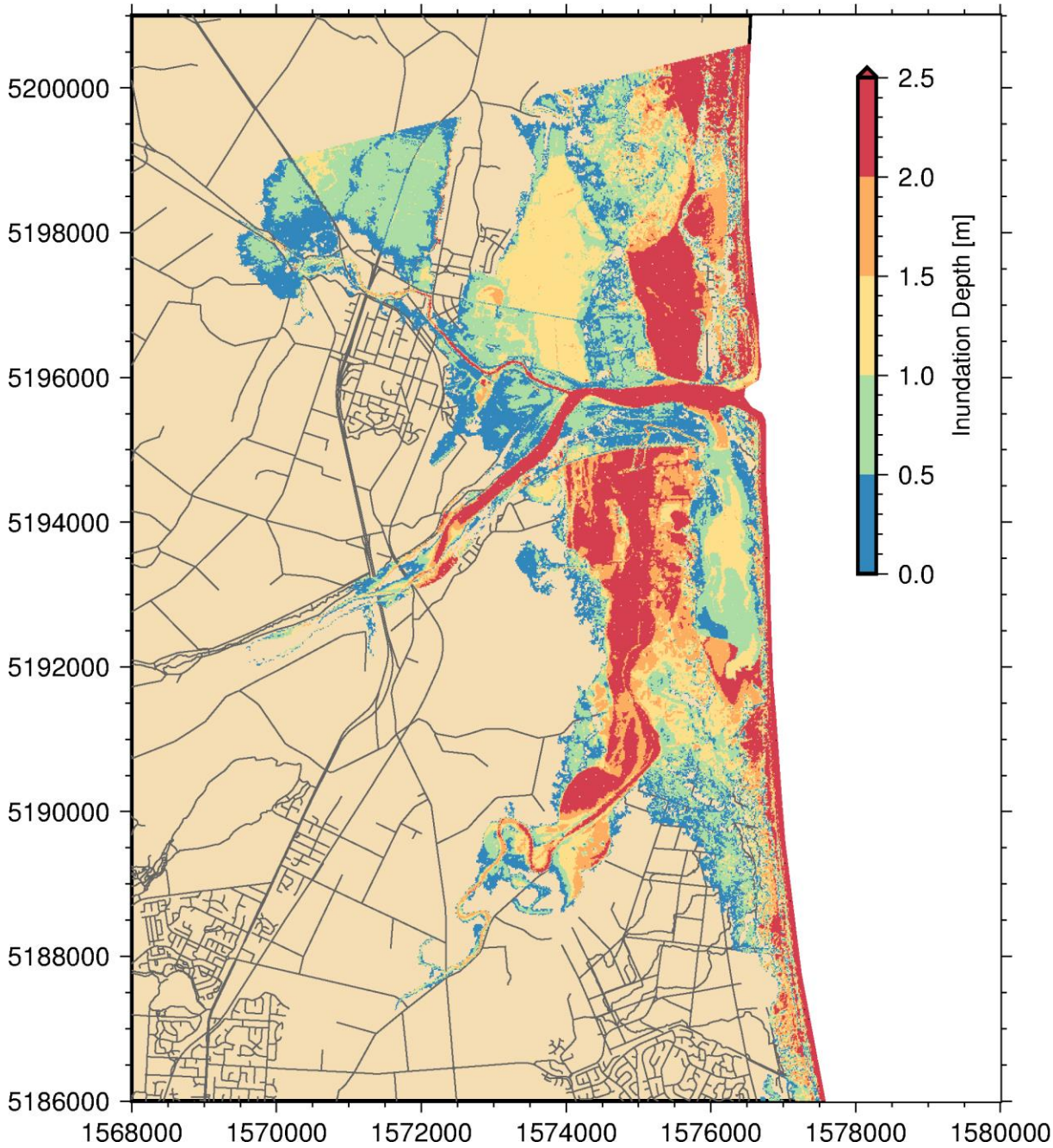

Figure 3-41: Maximum inundation depth (i.e., height above ground) for 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Northern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

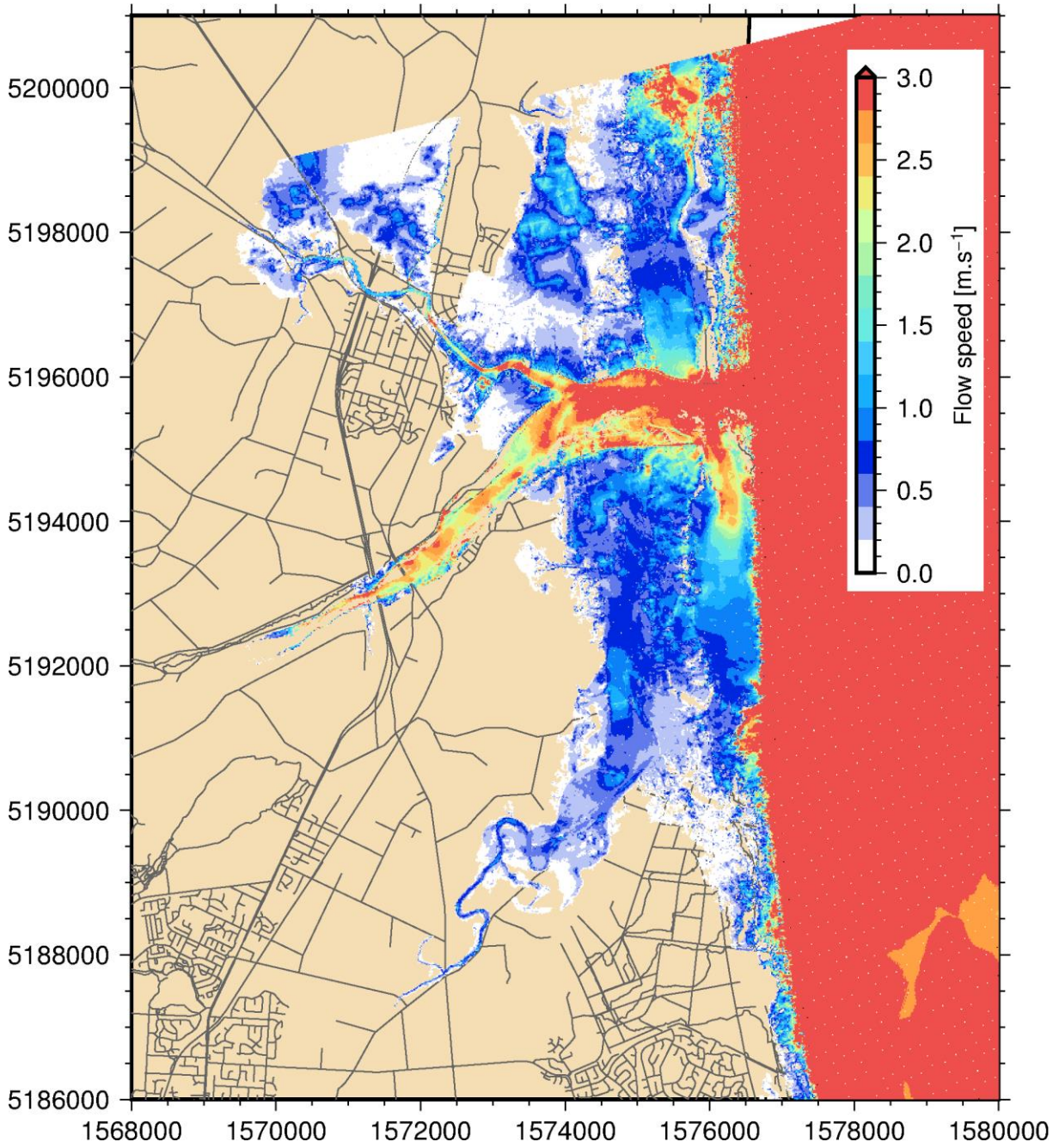

Figure 3-42: Maximum flow velocity for 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Northern Section.

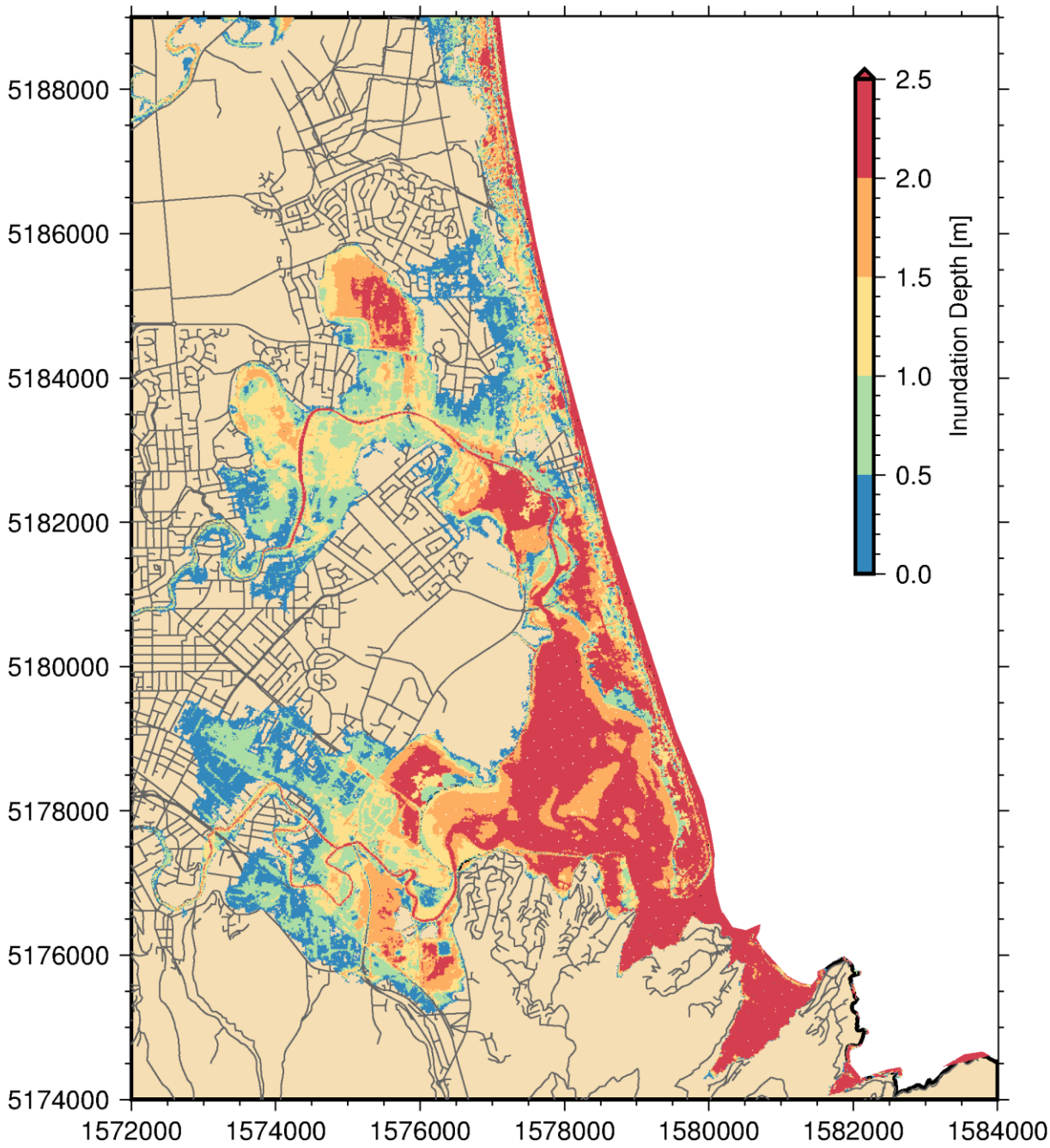

Figure 3-43: Maximum inundation depth (i.e., height above ground) for 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Southern Section. Note that for the river channels the value given is the height above the pre-tsunami water level.

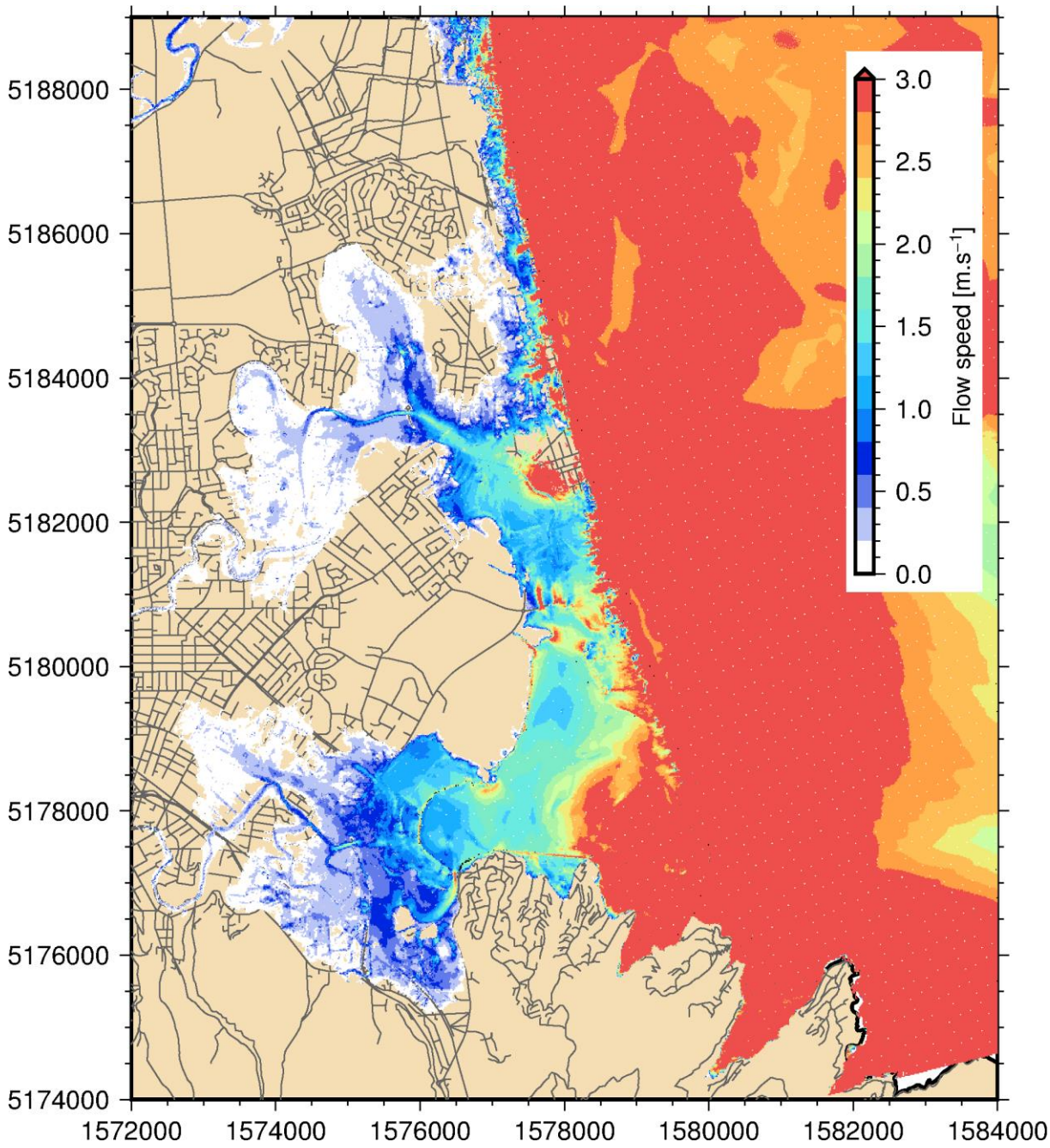

Figure 3-44: Maximum flow velocity for 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Southern Section.

3.3 Erosion

Tsunami waves can cause strong currents capable of transporting large amount of non-cohesive sediment. These high velocities predominantly occur at (but are not restricted to) the mouth of rivers and below bridges where the flow is constricted. When high flow velocities are sustained, they can cause scouring and severe erosion. The extent and depth of the erosion depends on the type of scouring, the bed sediment and other flow characteristics. Qualitatively, scouring and severe erosion is likely to occur:

- around channel bend (Bend scour)
- where flow is constricted (by debris or structures) (constriction scour)
- near weirs and drops in the topography (weir scour)
- near piers, abutments and near buildings (local scour).

Erosion potential can be evaluated using empirical relationships specific to each scour type but are designed for specific bed type with specific geometric parameters that are not directly applicable in the case of tsunami inundation. In particular, many empirical equations are available to assess the constriction scour but most of these relationships assumes that the flow upstream is restricted to a channel. These types of empirical relationships are not applicable for dune overtopping or scouring around buildings. The effect of flow constriction is calculated in the model for features that are larger than the model finest resolution (13.2 m) and the sediment transport potential is described by the flow bottom shear stress. This allow for a qualitative assessment of the locations where scouring is most likely to occur for each scenario using information of maximum bottom shear-stress, and results presented above (maximum flow velocity and maximum inundation depth). This is done on a broad scale and does not capture smaller scale scouring that may occur around buildings, small-scale structures or small-scale channels.

In all the scenario presented here, the shear-stress exceeds 30 $N.m^{-2}$ at the mouth of the Waimakariri River and at the mouth of the Avon-Heathcote Estuary (Figure 3-45 – Figure 3-58). These values far exceed the critical shear stress necessary to transport fine sand (0.14 – 0.20 $N.m^{-2}$) present there. The duration where the flow exceeds the critical shear stress for sand was not recorded in the model but major scour can be expected there.

3.3.1 1:500-year return period tsunami scenarios

For the 1:500-year return period tsunami scenario, the bottom shear-stress is also high in the area where the dune is overtopped (New Brighton, North New Brighton, South Sumner) (10-15 $N.m^{-2}$) (Figure 3-46, Figure 3-48 and Figure 3-50). This is likely to cause localised dune overwash and breach causing significant erosion and locally worsen the inundation. The shear stress further in the estuary is high on the Avon at the Bridge Street bridge (5-10 $N.m^{-2}$) and on the Heathcote River at the Ferry Road bridge (5-10 $N.m^{-2}$). There, significant scouring can be expected. At higher sea level rise scenarios, the shear-stress near these bridges is somewhat reduced as the inundation extends around the structures so the flow can go around the structure. This is likely to cause erosion around the structure but this is not captured in the model and difficult to assess. Large areas of inundation show a shear-stress lower than 1 $N.m^{-2}$ (Figure 3-45, Figure 3-47, Figure 3-49, Figure 3-51), in these areas erosion could still occur but may be localised or limited.

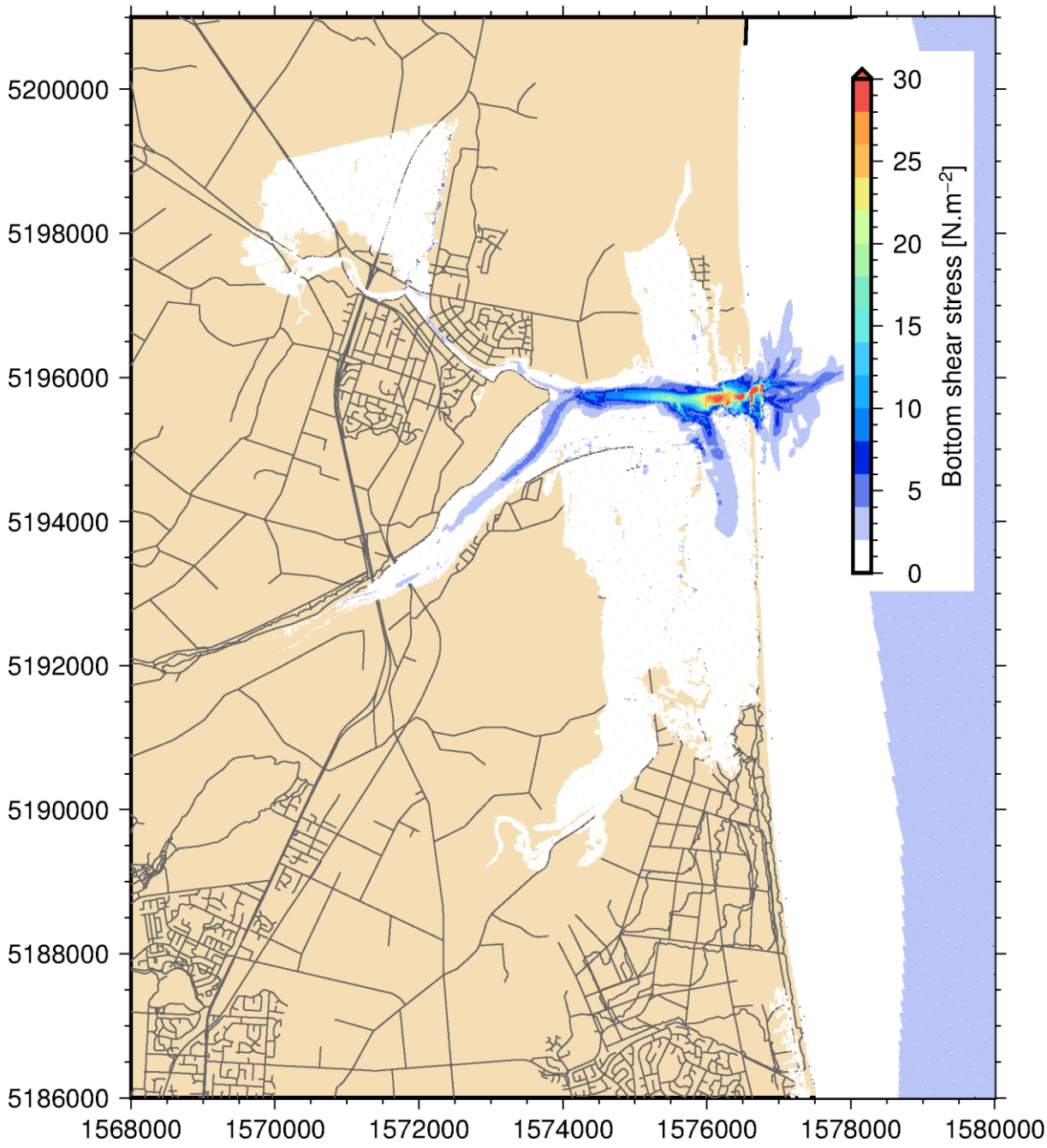

Figure 3-45: Maximum bottom shear stress for 1:500-year return period event Current Sea Level - Northern Section.

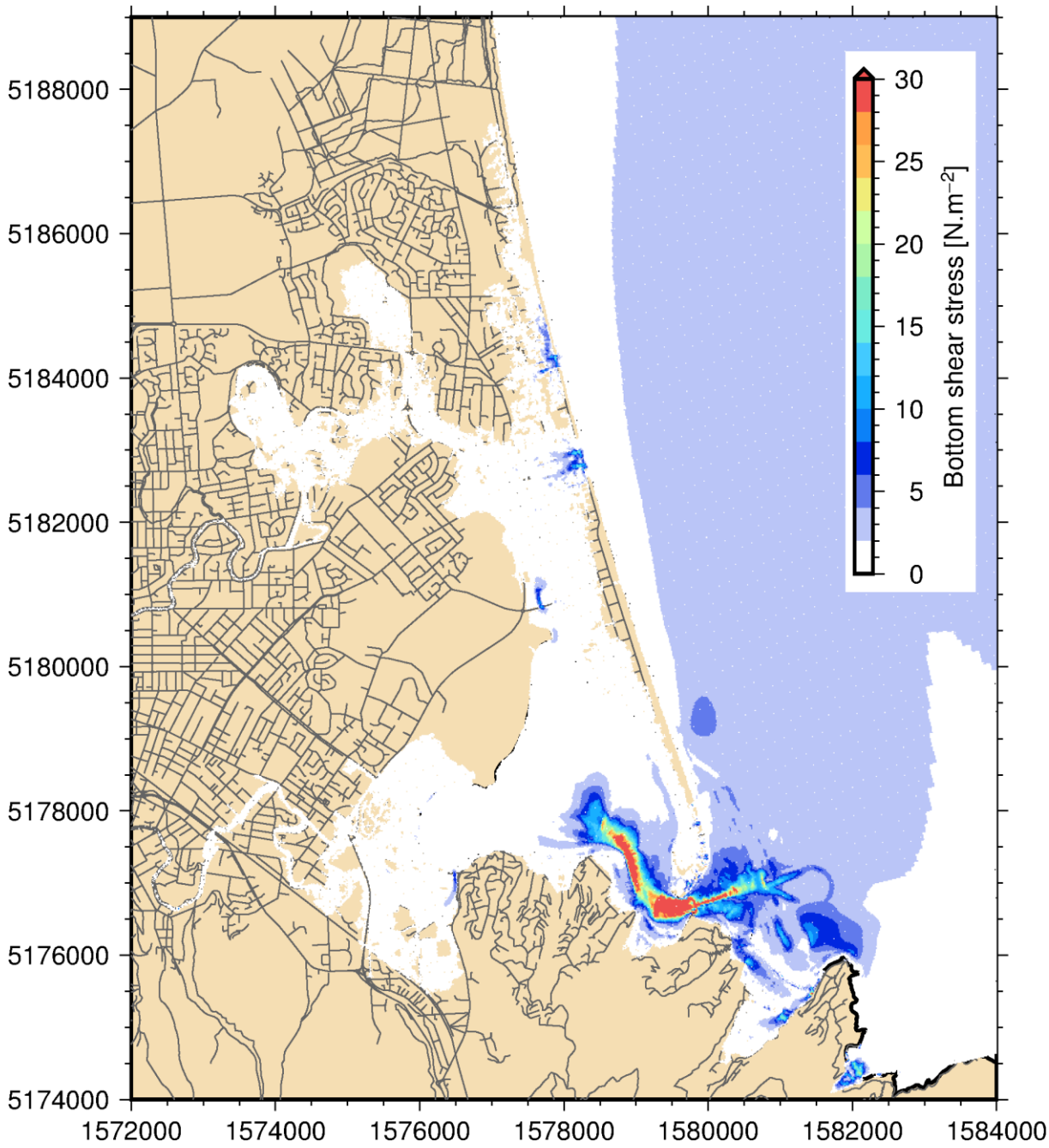

Figure 3-46: Maximum bottom shear stress for 1:500-year return period event Current Sea Level - Southern Section.

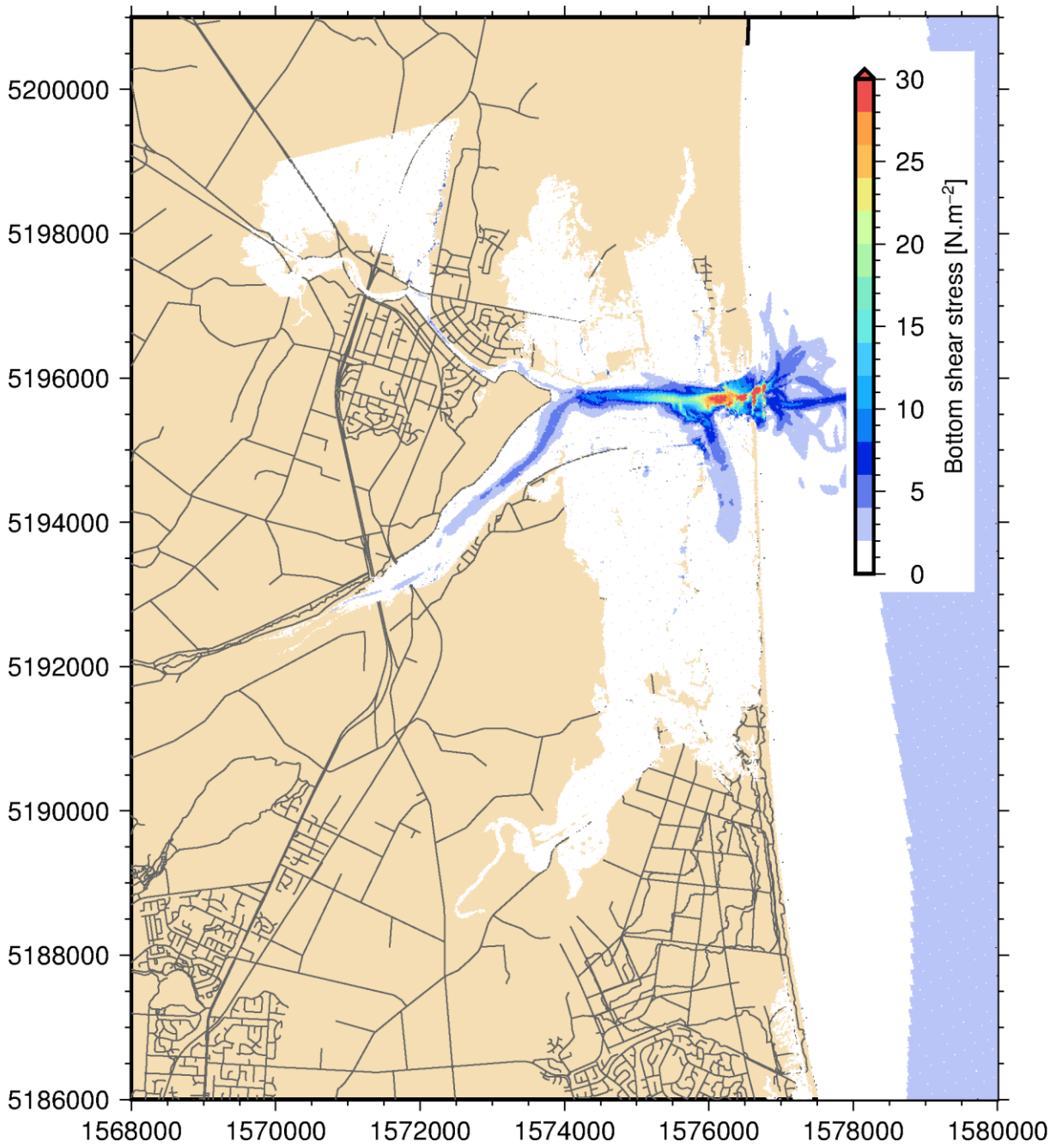

Figure 3-47: Maximum bottom shear stress for 1:500-year return period event 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Northern Section.

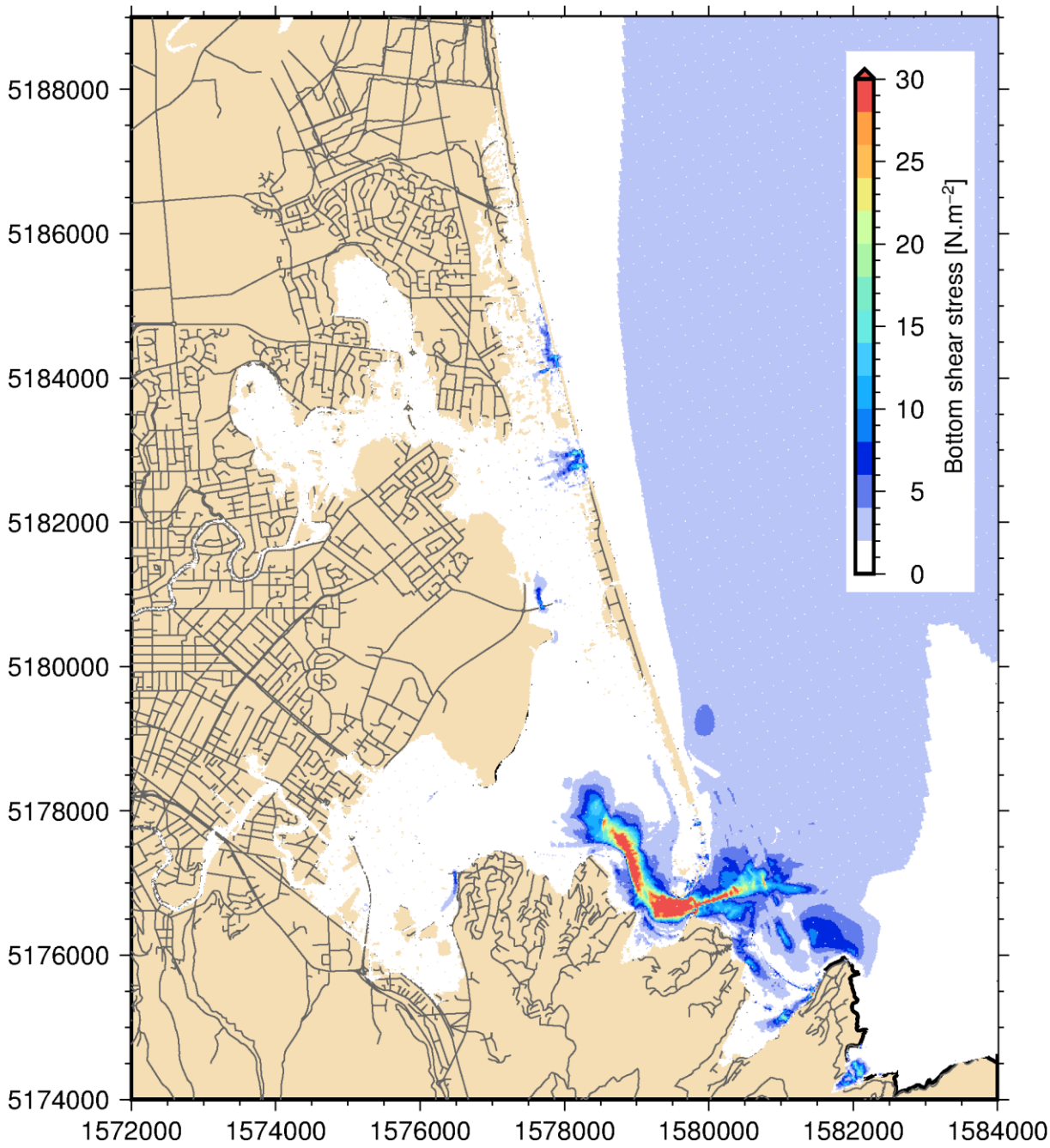

Figure 3-48: Maximum bottom shear stress for 1:500-year return period event 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Southern Section.

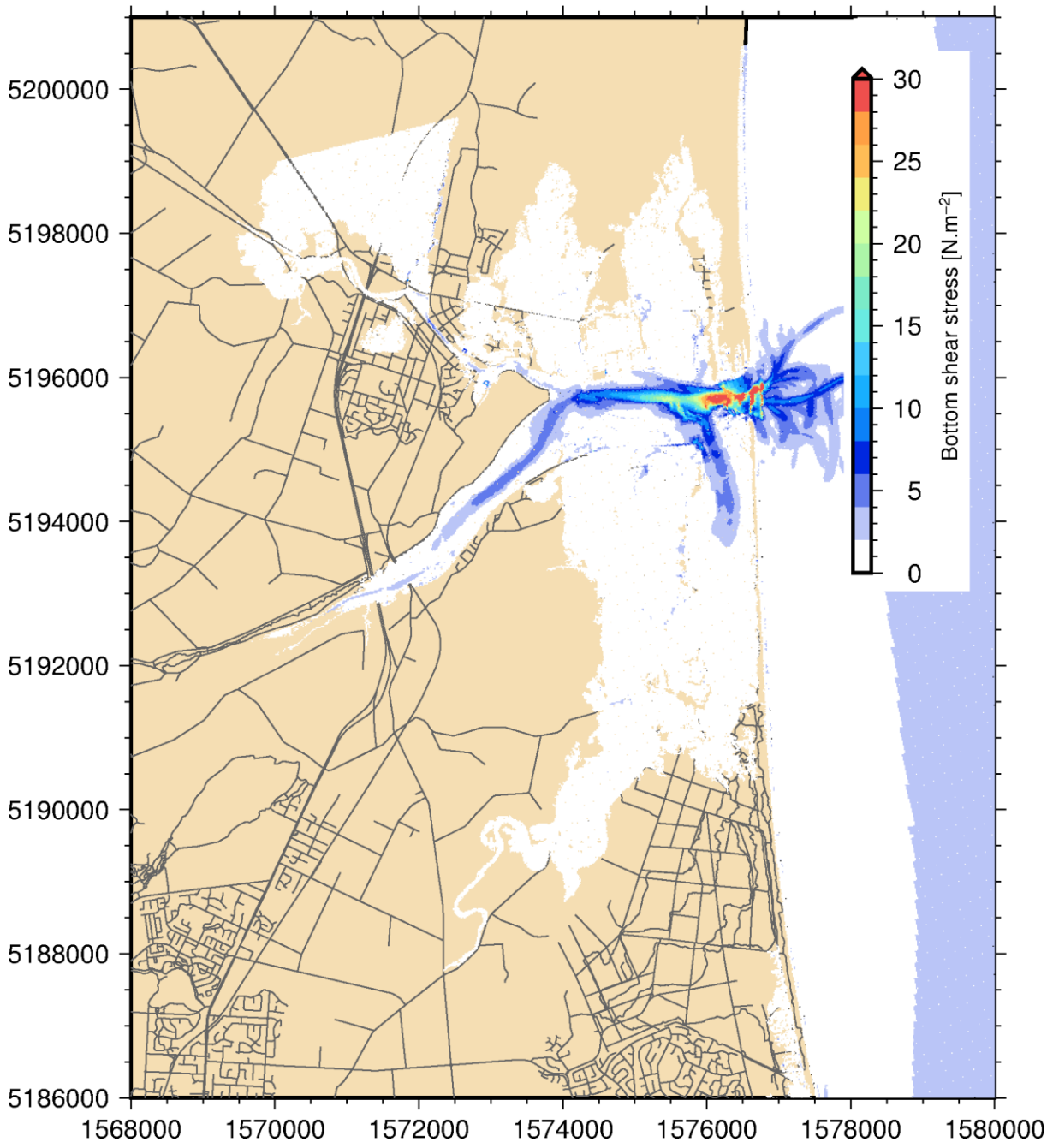

Figure 3-49: Maximum bottom shear stress for 1:500-year return period 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Northern Section.

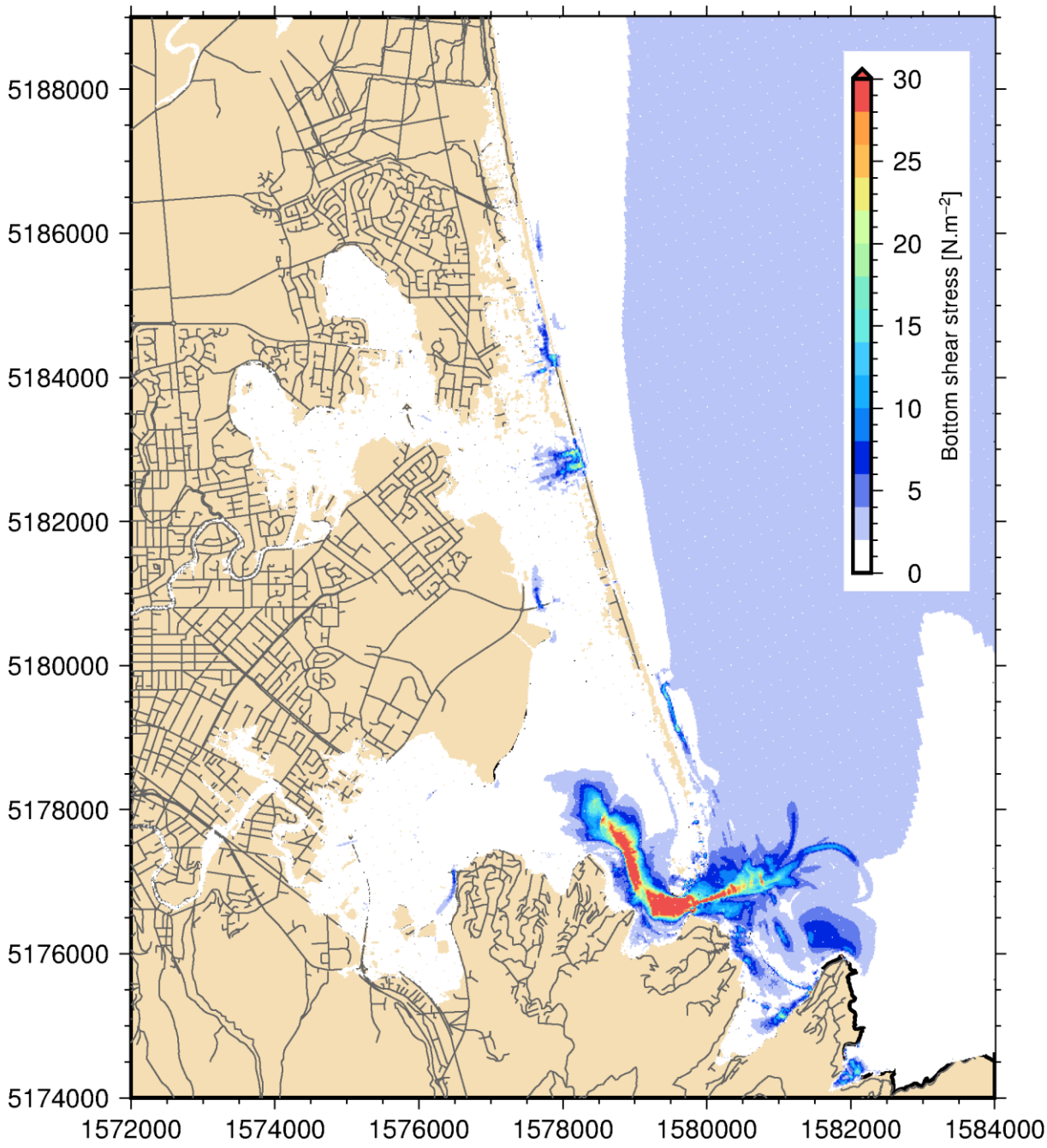

Figure 3-50: Maximum bottom shear stress for 1:500-year return period 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Southern Section.

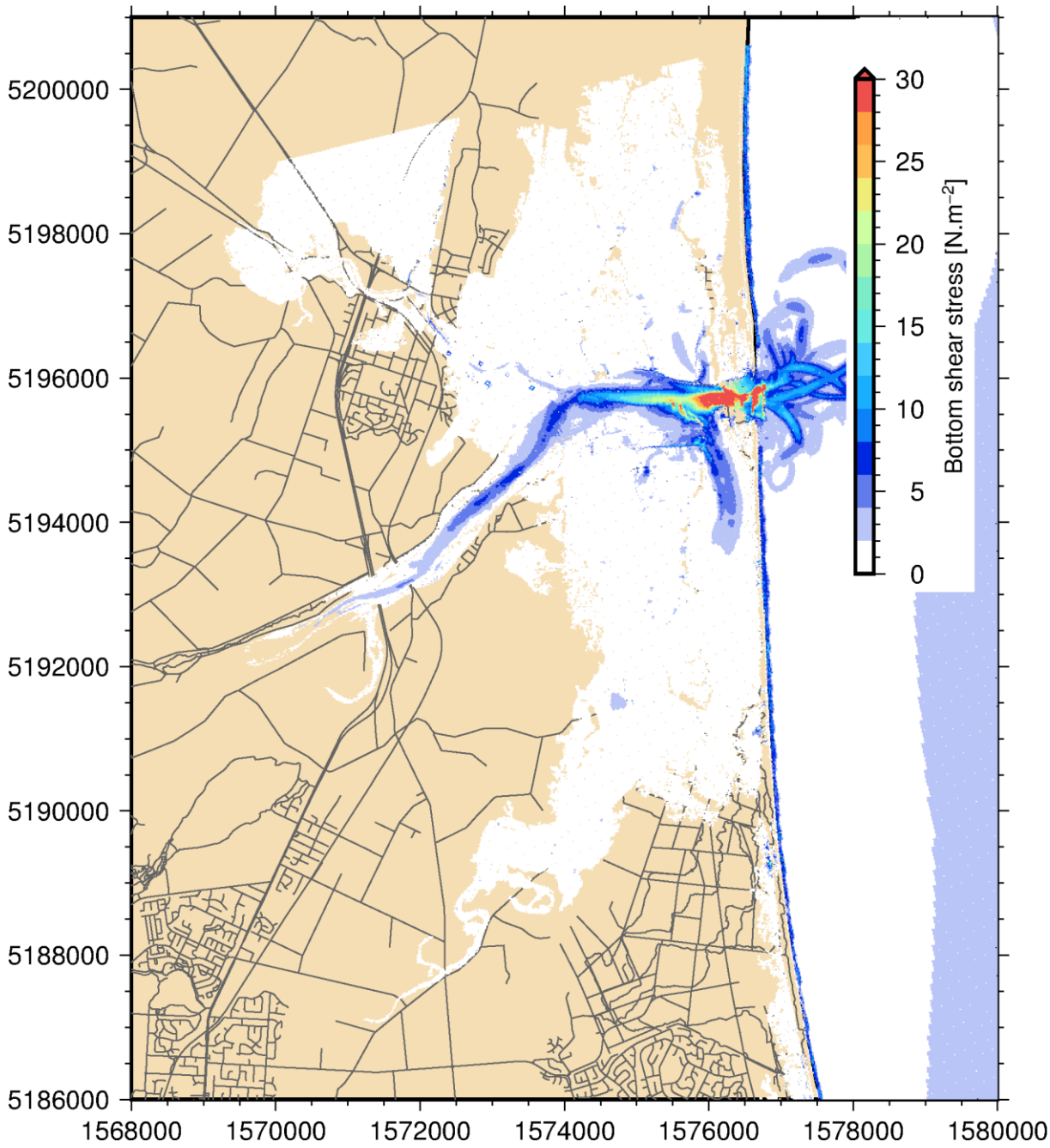

Figure 3-51: Maximum bottom shear stress for 1:500-year return period event 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Northern Section.

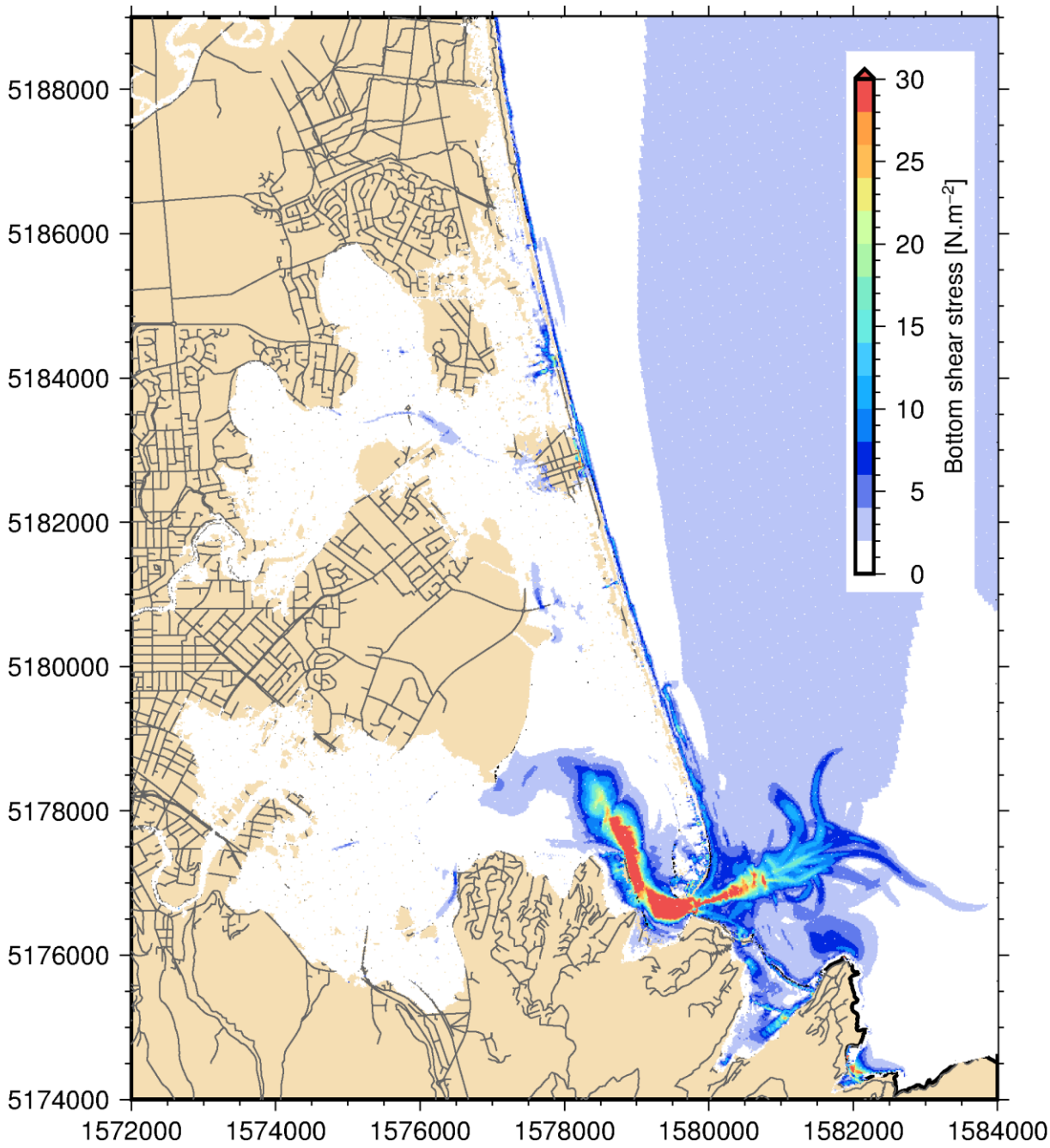

Figure 3-52: Maximum bottom shear stress for 1:500-year return period event 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Southern Section.

3.3.2 1:2,500-year return period tsunami scenarios

For the 1:2,500-year return period tsunami scenario, the dunes are consistently overtopped with flows at high shear-stress (>30 N.m^{-2}) likely to cause severe dune overwash along the entire coastal strip (Figure 3-53 – Figure 3-58). Dune overwash is likely to also erode the dunes and severely worsen the inundation depth in the coastal strip, a process not included in this modelling. The maximum shear-stress in the lower part of the Waimakariri River channel (downstream of the Kaiapoi confluence) and in the lower part of the Avon-Heathcote estuary exceeds 20 N.m^{-2} which implies that

major scouring and sediment transport is likely. In all the sea-level scenario, a high shear stress also occurs (5-15 N.m^{-2}) on the shore of the Avon-Heathcote estuary. Although vegetation is likely to limit the extent of the scouring there, significant erosion can be expected. In this tsunami scenario, high shear-stress in the nearshore is likely to cause significant erosion.

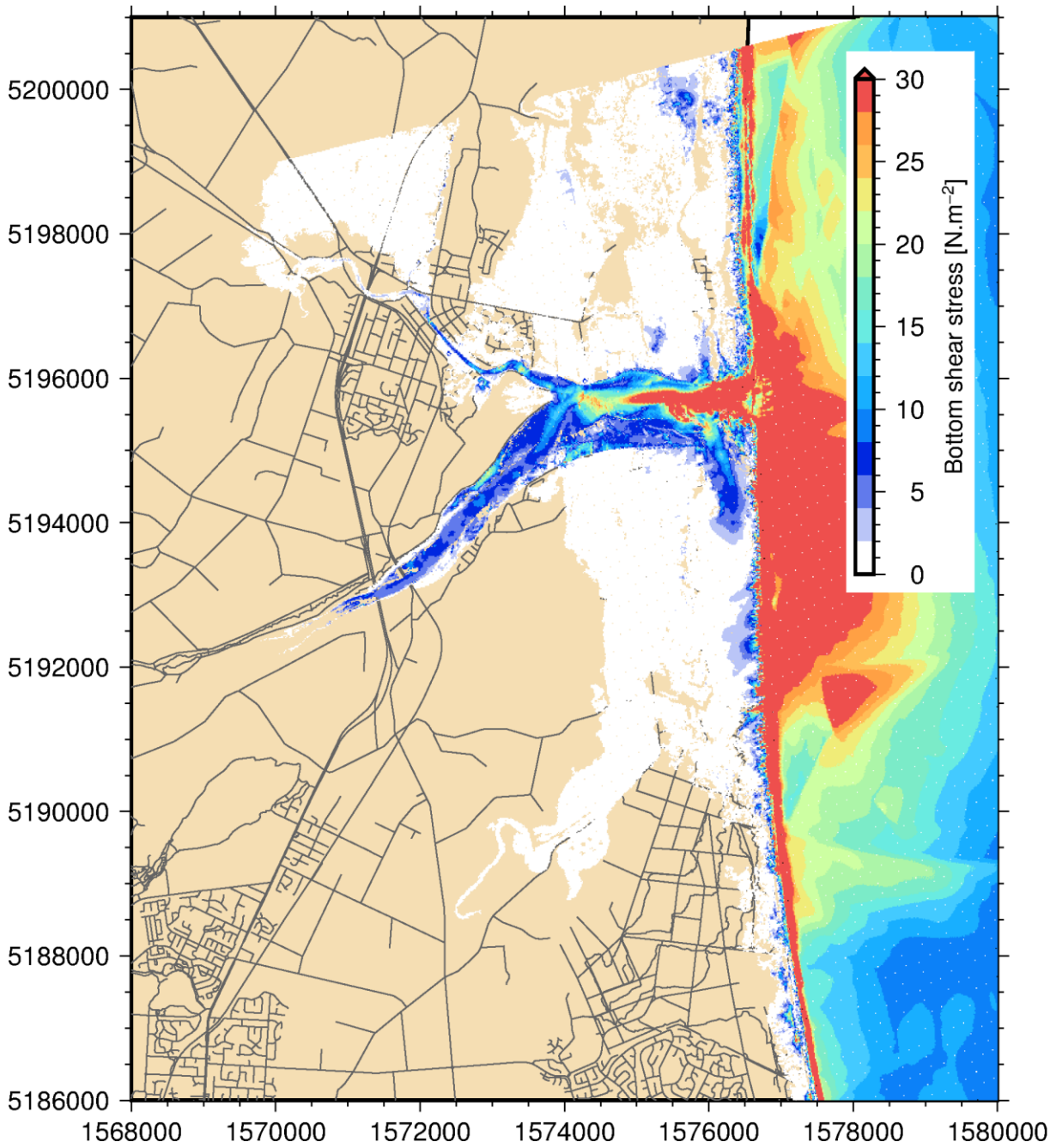

Figure 3-53: Maximum bottom shear stress for 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Northern Section.

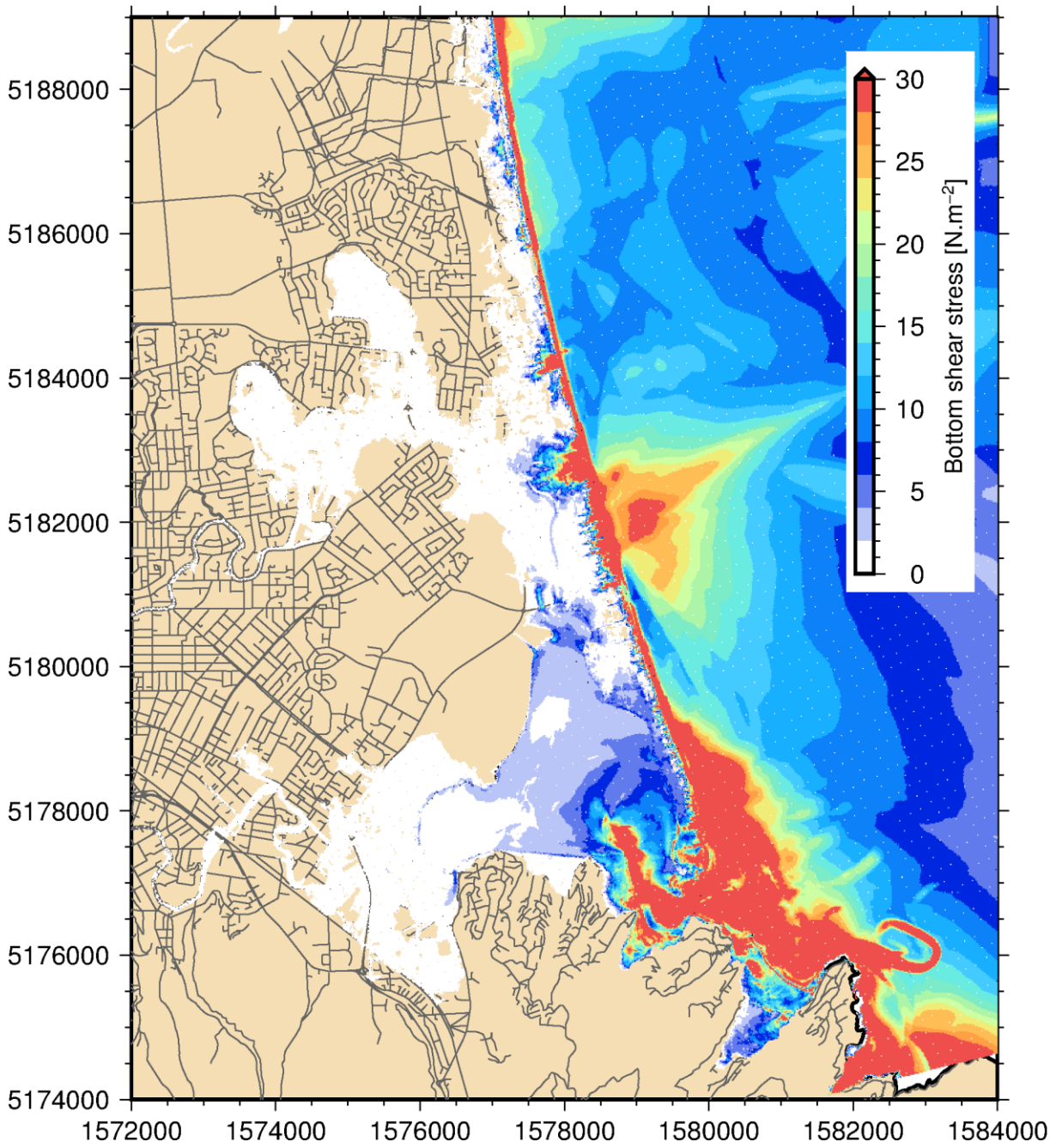

Figure 3-54: Maximum bottom shear stress for 1:2500-year return period - 2040 Sea Level Scenario – 0.19 m Sea Level Rise - Southern Section.

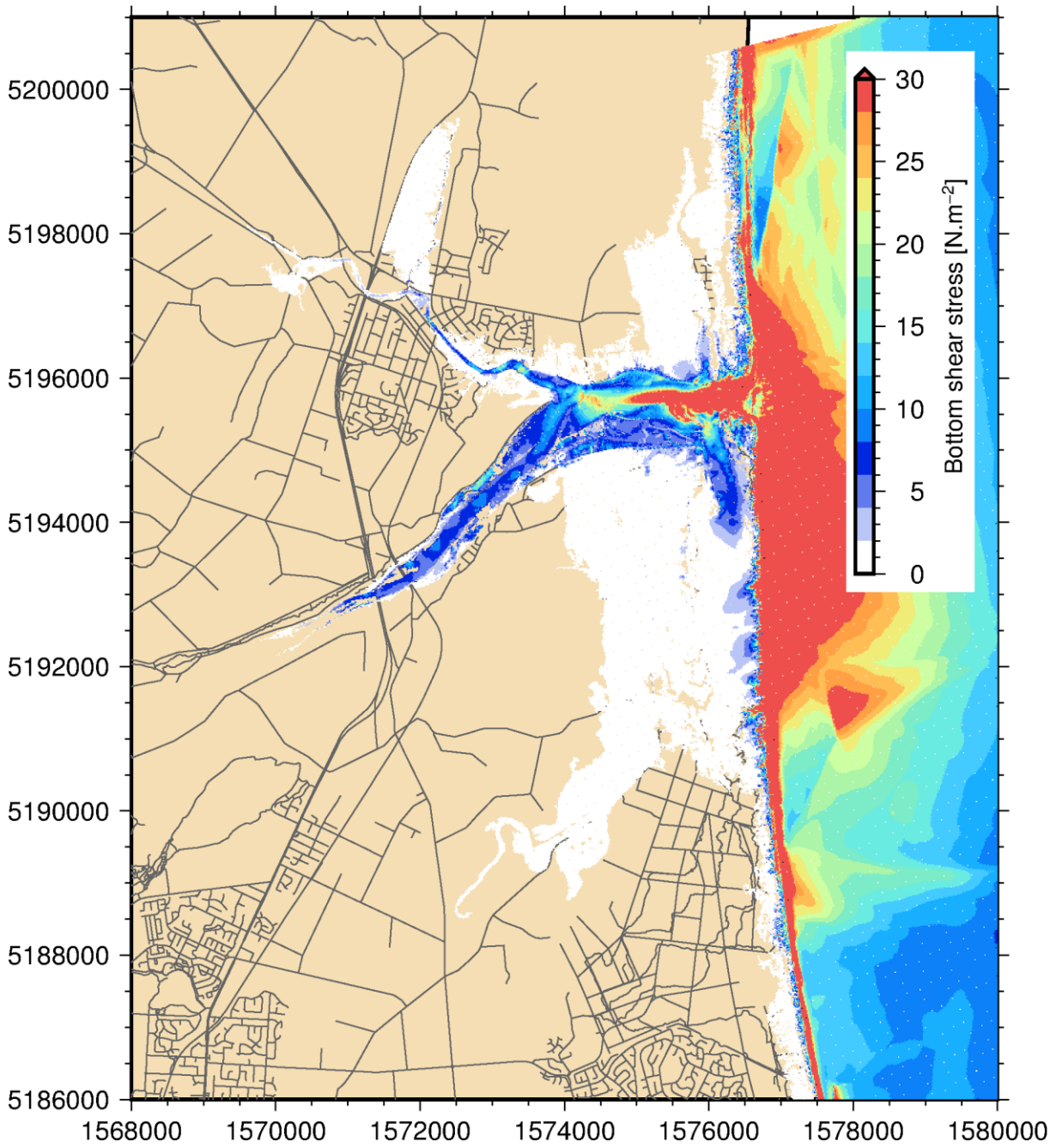

Figure 3-55: Maximum bottom shear stress for 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Northern Section.

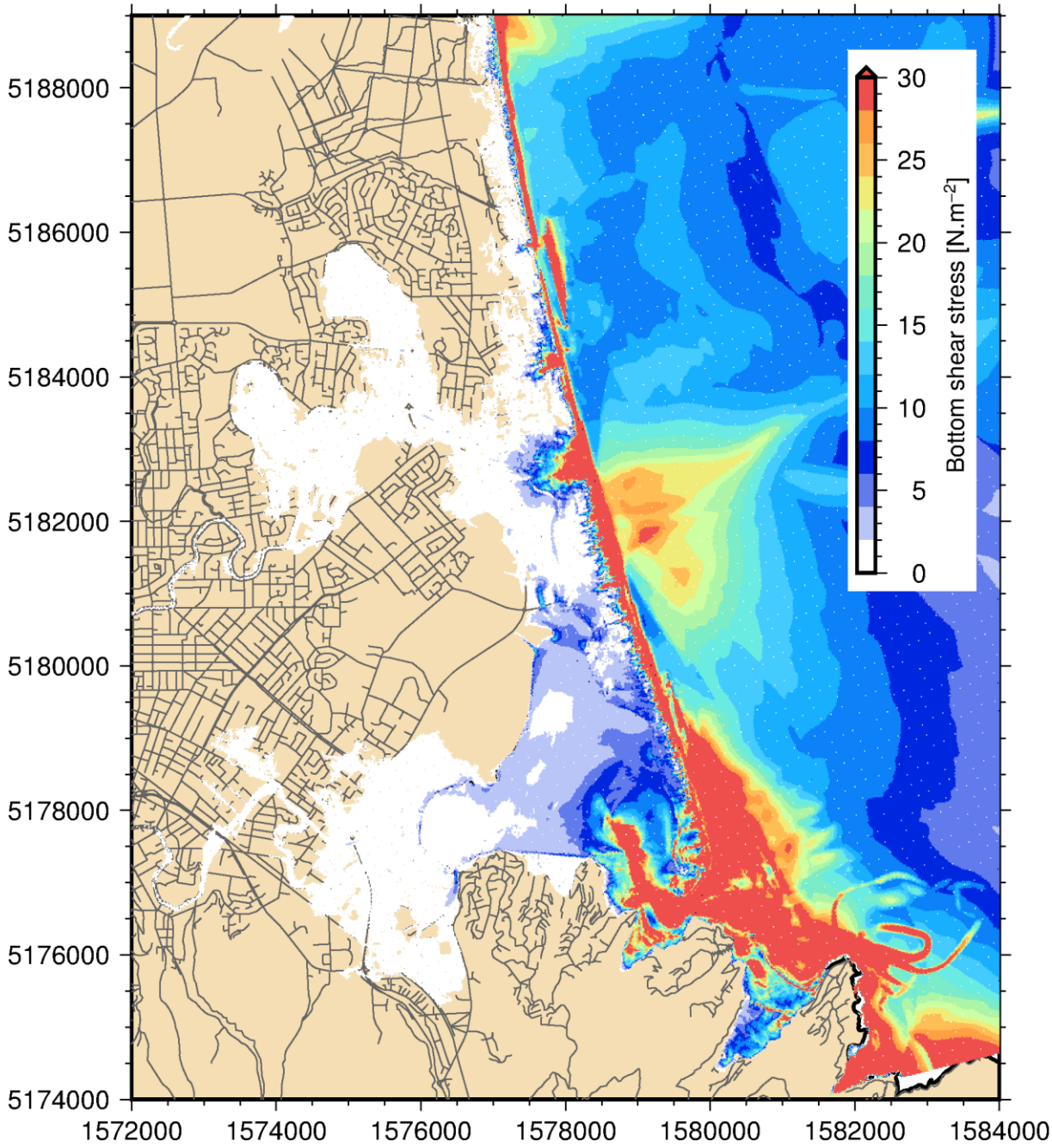

Figure 3-56: Maximum bottom shear stress for 1:2500-year return period - 2065 Sea Level Scenario – 0.41 m Sea Level Rise - Southern Section.

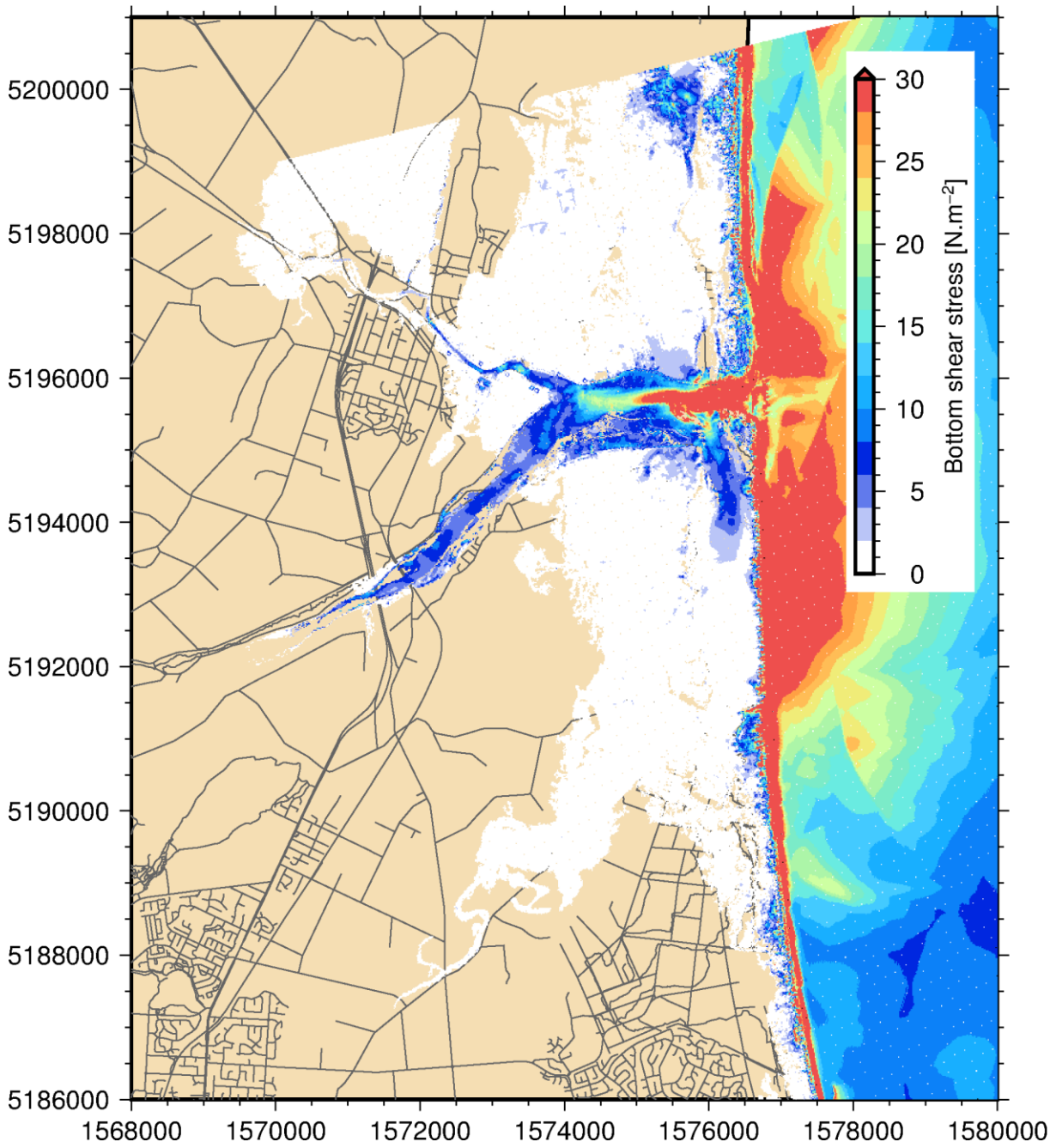

Figure 3-57: Maximum bottom shear stress for 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Northern Section.

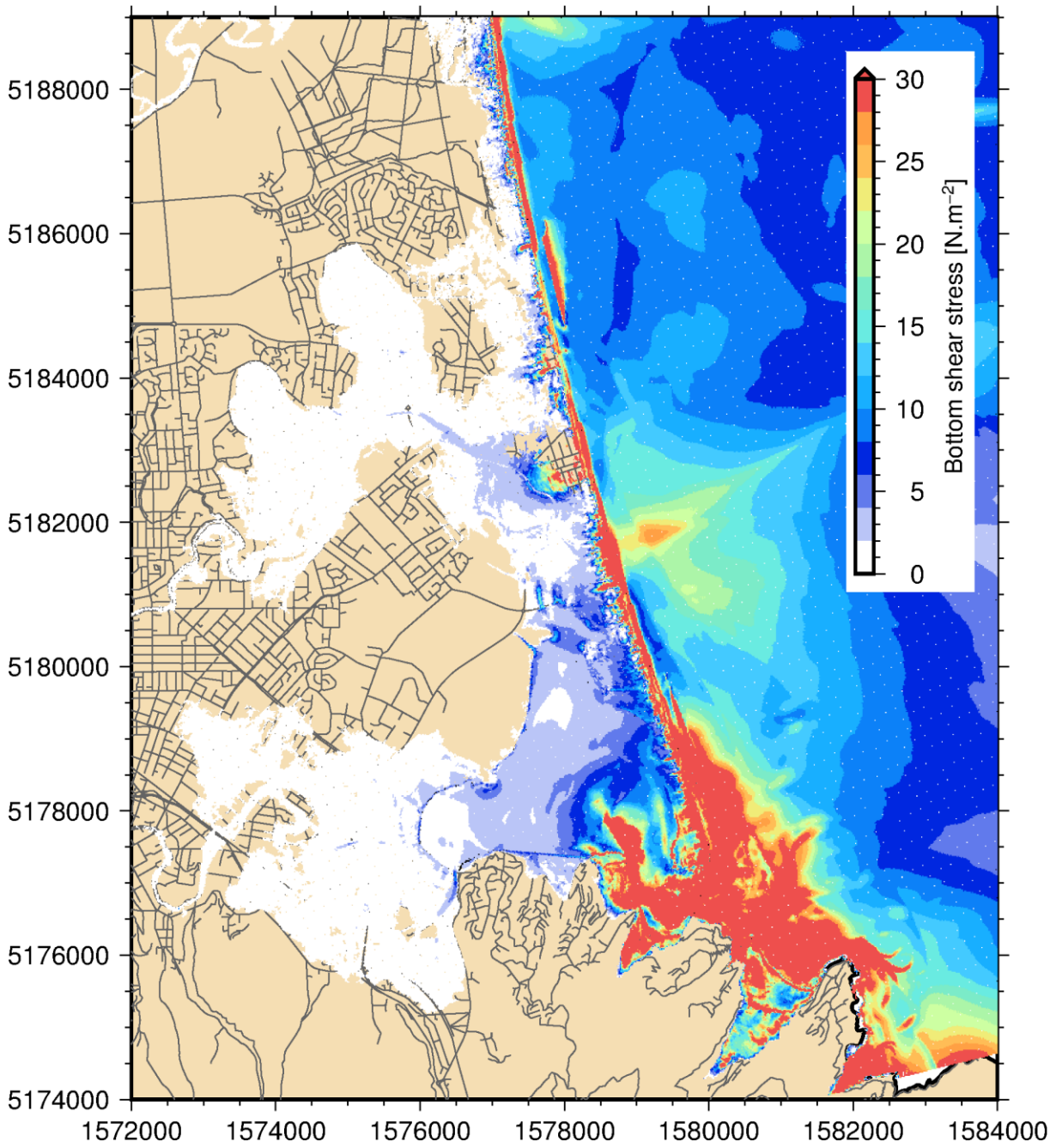

Figure 3-58: Maximum bottom shear stress for 1:2500-year return period - 2120 Sea Level Scenario – 1.06 m Sea Level Rise - Southern Section.

3.3.3 Flow velocity at bridges

Bridges are often associated with a flow constriction and subject to constriction scour during tsunami events. Depth-averaged flow velocity is presented here to qualitatively assess the scour at bridges. The tsunami simulation here does not take into account the flow under the bridge as the water level reaches the deck of the bridge. It is also important to consider that tsunami transport large quantities of debris that can get caught by the bridge structure and further restrict the flow under a bridge.

Bridges that experience the highest flow velocity (Table 3-3 Table 3-4) are the Avon River Bridge Street bridge (e.g., Figure 3-59 and Figure 3-60), the Heathcote River Ferry Road bridge (e.g., Figure

3-61 and Figure 3-62), Heathcote River Tunnel Road bridge (e.g., Figure 3-63 and Figure 3-64) and bridges on the Waimakariri River (e.g., Figure 3-65 and Figure 3-66)

Table 3-3: Bridges on Waimakariri, Avon and Heathcote rivers with heights above LVD37 and modelled maximum tsunami flow velocity at those locations for the 1:500-year return period scenario.

Bridge	Bridge underside deck level above LVD37 (m)	1:500-year return period Tsunami flow speed [m/s]			
		Current Sea Level	2040 Sea Level 0.19 m Rise	2065 Sea Level 0.41 m Rise	2120 Sea Level 1.06 m Rise
Waimakariri River Main North Rd	7.8	1.47	1.58	1.65	1.76
Waimakariri River SH1		1.34	1.46	1.56	1.62
Avon River Bridge Street	6.2	3.08	3.17	3.00	2.75
Avon River Pages Road	4.2	0.47	0.42	0.51	0.44
Avon River Anzac Drive	4.2	0.68	0.94	1.24	2.00
Avon River Avondale Road	3.8	0.63	0.79	1.05	1.66
Heathcote River Ferry Road	4.6	2.77	2.91	2.98	2.99
Heathcote River Tunnel Road	4.3	0.86	1.15	1.52	1.91
Heathcote River Bamford Street	2.1	0.56	0.65	0.75	0.99
Heathcote River SH 74A		0.61	0.71	0.81	1.19
Heathcote River Connal Street		0.49	0.54	0.60	1.00
Heathcote River Radley Street		0.27	0.30	0.27	0.39

Table 3-4: Bridges on Waimakariri, Avon and Heathcote rivers with heights above LVD37 and modelled maximum tsunami height at those locations for the 1:2,500-year return period scenario.

Bridge	Bridge underside deck level above LVD37 (m)	1:2,500-year return period Tsunami height above LVD37 (m)		
		2040 Sea Level 0.19 m Rise	2065 Sea Level 0.41 m Rise	2120 Sea Level 1.06 m Rise
Waimakariri River Main North Rd	7.8	2.34	2.45	2.53
Waimakariri River SH1		2.26	2.45	2.67
Avon River Bridge Street	6.2	3.91	3.67	3.67
Avon River Pages Road	4.2	0.97	1.22	1.19
Avon River Anzac Drive	4.2	0.91	1.16	1.69
Avon River Avondale Road	3.8	0.74	0.91	1.30
Heathcote River Ferry Road	4.6	2.90	3.03	3.10
Heathcote River Tunnel Road	4.3	1.06	1.39	1.73
Heathcote River Bamford Street	2.1	0.58	0.62	0.86
Heathcote River SH 74A		0.62	0.66	0.96
Heathcote River Connal Street		0.45	0.50	0.73
Heathcote River Radley Street		0.23	0.28	0.29

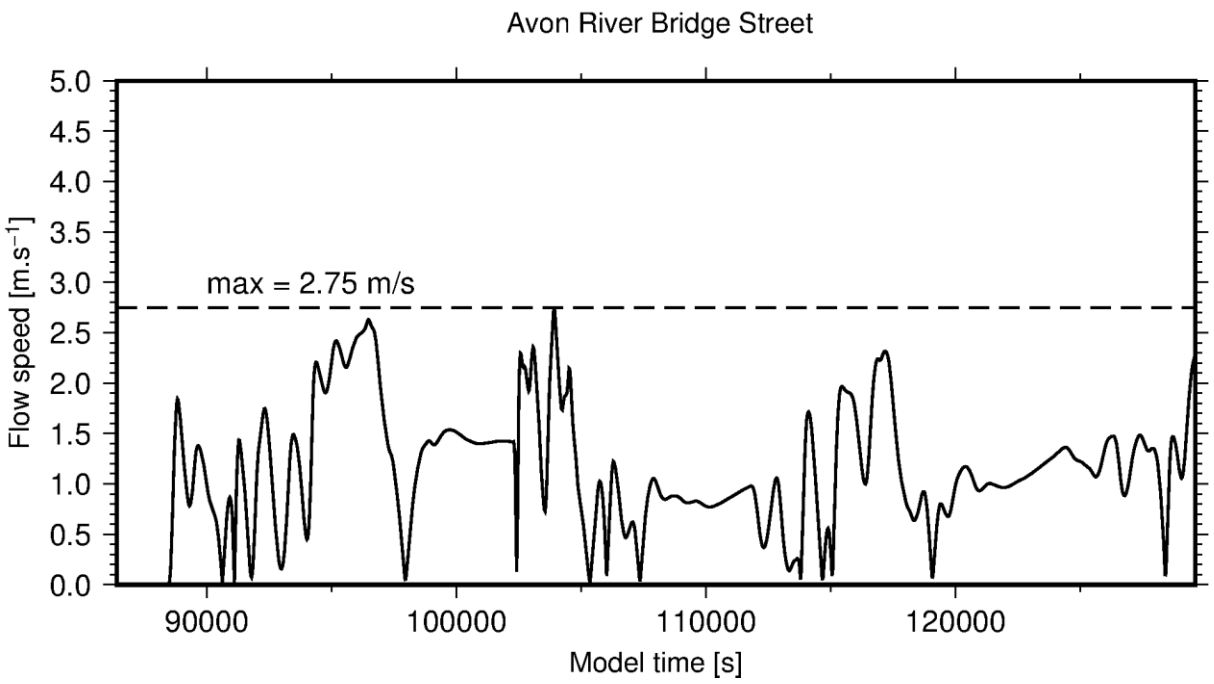

Figure 3-59: Flow velocity timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Avon River Bridge Street bridge.

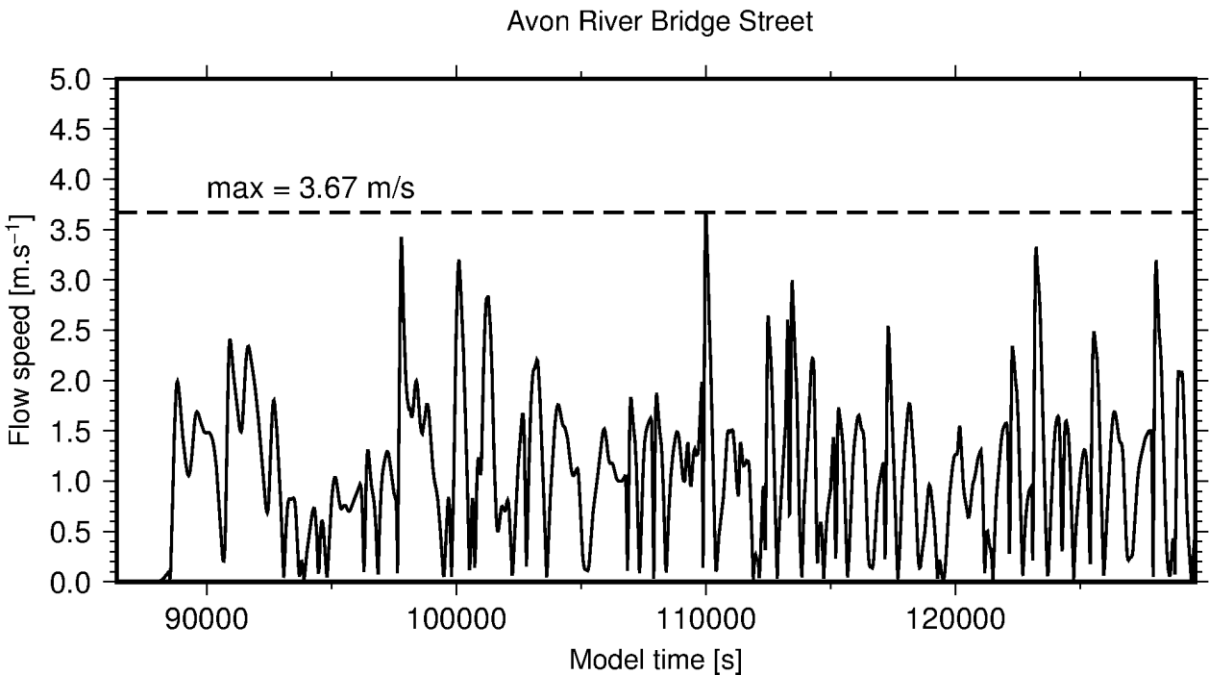

Figure 3-60: Flow velocity timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Avon River Bridge Street bridge.

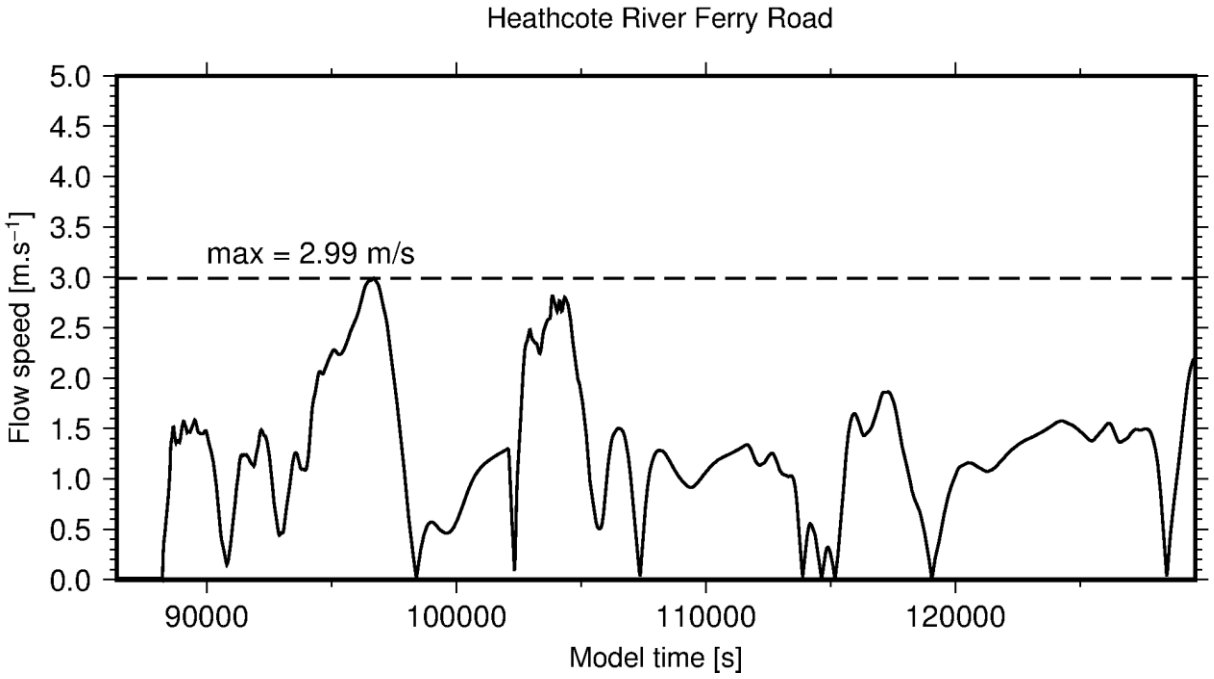

Figure 3-61: Flow velocity timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Heathcote River Ferry Road bridge.

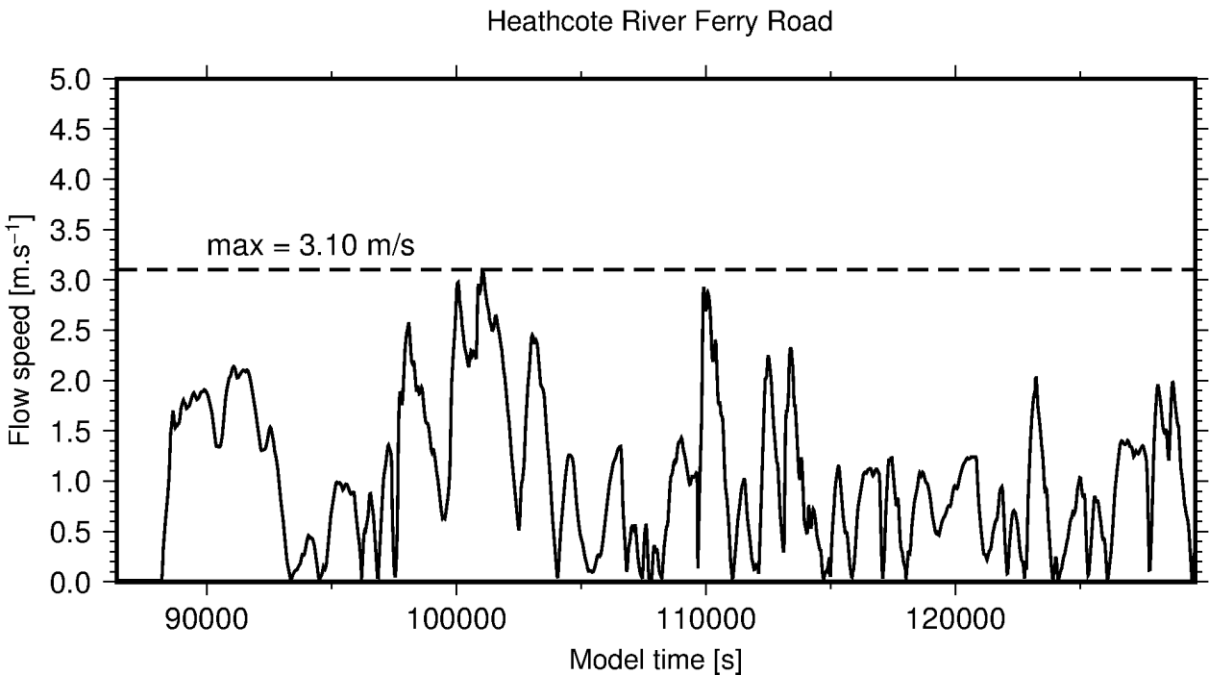

Figure 3-62: Flow velocity timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Heathcote River Ferry Road bridge.

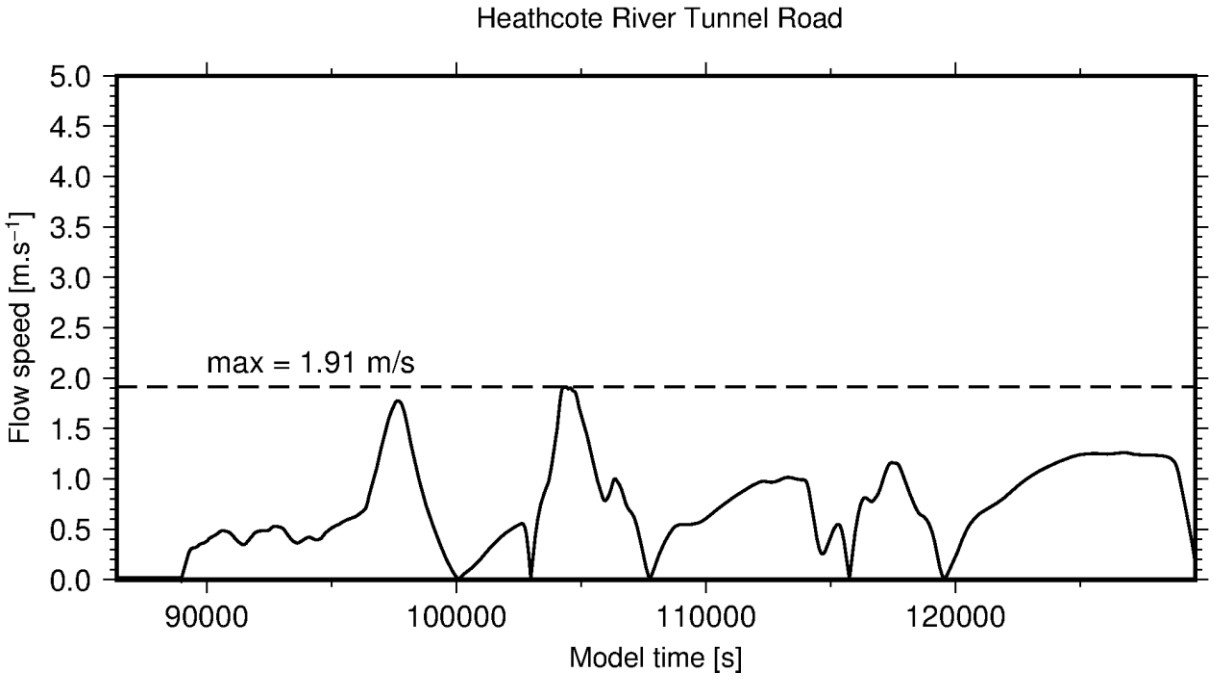

Figure 3-63: Flow velocity timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Heathcote River Tunnel Road bridge.

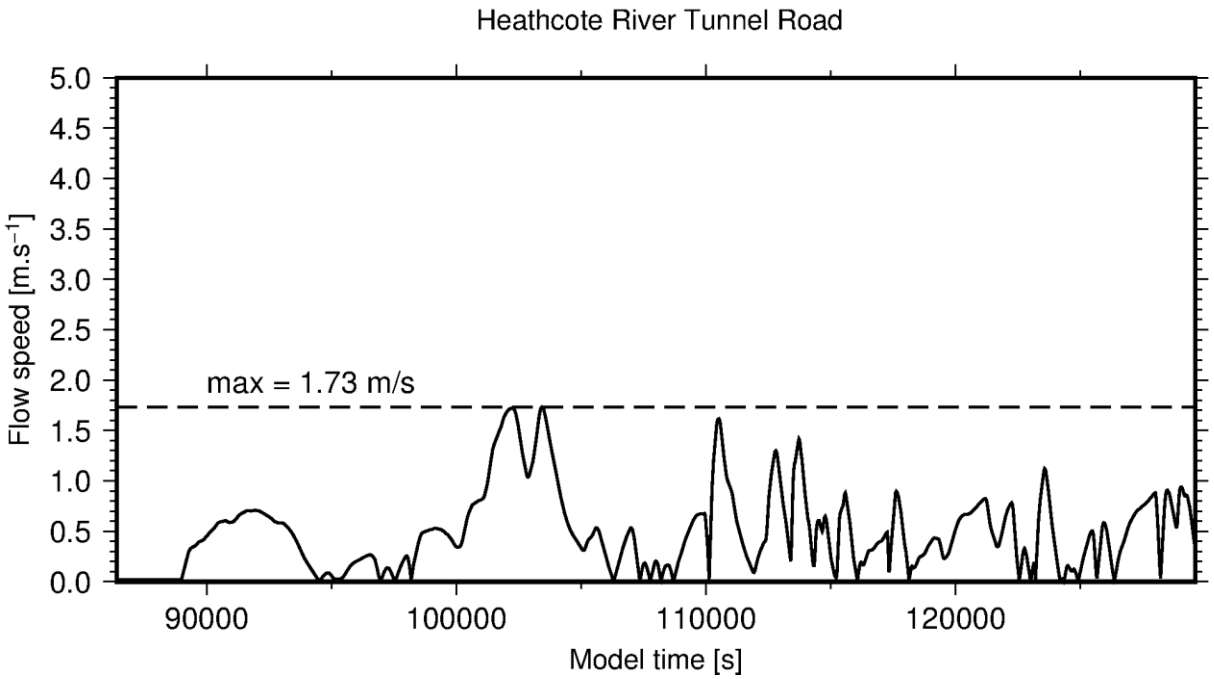

Figure 3-64: Flow velocity timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at Heathcote River Tunnel Road bridge.

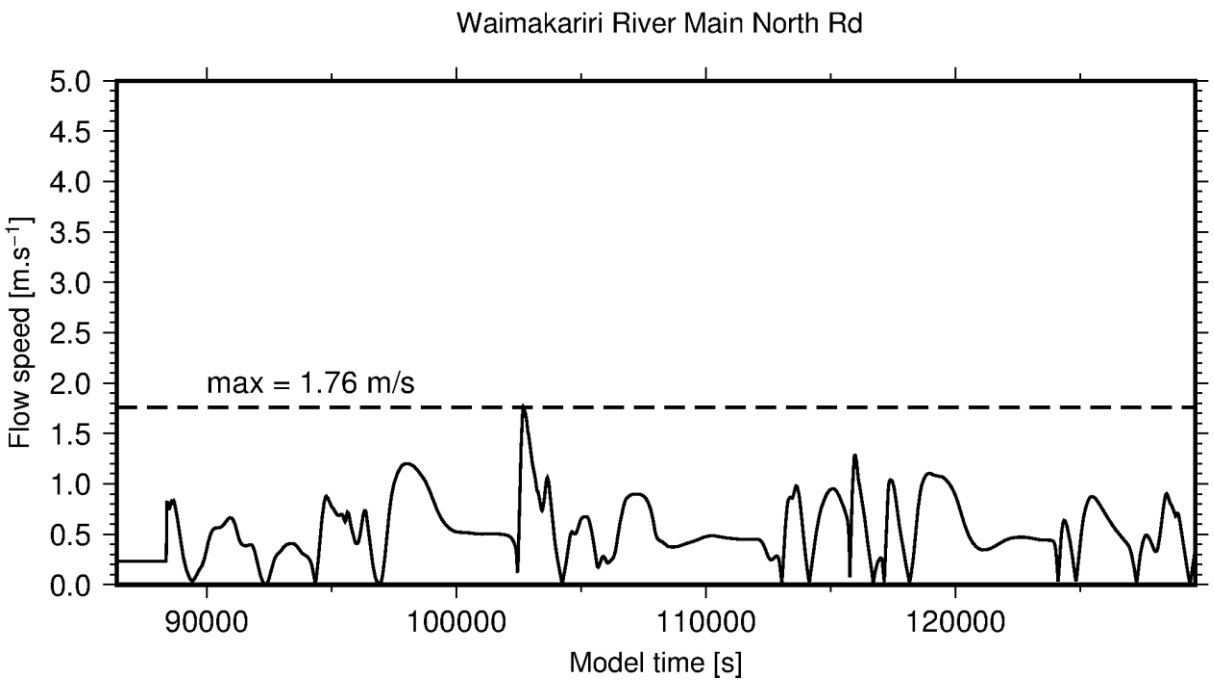

Figure 3-65: Flow velocity timeseries for 1:500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Waimakariri River Main North Road bridge.

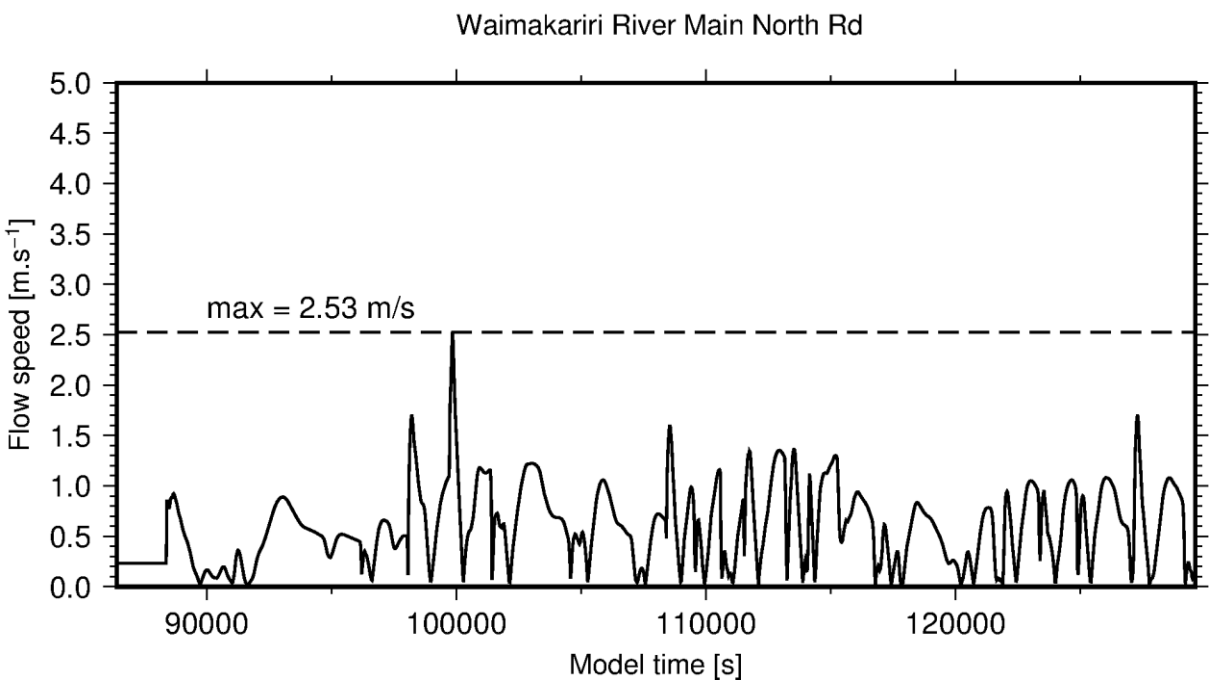

Figure 3-66: Flow velocity timeseries for 1:2,500-year return period – 2120 Sea Level Scenario – 1.06 m Sea Level Rise at the Waimakariri River Main North Road bridge.

4 Conclusion

NIWA was commissioned by Christchurch City Council (CCC) to carry out a numerical modelling study of tsunami inundation in Christchurch caused by two tsunamis originating from distant sources. The selected tsunami sources were a 1:500-year return period event cause by a magnitude 9.28 earthquake and a 1:2,500-year return period event caused by a magnitude M_w 9.485 earthquake both at the Peru subduction zone. The simulations were completed for different sea-level rise scenario (present day, 0.19 m, 0.41 m and 1.06 m) taking into account predicted shoreline changes predicted for 2065 and 2120. Note that the magnitude M_w 9.485 scenario at current sea-level was produced in a previous study (Lane et al. 2017) and not replicated here.

The simulations were completed at MHWS (1.2 m above the Lyttelton Vertical Datum 1937) adjusted according each sea level rise scenario. The flow of the Waimakariri River, Avon River and Heathcote River was also included in the model.

Both tsunami scenarios result in major inundation in Christchurch which, as expected, worsen with the higher sea-level scenarios. The inundation extent was similar for both tsunami scenarios but the inundation depth and flow velocity along the coastal strip was much larger for the worst-case tsunami (1:2,500-year scenario). The total inundation extent for the higher sea level rise scenario (1.06 m above present sea level) was 53 km^2 for the 1:500-year return period tsunami event, 75 per cent more than for the same tsunami occurring at present day sea level.

Such large tsunami events are expected to cause severe erosion on the coastal strip and at the mouth of the Waimakariri River and the Avon-Heathcote estuary. Severe erosion can also be expected at the Avon Bridge Street bridge and the Heathcote Ferry Road bridge.

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Appendix A Future Topography

Future sea level rise is associated with shoreline retreat for the coast south of Christchurch (Tonkin & Taylor Ltd 2017). This shoreline retreat was applied to the topography of the shore, for the scenario with sea level rise for 2065 (0.41 m) and the scenario for 2120 (1.06 m), by shifting, landward, the present shore topography based on the shoreline retreat estimated by Tonkin & Taylor Ltd (2017). Below are figure showing the present topography (Figure A-1) and the future topography (Figure A-2 and Figure A-3). The comparison of the different topography is is illustrated in (Figure A-4).

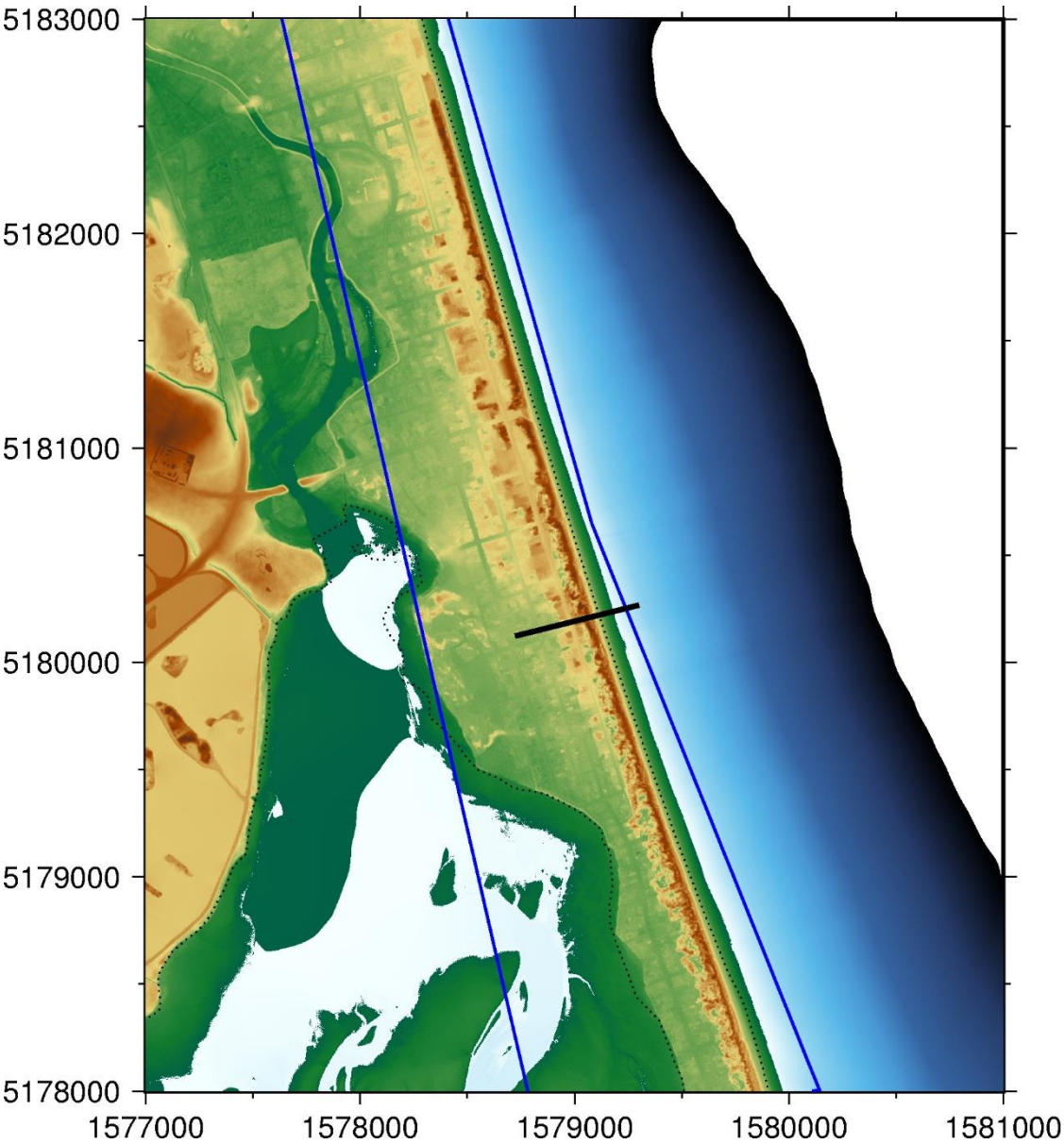

Figure A-1: Topography and bathymetry of the Brighton shore – Present. The dotted line shows the present shoreline; the Blue plain line shows the extent of the domain change in the tsunami simulations; the thick black line shore the 600 m long cross-shore profile presented in Figure A-4.

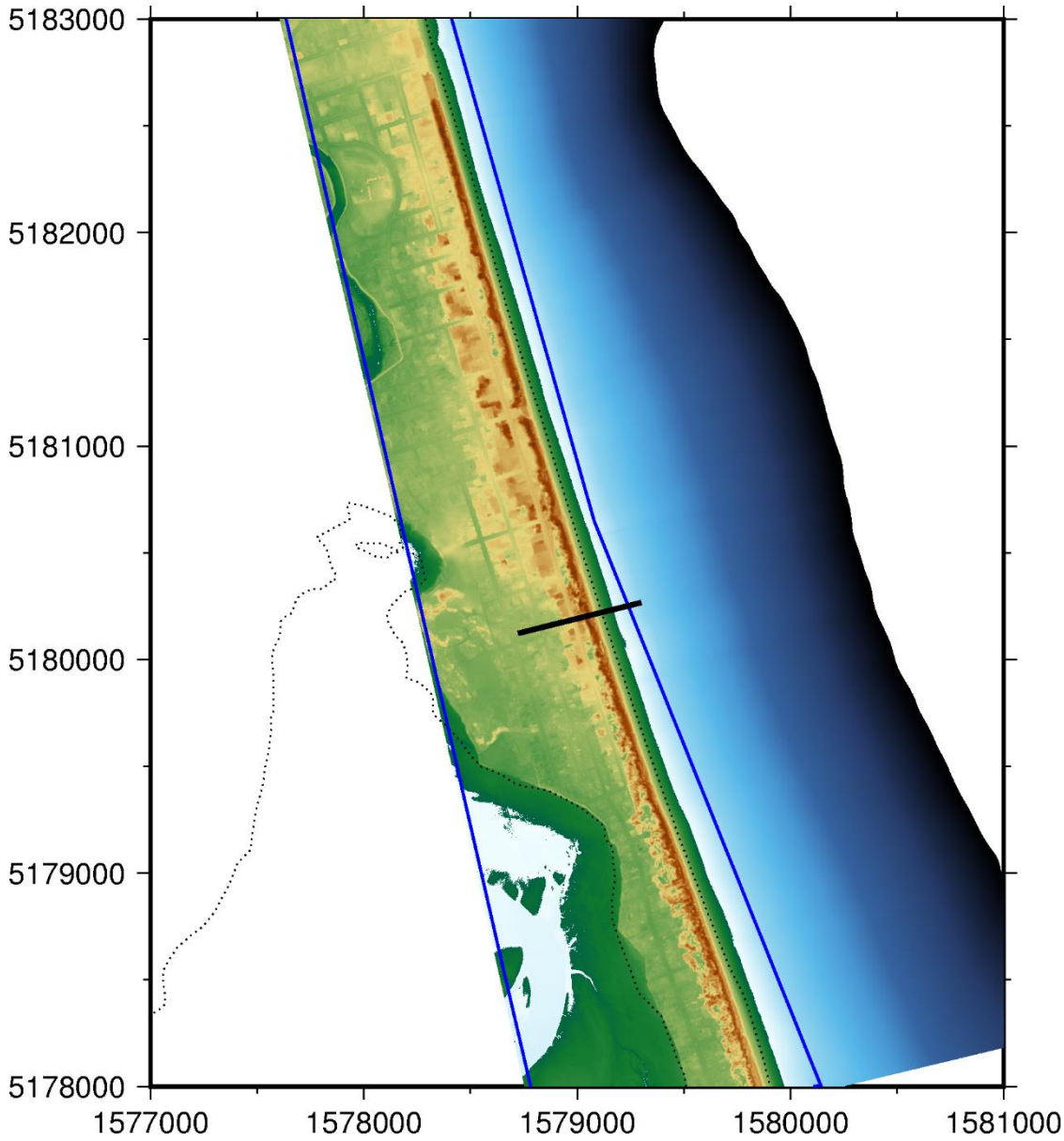

Figure A-2: Topography and bathymetry of the Brighton shore – 2065. The dotted line shows the present shoreline; the Blue plain line shows the extent of the domain change in the tsunami simulations; the thick black line shore the 600 m long cross-shore profile presented in Figure A-4.

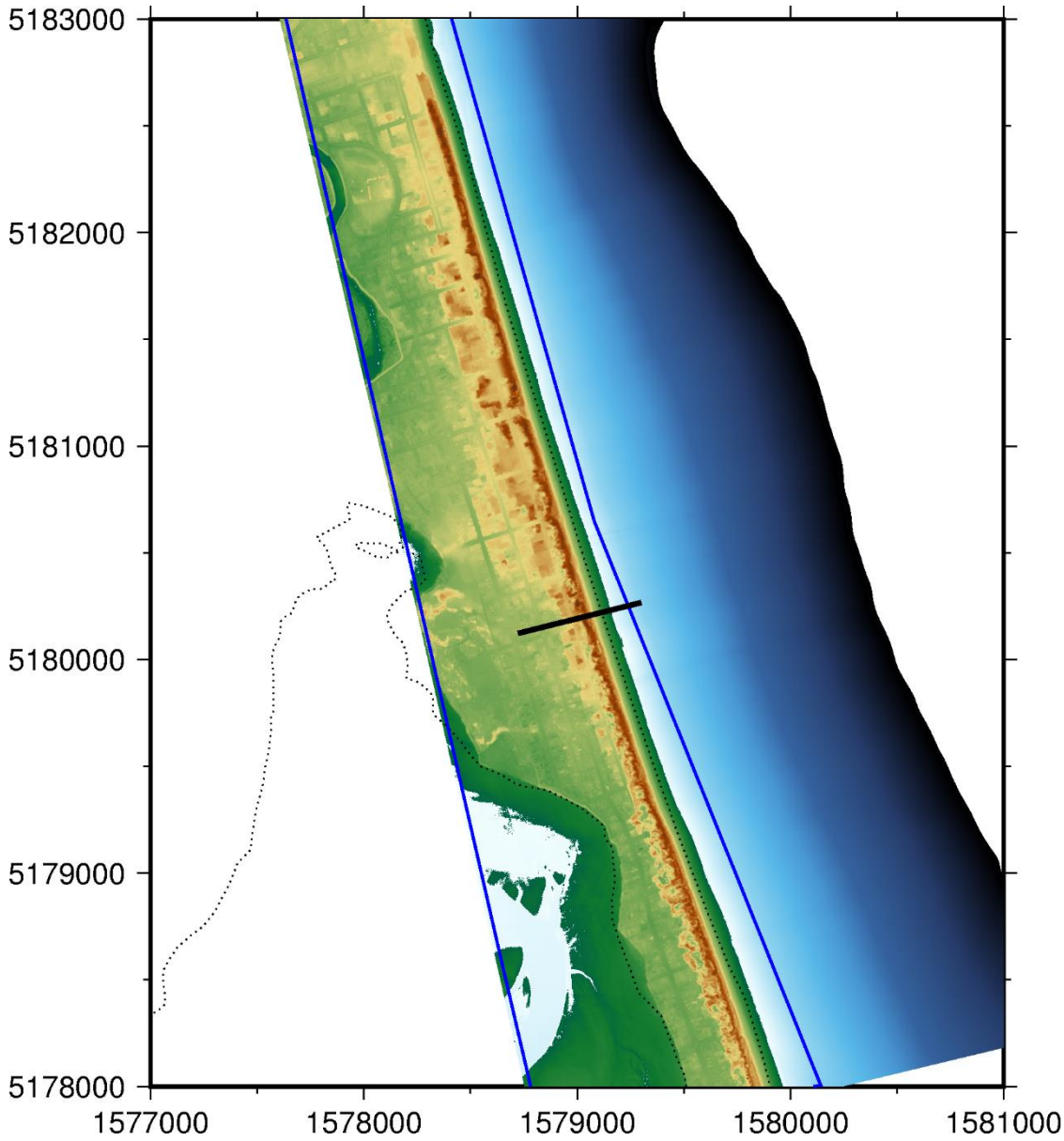

Figure A-3: Topography and bathymetry of the Brighton shore – 2120. The dotted line shows the present shoreline; the Blue plain line shows the extent of the domain change in the tsunami simulations; the thick black line shore the 600m long cross-shore profile presented in Figure A-4.

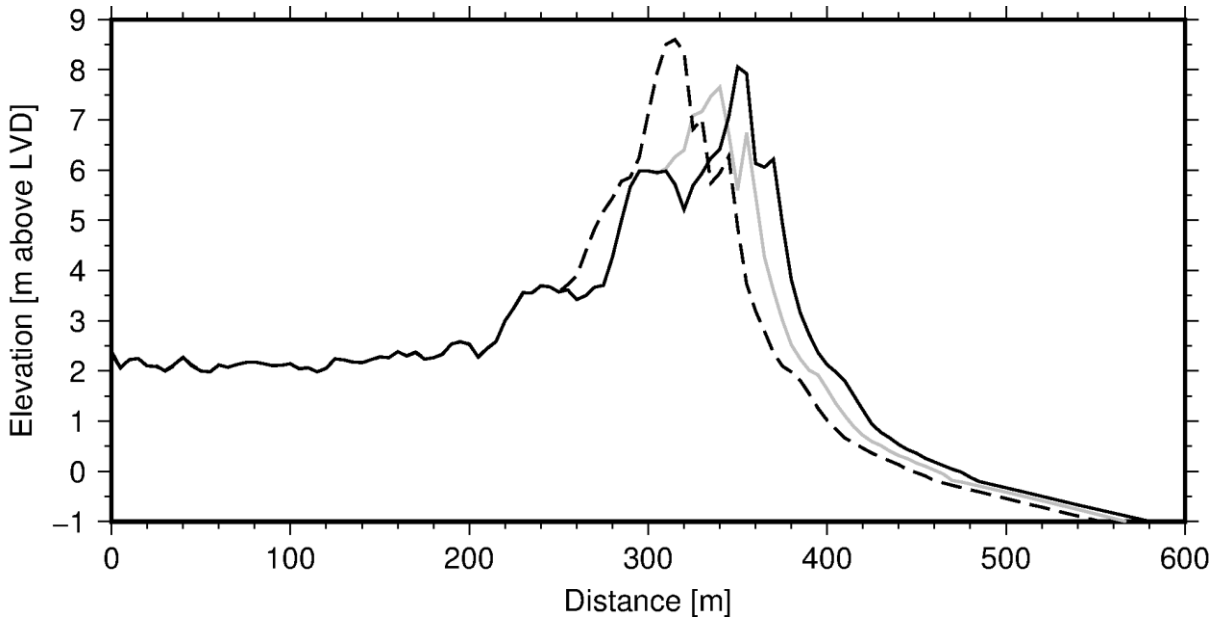

Figure A-4: Topography along a cross-shore profile. The black line is the present topography, the grey line is the 2065 topography, the dashed line is the 2120 topography. Where only the black line is visible, the three lines are on top of each other. The location of the cross-shore profile can be seen in above figures.

Appendix B Local Source

Local faults with a high likelihood of causing a significant tsunami in Christchurch between Sumner and Waimakariri River mouth were identified in consultation with Dr Phil Barnes based on data in Barnes et al. (2016). Faults rupture parameters are taken from Barnes (personal communication). Figure B-1 shows the locations of the faults used and Table B-1 give some of their parameters. The maximum values for rupture parameters were used to test the worst-case scenarios for local faults. The four scenarios modelled were two single fault ruptures and two multiple fault ruptures, viz.:

- LeithfieldNC1137.
- Pegasus1nw.
- LeithfieldNC1137 and NorthCant8.
- Pegasus1nw and NorthCant4.

Figure B-1: Faults used in local tsunami modelling. Single fault rupture scenarios of LeithfieldNC1137 and Pegasus1nw are modelled as well as combined fault of LeithfieldNC1137 and NortCant8 and Pegasus1nw and NorthCant4.

Table B-1: Faults used in local tsunami scenarios. Maximum length, slip, magnitude and associated recurrence interval.

Fault Name	Length (km)	Slip (cm)	Mw	Recurrence interval (years)
Leithfield1137	45.1	236	7.4	12,500
Pegasus1nw	40.7	213	7.3	22,500
NorthCant4	25.3	132	7.0	35,000
NorthCant8	37.4	195	7.3	21,000

The magnitude of the combined LeithfieldNC1137 and NorthCant8 faults rupturing is M_w 7.7, and for Pegasus1nw and NorthCant4 combined it is M_w 7.6.

Figure B-2 to Figure B-5 show the maximum water level over four hours of simulation from the four scenarios and Figure B-6 to Figure B-9 show close-ups for the region of interest. Note that the baseline water level for these runs is set to mean sea level. In all four scenarios, the northern portion of Pegasus Bay and the northern facing bays on Banks Peninsula are considerably more affected than the area of Christchurch City between Sumner and the Waimakariri River mouth. The scenario that most affects that region is the combined LeithfieldNC1137 and NorthCant8, where maximum wave height at coast exceed 3 m in some parts of that region and run-up can be up to 6 m. The combined Pegasus1nw and NorthCant4 scenario has maximum wave heights at coast of up to 2 m, with run-ups potentially higher. The single faults scenarios (LeithfieldNC1137 fault and Pegasus1nw fault) give maximum wave heights at coast around Christchurch of up to 1.5 m. Figure B-10 shows time series of the water levels at locations approximately 500 m off-shore New Brighton, Sumner and Lyttelton for the four scenarios. Based on this modelling we recommend inundation modelling of the combined LeithfieldNC1137 and NorthCant8 scenario and the combined Pegasus1nw and NorthCant4 rupture scenario.

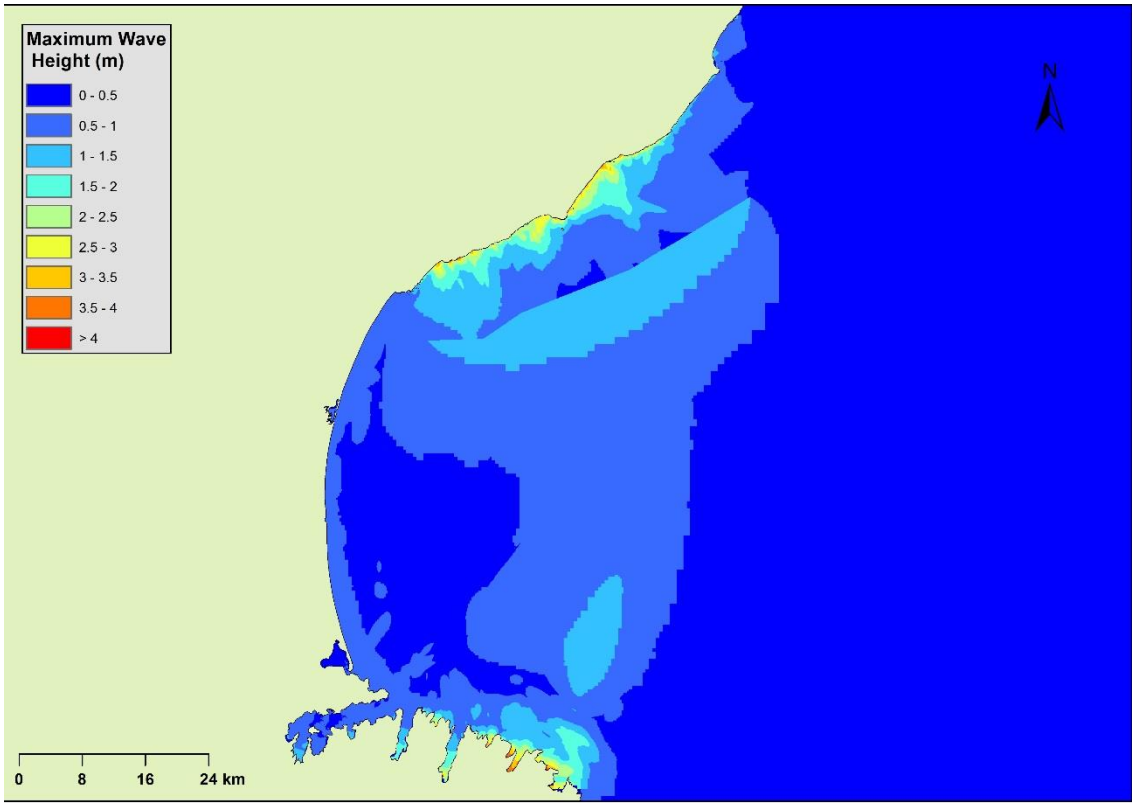

Figure B-2: Maximum water level over entire simulation for rupture of LeithfieldNC1137 fault.

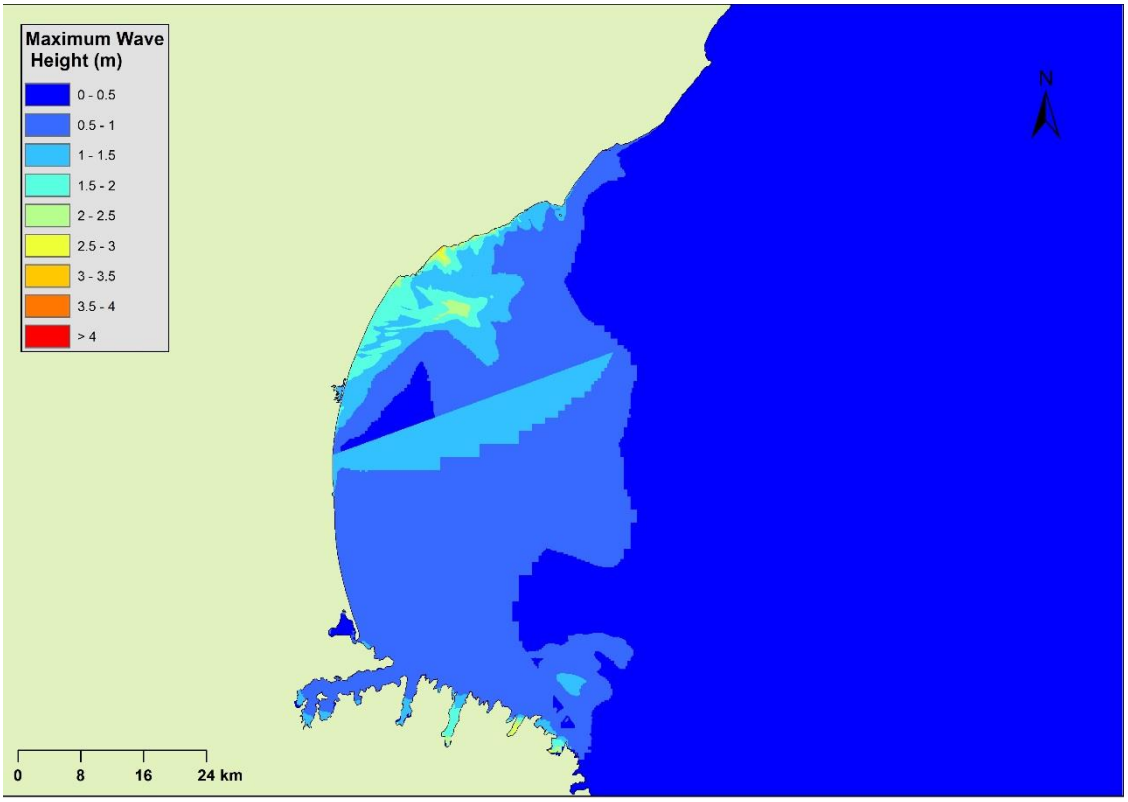

Figure B-3: Maximum water level over entire simulation for rupture of Pegasus1nw fault.

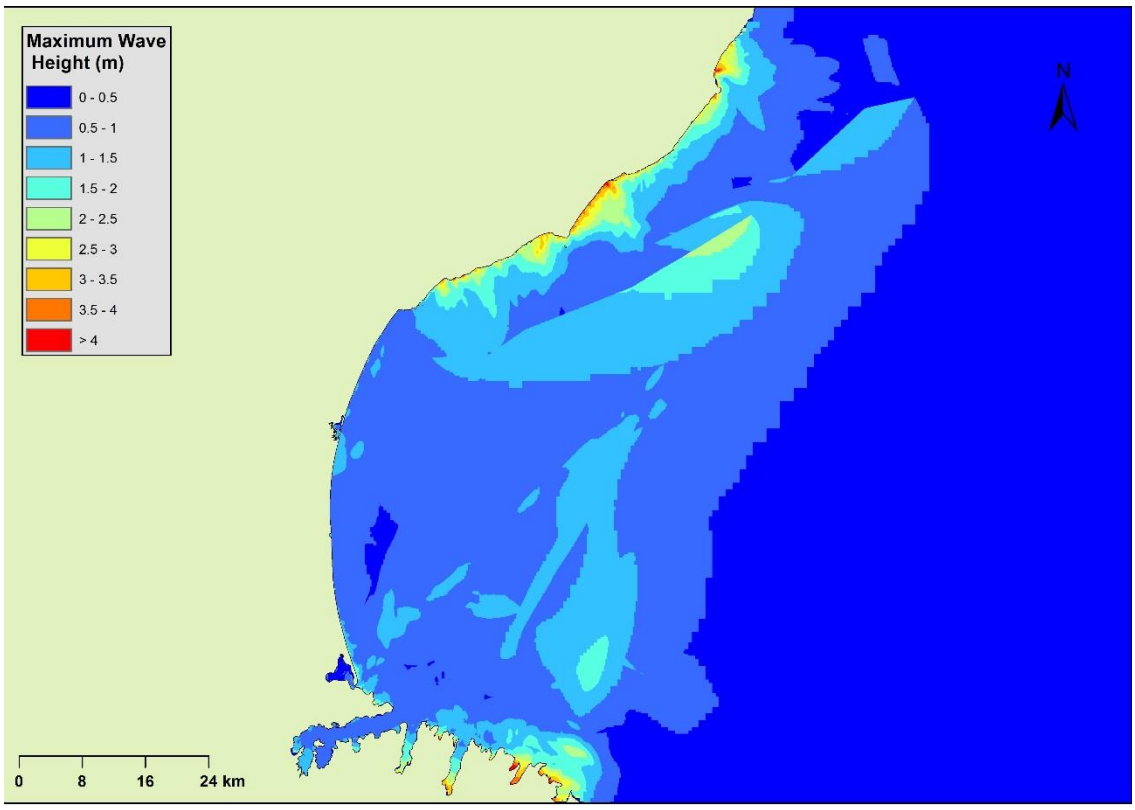

Figure B-4: Maximum water level over entire simulation for rupture of LeithfieldNC1137 and NorthCant8 faults.

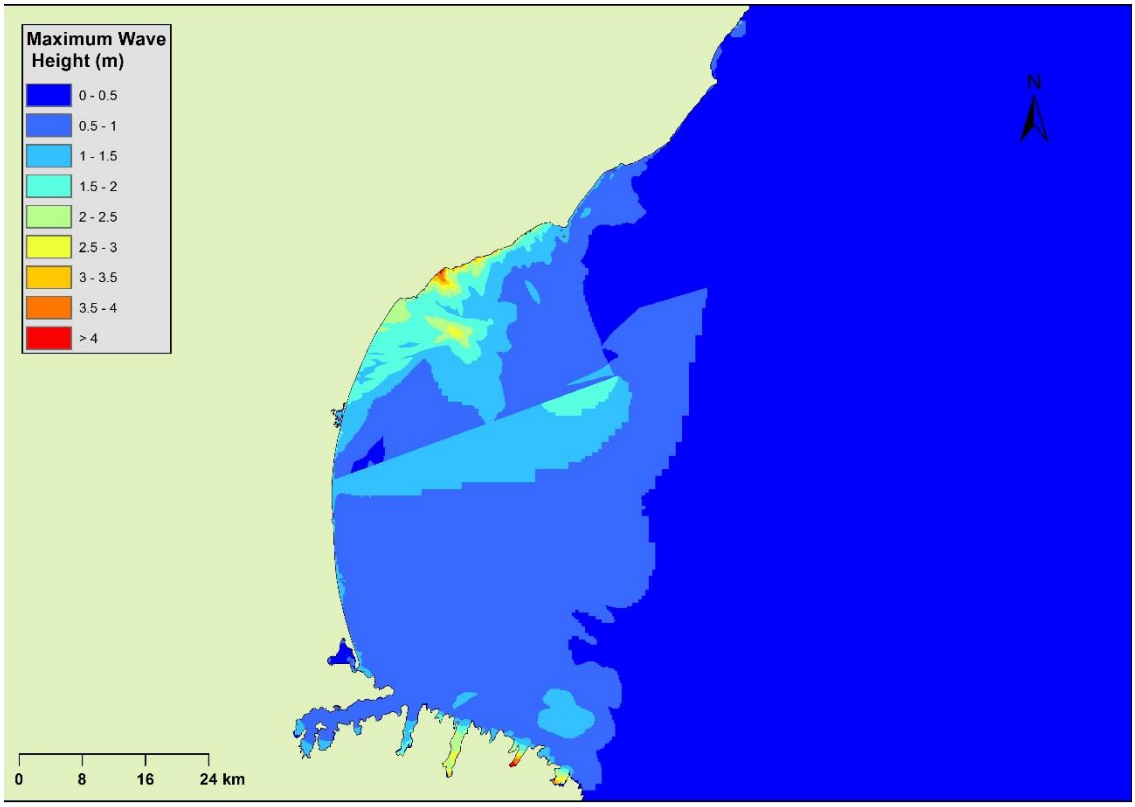

Figure B-5: Maximum water level over entire simulation for rupture of Pegasus1nw and NorthCant4 faults.

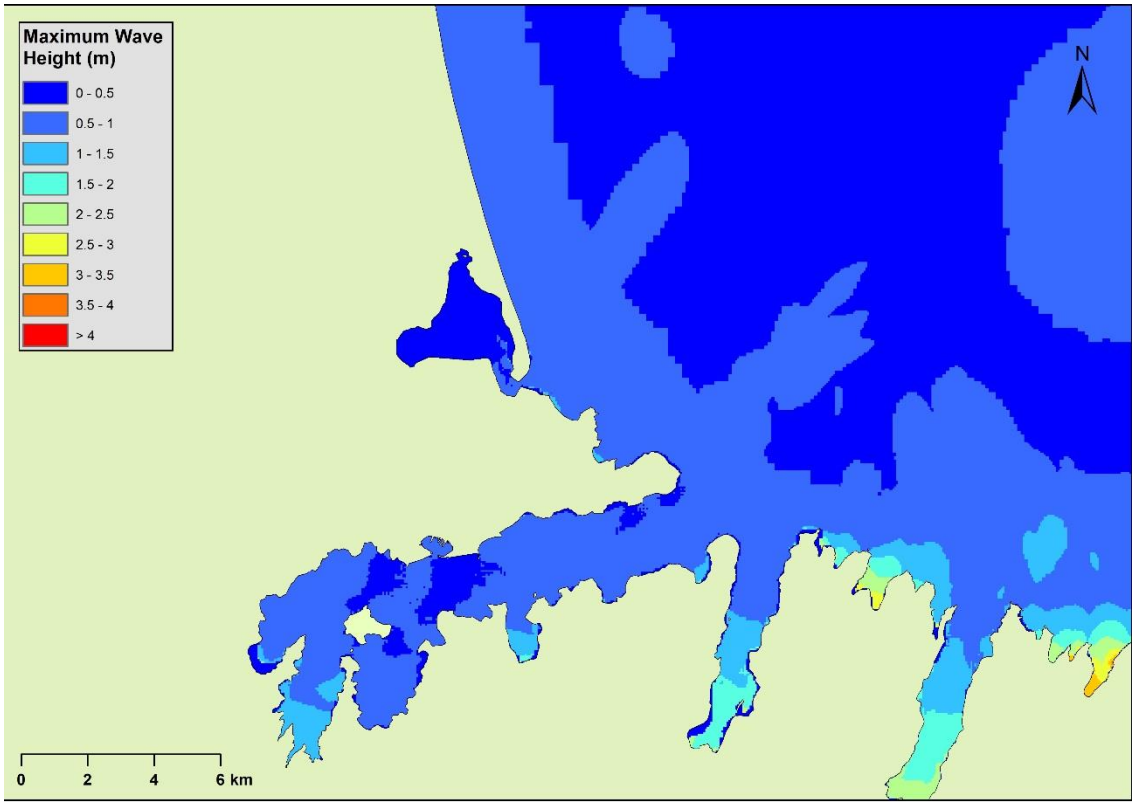

Figure B-6: Close-up of Christchurch City: Maximum water level over entire simulation for rupture of LeithfieldNC1137 fault.

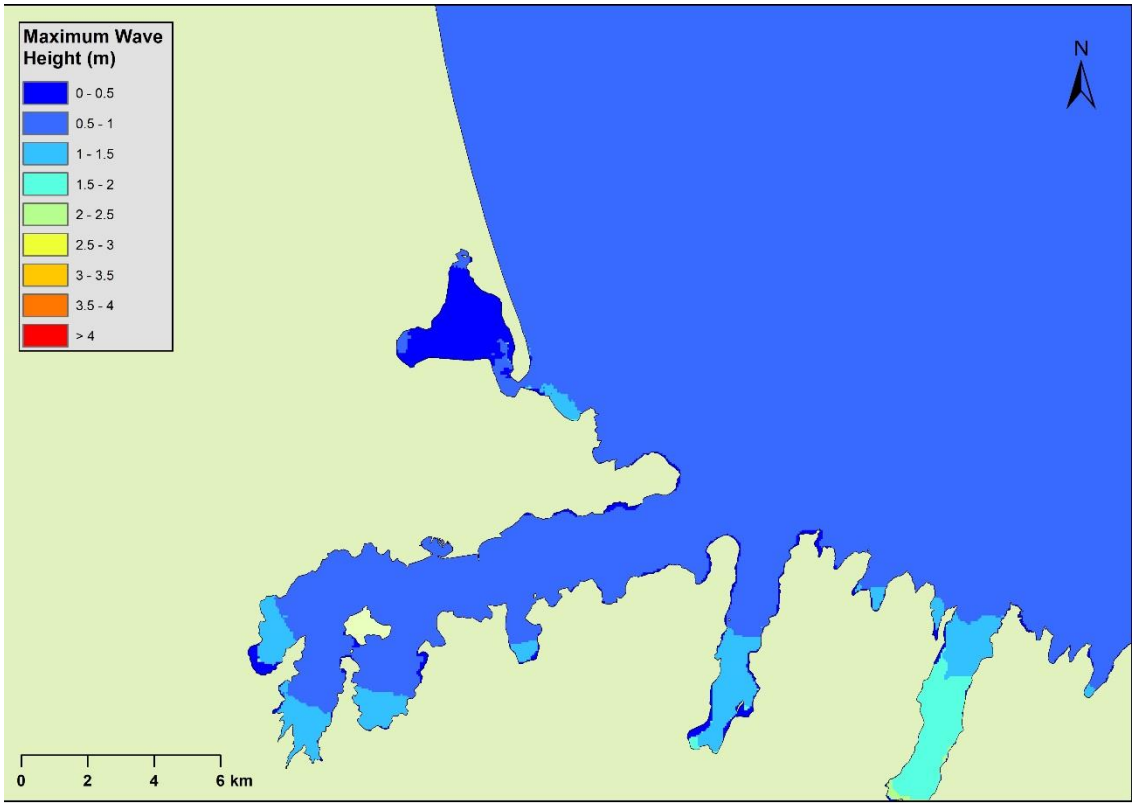

Figure B-7: Close-up of Christchurch City: Maximum water level over entire simulation for rupture of Pegasus1nw fault.

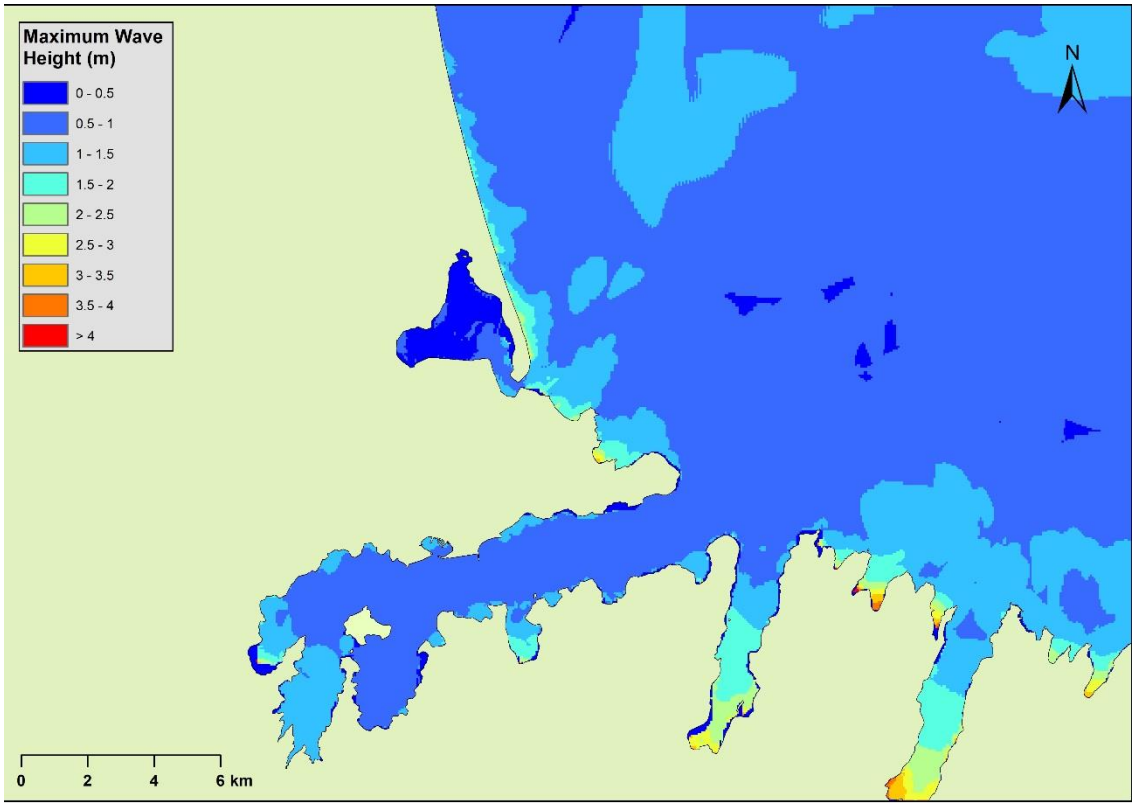

Figure B-8: Close-up of Christchurch City: Maximum water level over entire simulation for rupture of LeithfieldNC1137 and NorthCant8 faults.

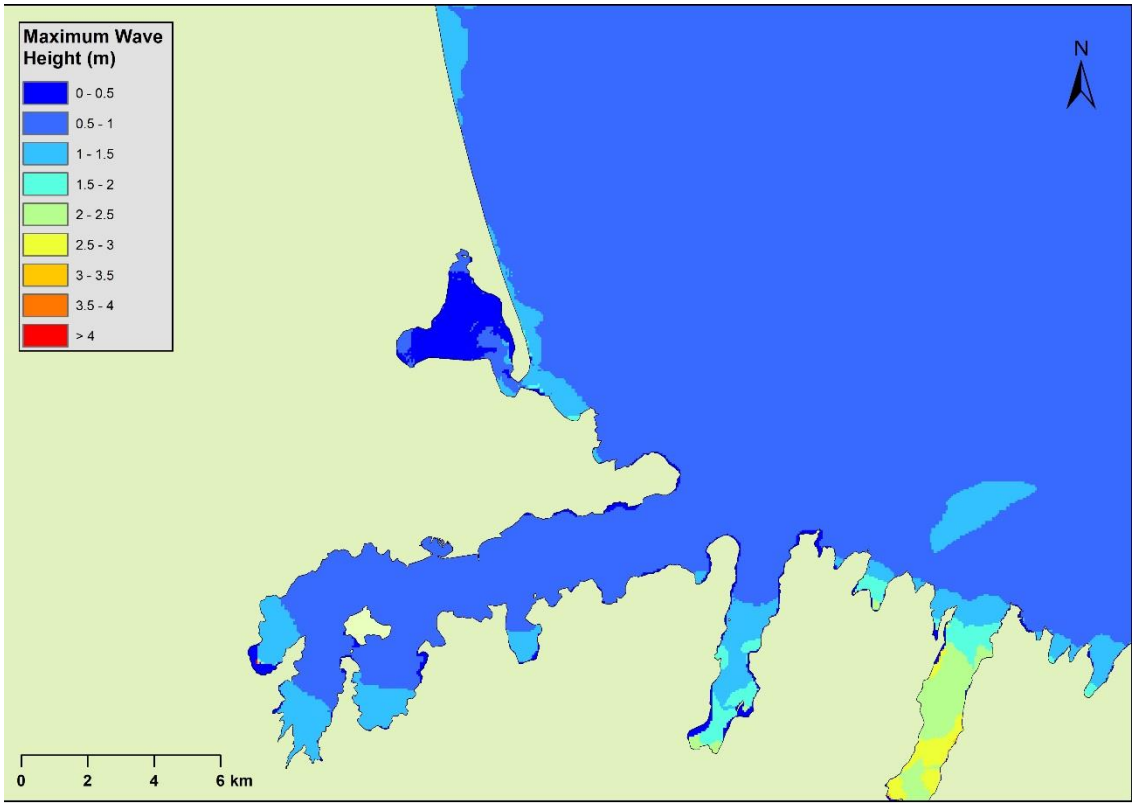

Figure B-9: Close-up of Christchurch City: Maximum water level over entire simulation for rupture of Pegasus1nw and NorthCant4 faults.

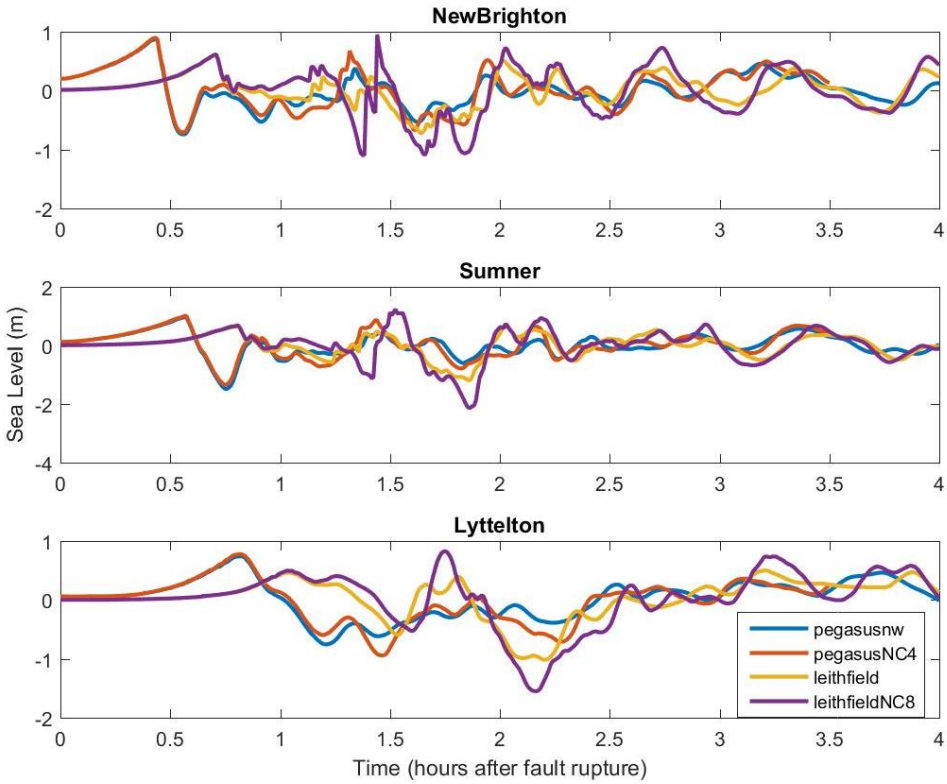

Figure B-10: Time series for tsunamis off-shore New Brighton, Sumner and Lyttelton.

Appendix F. Current dune crest elevations against extreme water levels with SLR

NOTE: In the figures below the probability of water levels is expressed as Average Recurrence Interval (ARI) – i.e., the average time period between exceedances of a given water level. For ARIs greater than 10 years the ARI is equivalent to the reciprocal of the annual exceedance probability (AEP) used in the body of this report.

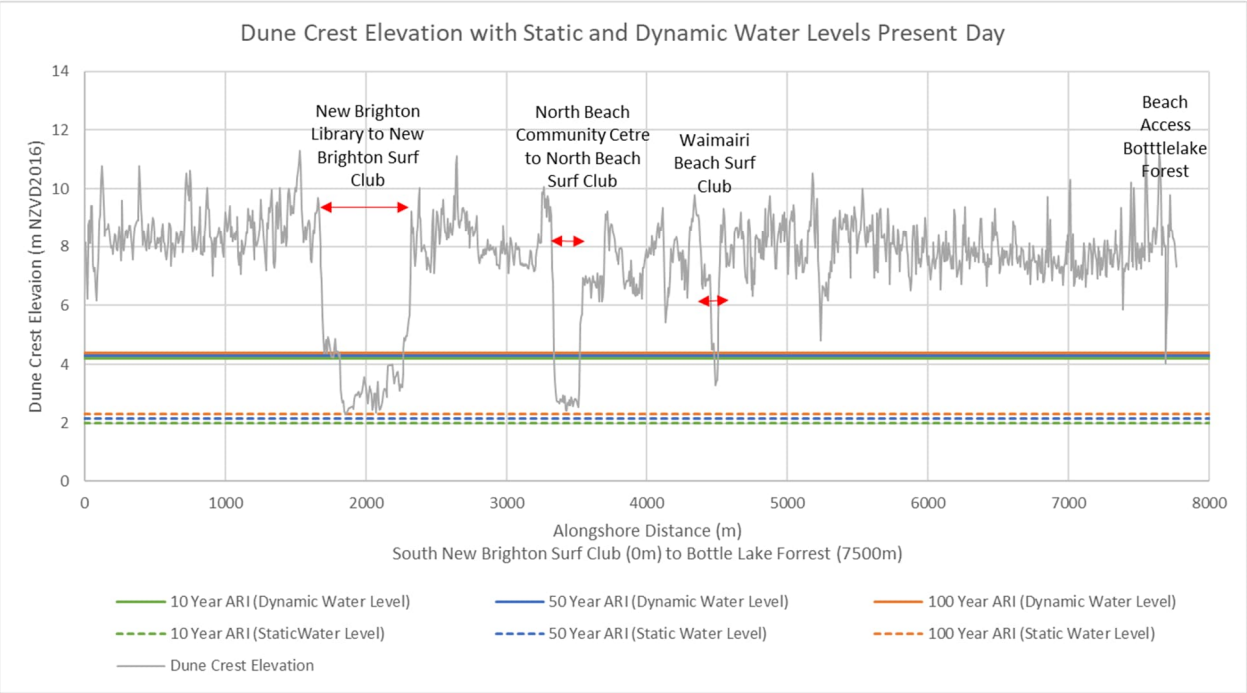

Figure F-1. Present day dune crest long-shore profile, with extreme water levels for present day sea levels.

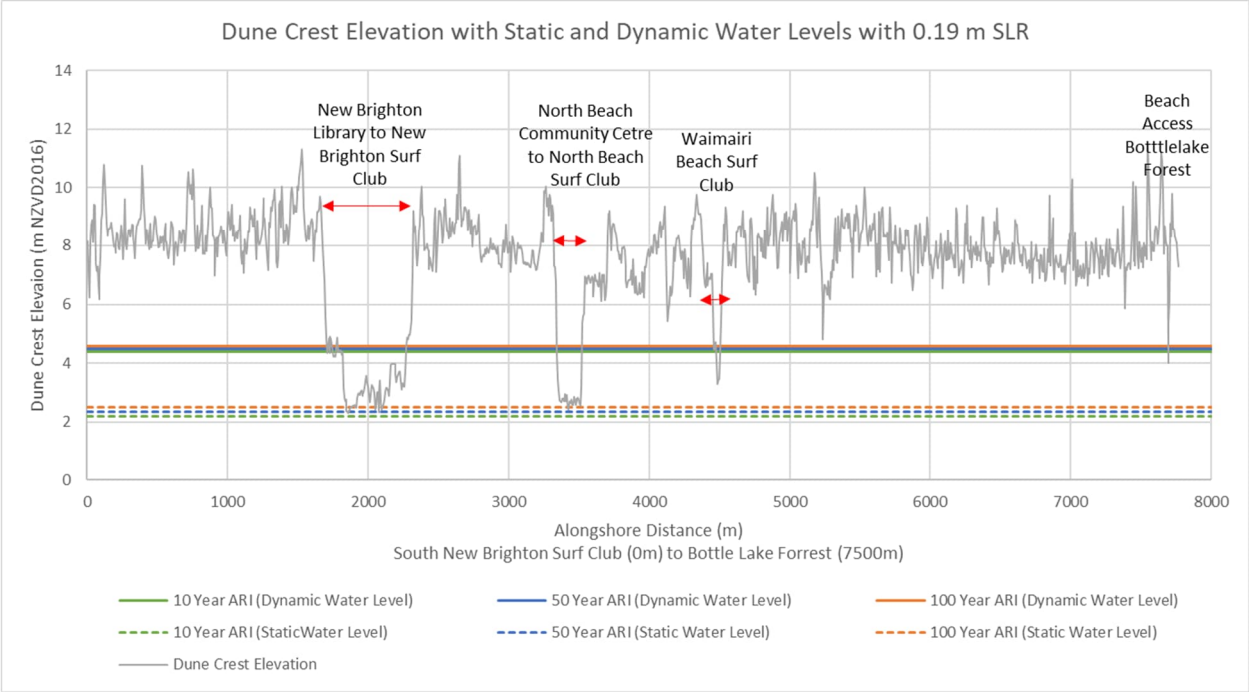

Figure F-2. Present day dune crest long-shore profile, with extreme water levels for 0.19 m SLR.

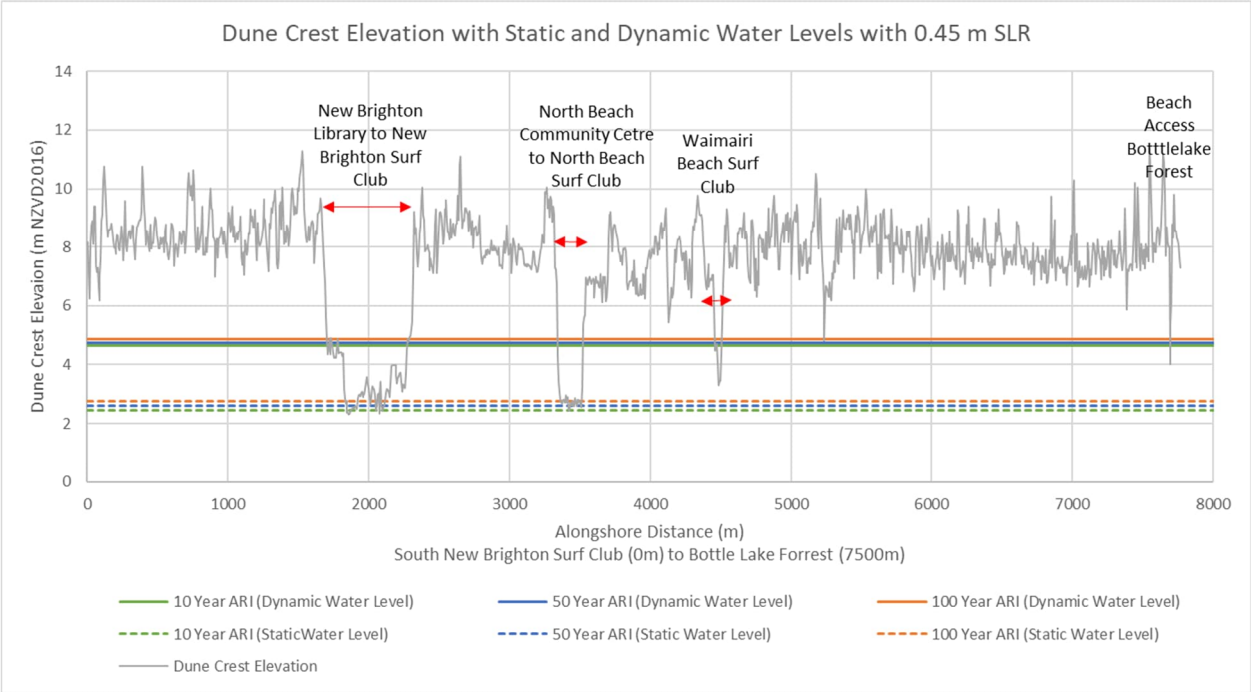

Figure F-3. Present day dune crest long-shore profile, with extreme water levels for 0.45 m SLR.

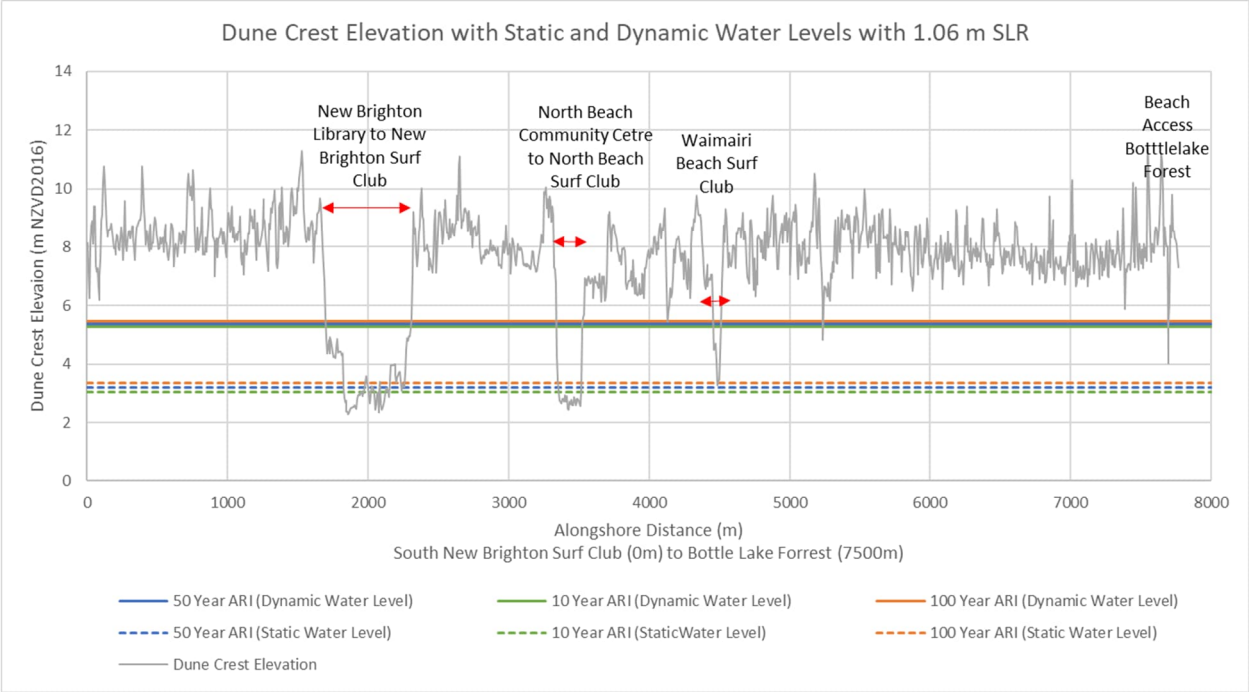

Figure F-4. Present day dune crest long-shore profile, with extreme water levels for 1.06 m SLR.

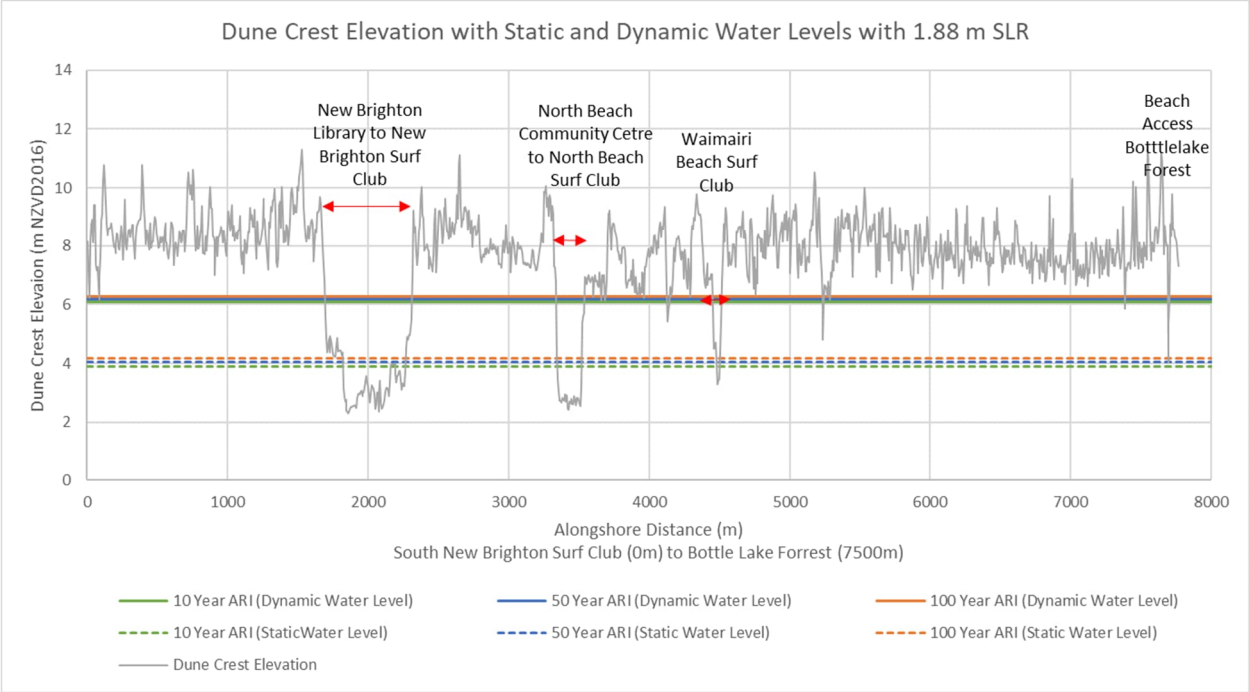

Figure F-5. Present day dune crest long-shore profile, with extreme water levels for 1.88 m SLR.

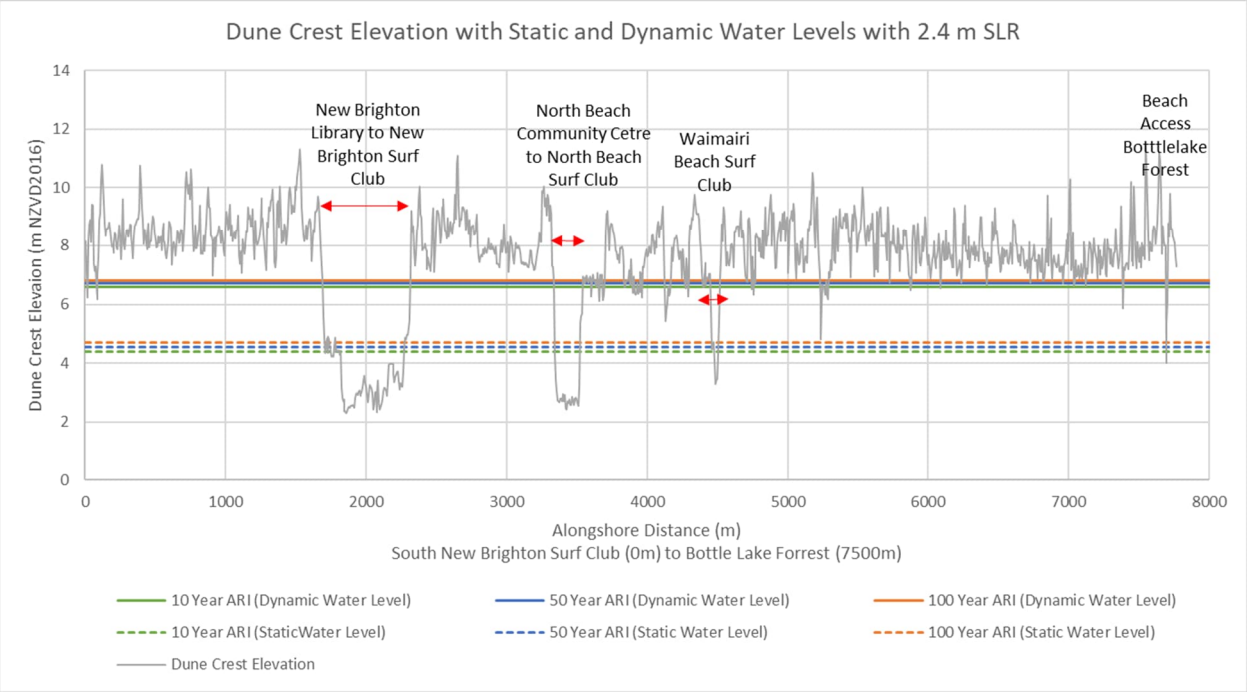

Figure F-6. Present day dune crest long-shore profile, with extreme water levels for 2.4 m SLR.

Appendix G. Eroded dune crest elevation scenarios against extreme water levels with SLR

NOTE: In the figures below the probability of water levels is expressed as Average Recurrence Interval (ARI) – i.e., the average time period between exceedances of a given water level. For ARIs greater than 10 years the ARI is equivalent to the reciprocal of the annual exceedance probability (AEP) used in the body of this report.

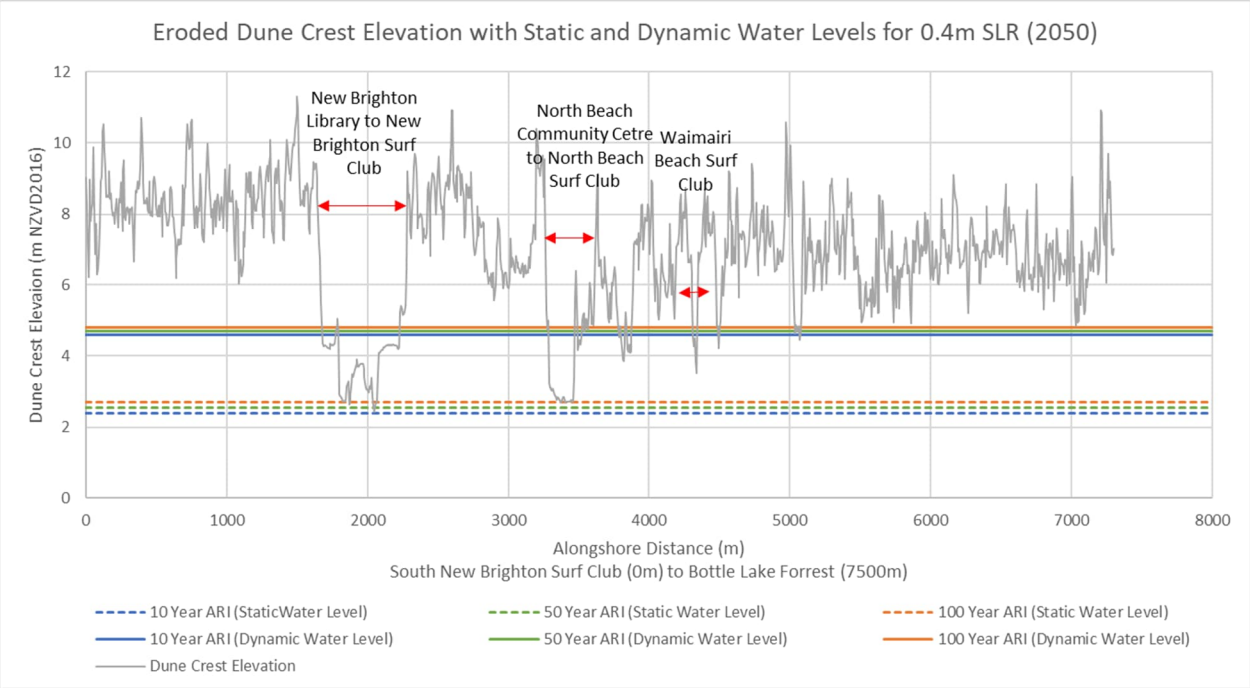

Figure G-1. Eroded dune crest long-shore profile under 0.4 m SLR scenario, with extreme water levels including SLR.

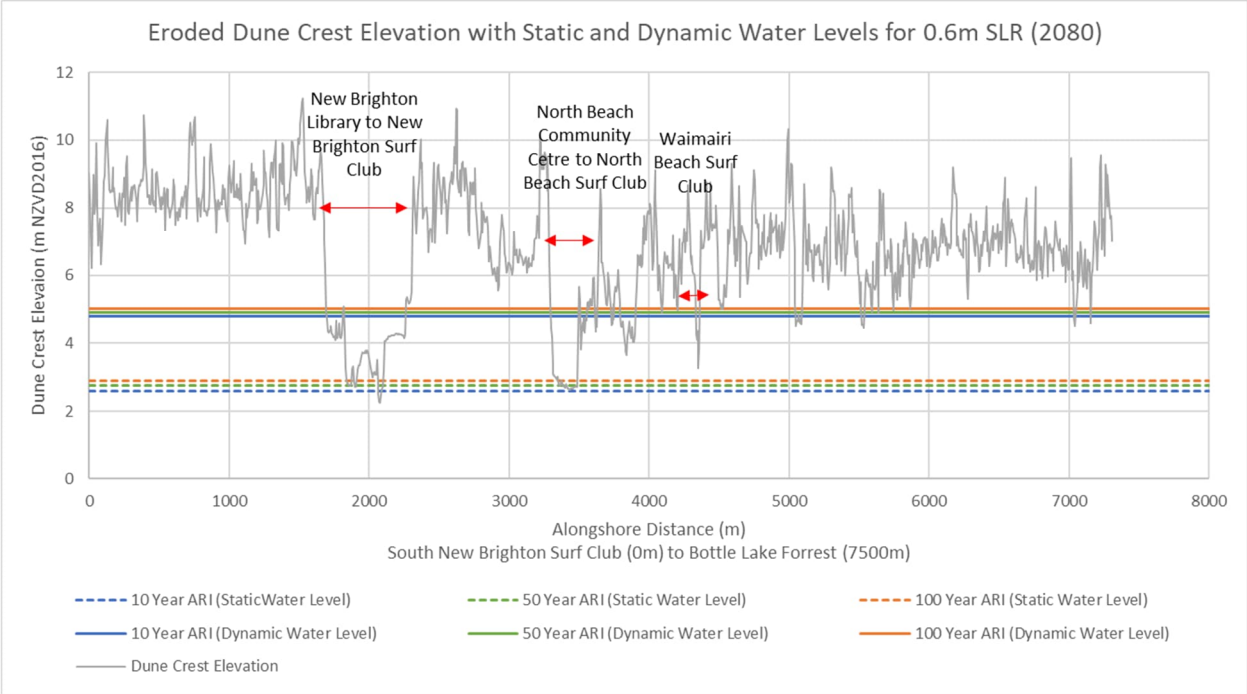

Figure G-2. Eroded dune crest long-shore profile under 0.6 m SLR scenario, with extreme water levels including SLR.

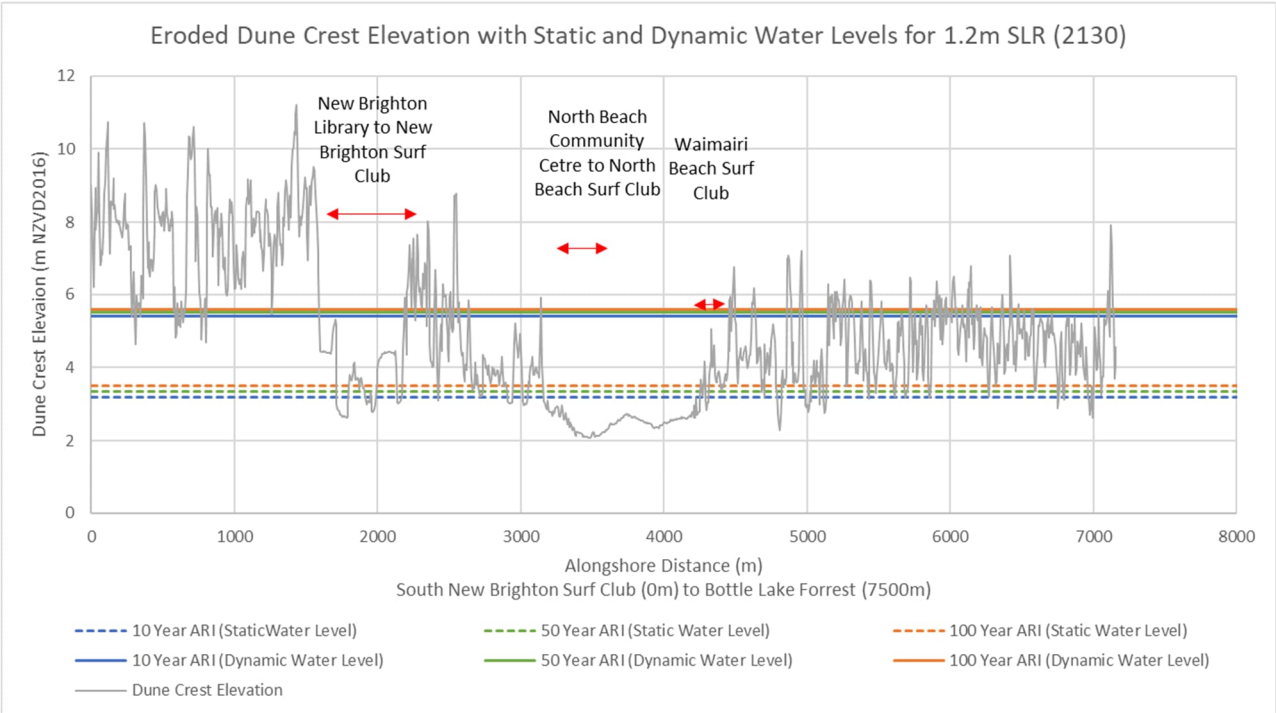

Figure G-3. Eroded dune crest long-shore profile under 1.2 m SLR scenario, with extreme water levels including SLR.

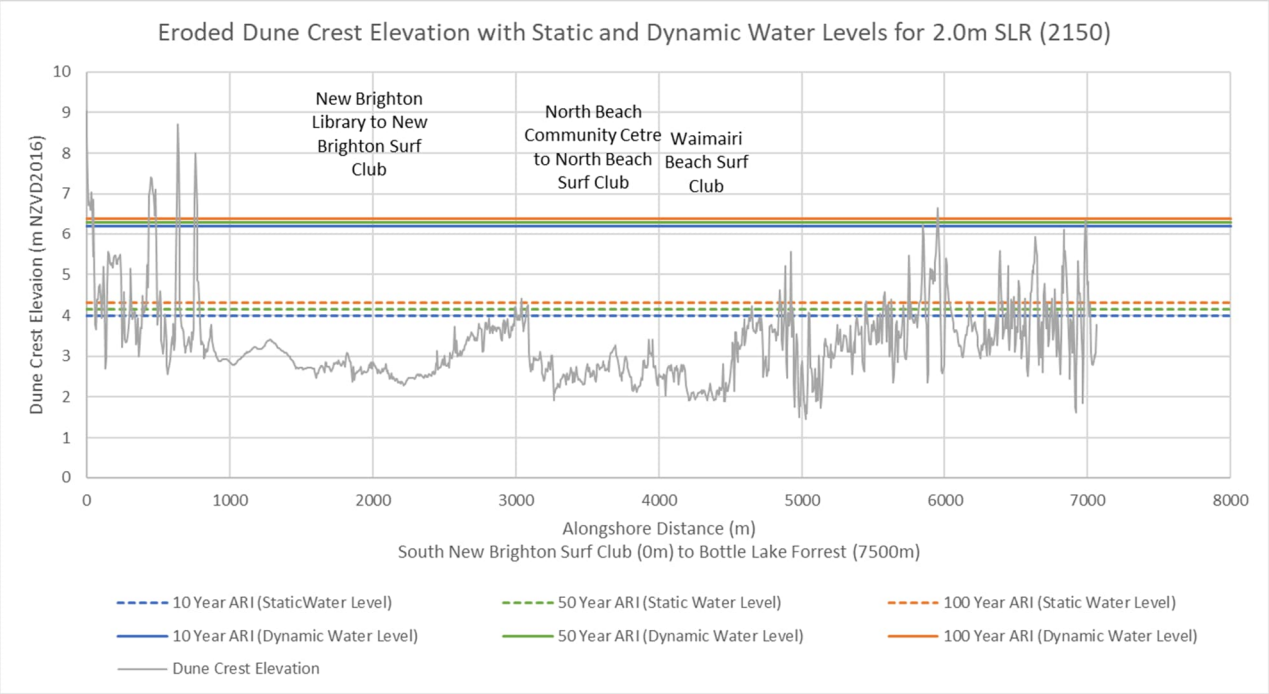

Figure G-4. Eroded dune crest long-shore profile under 2.0 m SLR scenario, with extreme water levels including SLR.

Appendix H. Model method statement memo

Task 3: Model Build Statement

Date:	20 October 2025
Project name:	LDRP97 Multi Hazards Stage 3
Project no:	IZ084400
Attention:	Martin Densham, Tom Parsons
Company:	Christchurch City Council
Prepared by:	Kristin Stokes, Camille Cuadra
Reviewed by:	Damian Debski
Document no:	IZ084400-NW-MEM-0008
Revision no:	E -Updated to incorporate VLM method
Copies to:	Matt Balkham

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The purpose of Task 3 of the Multi Hazards Stage 3 project is to include a representation of the flood management measures which will be implemented as part of the Ōtākaro Avon River Corridor (OARC) Regeneration Plan in the Avon River City Wide Model. The baseline model was developed by GHD on behalf of Christchurch City Council (CCC). The model will then be used to simulate a selection of the scenarios previously modelled with the baseline model.

This memo records the changes we have made to the baseline model to represent the OARC Regeneration Plan elements of:

- New, setback, stopbanks along the lower Ōtākaro Avon River
- Additional stormwater pump stations for catchments along the lower Ōtākaro Avon River
- Additional modification of model elements to realise the intended hydraulic performance

1. Data provided

Data provided by CCC for use in Task 3 are as follows:

- Three-way coupled MIKE FLOOD Avon River City Wide Model (version 114c), baseline model simulation results and model schematisation repot (Model Schematisation 2020 Update - Avon/Estuary, Heathcote and Sumner - Rev 7, GHD, July 2022).
- GIS data for the OARC Regeneration Plan (*20230228_Geopackage_update.zip)*
  - Spatial layers for proposed stopbank alignments, proposed stormwater management areas, proposed pump stations and proposed housing areas.
- GHD pump station calculations spreadsheet – "*AvonPumpStations.xlsm*" detailing estimated pump capacities for each proposed catchment pump station.
- GHD maps showing pump station catchment delineations (51_33273_G002_RevB_AssumedPumpStationsCombinedMapbook.pdf).

2. Approach to representing OARC elements

We have used the 'stopbanks down' version of the baseline model as the basis for the model including the OARC elements. In this version of the model, the existing stopbanks have been removed from the model DEM and the lateral links between the Ōtākaro Avon River 1D model and the 2D floodplain are set to reference ground levels in the modified DEM.

We have used the naming convention for our models as provided in Table C2: File naming convention of "*Citywide Flood Modelling (LDRP097) Model Schematisation 2020 update – Avon/Estuary, Heathcote and Sumner, Rev 7*" (GHD, July 2022). We were provided with model version *114c_Avon*. Our scenario which includes the OARC Scheme uses a scenario suffix… "*_MHvxx_SBPump*" for the Mike 21, Mike 11, MU and couple files. Our final model version used the suffix …"*_MHv06_SBPump*".

We have represented the new OARC stopbanks using linear 'Dike' elements in the 2D model domain. We have set the crest level of the dikes artificially high (100 m CDD compared to typical ground levels within the scheme of 9-13m CDD) since the design crest levels will be set to prevent overtopping, including freeboard, settlement and climate change allowances. In this way the 1D model water levels give an indication of the water levels which need to be retained by the proposed stopbanks.

We have represented the new stormwater pump stations as a combination of 'MU pumps' and '2D Pumps'. The MU pumps are modelled in Mike URBAN and are sited at the first manhole upstream of the new stopbanks on the largest network close to a proposed pump. The MU pumps discharge to the Avon River and are linked to the nearest river cross section. The 2D pumps are represented by point source-sink pairs which extract surface water from the 2D surface outside the stopbanks and transfer the flow to the 2D surface that lies within the stopbanks. Further details of how these are represented within the model are provided in Section 4.

The OARC Regeneration Plan also includes stormwater basins. The basins will provide treatment of surface water together with some storage which can be used to reduce the required pump capacity. We have not included the basins in the model because the intention is to simulate the effect of the improvement in drainage of stormwater, through pumping or a combination of pumping and detention, on flooding rather than the treatment of stormwater. It may be possible to reduce pump capacity below those modelled through use of storage but the effects on flooding in the catchments are likely to be similar.

Prior to performing the intended simulations of future scenarios, we tested the functionality of the model and demonstrated the effects of the new flood management measures, as represented in the model, through performing simulations of selected future scenarios as follows:

- 0.45m SLR (~2060) 50 Year ARI rainfall (18 hour duration) with a 7 Year ARI tide
- 0.45m SLR (~2060) 200 Year ARI rainfall (18 hour duration) with a 13 Year ARI tide
- 0.45 m SLR (~2060) 50 Year ARI tide with 7 Year ARI rainfall (18 hour duration)
- 0.45 m SLR (~2060) 200 Year ARI tide with 13 year ARI rainfall (18 hour duration)

The full list of events and scenarios modelled in Task 3 is provided in Appendix C, Table C-1 and Table C-2. List **of Events and Durations to be modelled for each Scenario in Table C 1**

3. Stopbanks

The OARC geopackage included the spatial dataset 'main.Stopbank_cl_Proposed' which represents the centreline of the new stopbanks alignment. We have adopted this alignment for the Dikes within the MIKE21FM model component, using the same parameters as used for stopbank crests in the original model version.

Table 1. Model Dike parameters

Parameter	Value
Dikes>Type	Empirical Formula
Dikes>Critical_level_difference	0.01

Dikes>Coefficient	1.838	
Dikes>Specification_of_crest_level **(refer to Appendix A: Table A-1 for details of the specification used for each Dike)**	• 'Varying in space' for stopbank up scenario • 'Constant' with 0m crest level for existing stopbanks along the OARC scheme. • 'Constant' with 100m crest level for OARC stopbanks • Constant with 100m crest level for existing coastal stopbanks, e.g. South Shore	Existing model Dikes Some existing model Dikes Used for both existing and new Dikes
Dikes> Activated/Deactivated	Dike in list unticked	For dikes that overlapped the new OARC Dikes

We have made the following adjustments to the stopbank alignment provided in the OARC geopackage, listed from upstream to downstream along the left bank and right bank of the river.

Left Bank:

- Realigned to meet Mike 21 requirement of one triangle between a 1D void and a dike
- Extended north from adjacent to Fitzgerald Ave to Harvey Terrace.
- Split and snapped to 1D stream voids (see example in Figure 1)
- A short length to join the OARC centre line to Stop Bank East 3
- A short length to join Stop Bank East 3 and Stop Bank East 2
- A short length to join Stop Bank East 2 and Stop Bank East 1
- A short length to join Stop Bank East 1 and South Shore North

Right Bank:

- Extended along Oxford Terrace from Willow Street to Kilmore Street
- Split where it crosses 'Avon.Cowlstiv' 1D channel
- Joined at Pages Road and set back from the stream to meet MIKE21 requirement of one triangle between a 1D void and a dike line
- Extended south from the end of Seabreeze Close to high ground adjacent to Anzac Drive

Additional stopbank 'Dike PS205' along the right bank of the 'Avon.Horsehoe' tributary branch, past Pump Station 205.

Represented stopbank along tributary on right bank Avon.Horsehoe between chainage 212 and 280 as a lateral link crest file with a crest level of 100 ('AVON.HORSESHOE_Latlinkcrest.Txt').

Deactivated Stopbank North from the base model.

Ensured no overlapping dike lines by minor adjustments at start and end of Stopbank East 2 , Stopbank East 3 and Stopbank West.

A full listing of the Dike line parameters is provided in Appendix A: Table A-1. The stopbank alignment is shown in Appendix B: Figure B-1 to Figure B-4

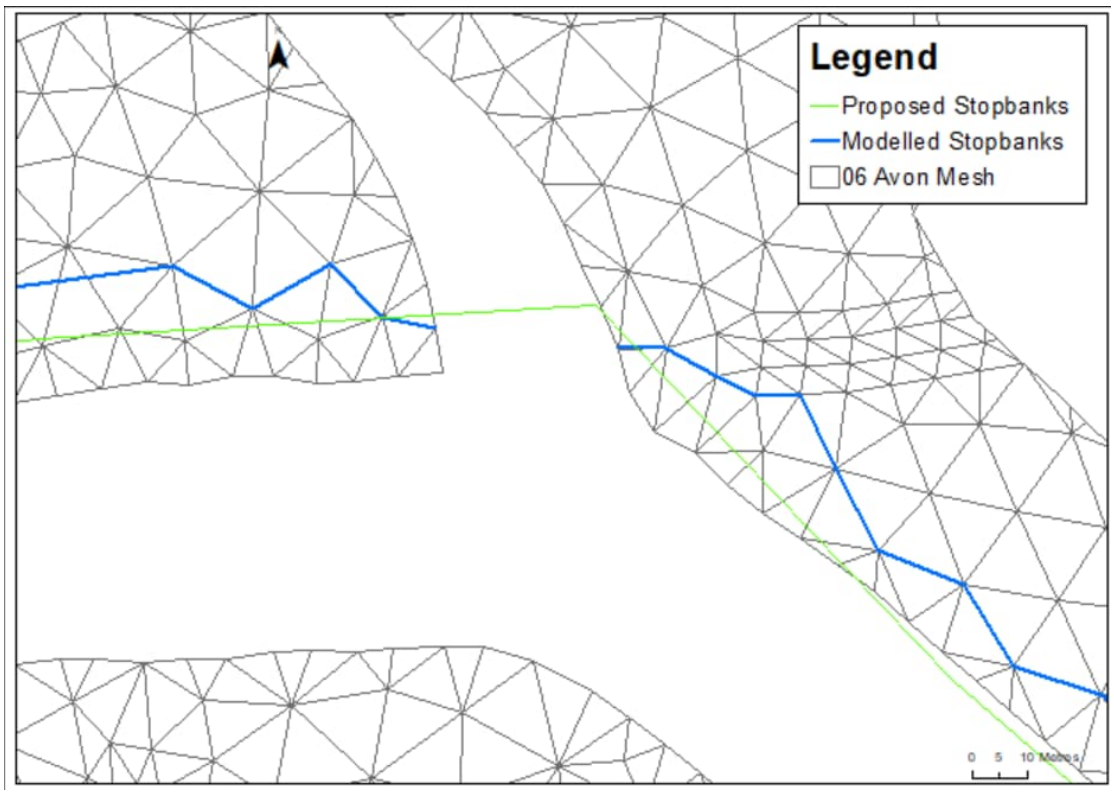


Figure 1. Stopbank alignment at 1D stream void (combined with a non-return valve culvert and weir set to 'No-flow')

Stormwater network

Initial model testing identified a need for changes to the MIKE URBAN model representation of the existing stormwater drainage network to avoid recirculation with the new setback stopbank alignment. To prevent backflow from the river into the floodplain we sealed manholes between the new stopbank and the river and added in non-return valves to pipes that crossed the new stopbank alignment as shown in Figure B-2, Figure B-3, and Figure B-4. Changes made to the MIKE URBAN network to represent these changes were:

- Sealed manholes were set to Cover Type 'sealed' within MIKE URBAN and links were removed from the couple file (Mike FLOOD does not allow sealed manholes to have links in the couple file)
- Pipes that we identified required non-return valves were set to non-return type 'true'
- We added a culvert with valve regulations set to 'no flow to prevent backflow through 'Avon.Cowlstiv' 1D channel at chainage 334. The culvert diameter of 400mm used was the same as the downstream closed cross sections that represent the piped section of this channel.
- Three weirs were set to 'no flow' to prevent backflow if the weirs were overtopped:
  - Avon.katshep at chainage 45
  - Avon.corserst at chainage 958
  - Avon.horsehoe at chainage 200

A full listing of the revisions made to represent the stopbanks are provided in Appendix A: Table A-2 and Table A-3, and is shown in Appendix B: Figure B-1 to Figure B-4.

4. Pumps

We were provided with the following information for the pump stations:

- OARC geopackage feature classes
  - 'main.PumpStation_Proposed' which provides spatial locations of the pump stations.
  - 'main.StormwaterManagementArea_Proposed' which provides polygons of stormwater basins
- GHD pump station calculations spreadsheet – "AvonPumpStations.xlsm" detailing estimated pump capacities for each proposed catchment pump station.
- GHD Memorandum 13 October 2015 "Pump station and detention assumptions.pdf" detailing the pump station and detention assumptions used for the pump station calculations.

Note that the geopackage feature class layer contained two additional pumps stations not listed in the GHD pump station calculations and mapbook: 'PS DC' and 'PS MP'.

GHD used catchments from the River and Tidal Flood Protection (RTFP) project (in some cases small catchments were combined into a consolidated outfall) and using a range of assumptions about flood levels available storage depth, and peak flow calculated using the rational method to estimate pump capacity for each pump. We did not limit the modelled pump capacity as the GHD methodology does not take account of the stormwater collection network capacity of each catchment.

We have represented new pump stations in the model, in the vicinity of the proposed OARC locations to simulate unrestricted pumping with a transfer of pumped flow to the 1D river. Modelling the pumped flow into the river will provide more reliable river levels. We have used the following schematisation :

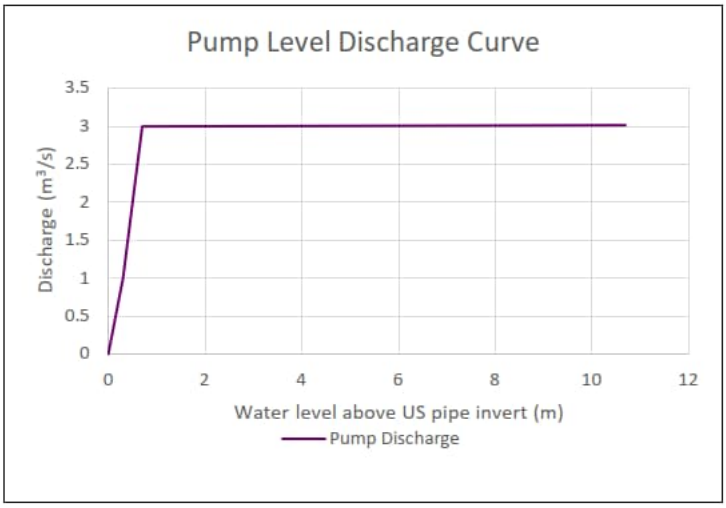
- Where the proposed OARC location is close to an existing stormwater pipe outfall to the river, we have simulated pumping in the 1D model domain by:
  - Disconnecting the Mike URBAN pipe network outlet from the 1D river branch and applying a static water level boundary level 2m above the pump start level.
  - Setting the pipe upstream of the outlet to have a non-return valve.
  - Locating a MIKE URBAN pump at the first manhole outside the stopbank alignment.
  - Representing the wetwell buffering effect by using a manhole diameter of >5m and lowering the manhole invert 1.5m.
  - The addition of a MIKE URBAN pump with a QH capacity type; we adopted a maximum pump capacity of 3.01 m^3/s as our previous modelling found that this should be sufficient for all the additional pumps with the current network configuration. The pump schematisation parameters are shown in Table 2 and a list of the pump names and values is in Appendix A: Table A-5.

  A full listing of the revisions made to represent the pumps are provided in Appendix A: Table A-4, Table A-5 and Table A-6. Locations of pumps is shown in Appendix B: Figure B-1 to Figure B-4.

Table 2. Pump Schematisation Parameters

Parameter	Value
Pump Stop Level	0.1m above downstream pipe invert
Pump Start Level	0.3m above stop level
Acceleration and Deceleration Time	10s

Pump QH capacity curve	H (m)	Q (m^3/s)
	start level	0
	start level +0.3	1
	start level +0.5	2
	start level +0.7	3
	start level +10.7	3.01



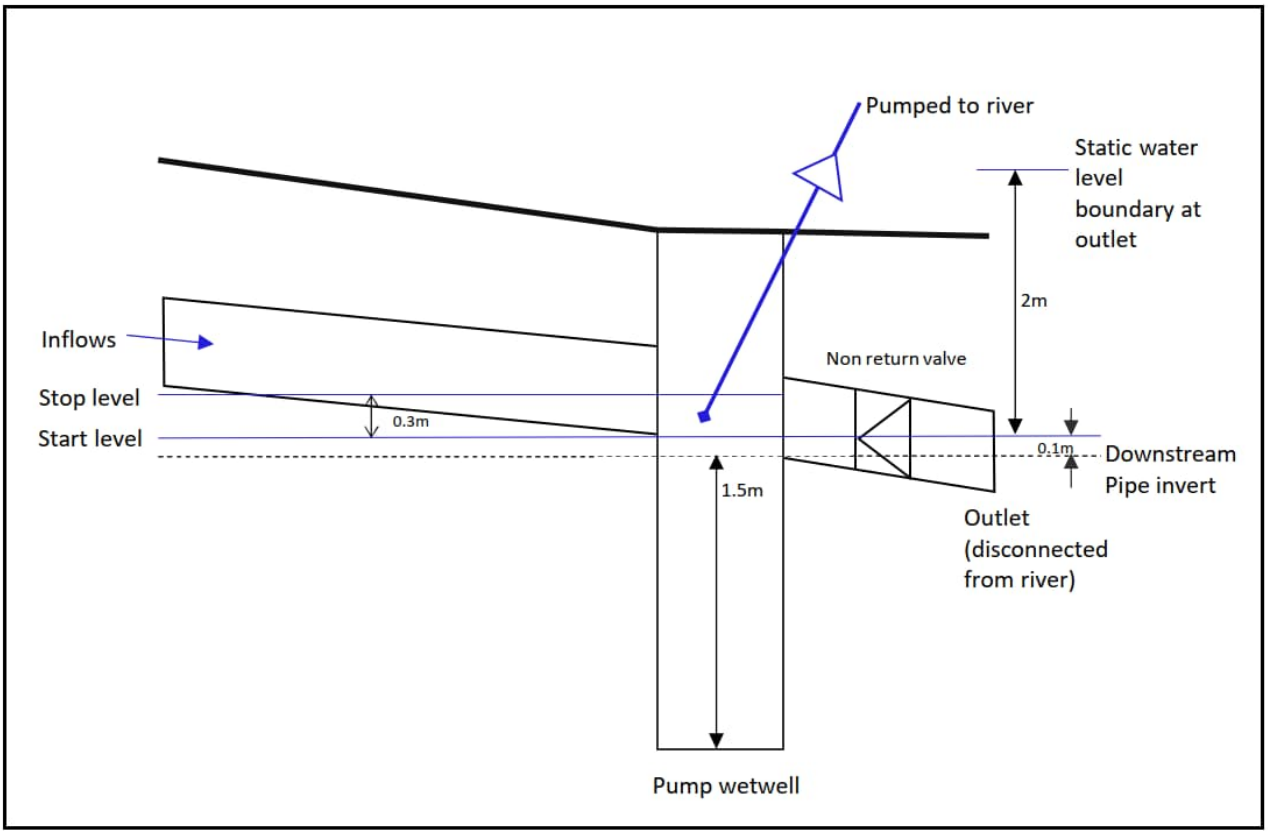


Figure 2. Pump schematisation

- We have also added a point source with negative flow (i.e., a sink) in the 2D model domain outside the stopbank, close to the nominated pump station location, adjusted, where necessary, to be located within

the model flood extent, and within a nominated stormwater basin where possible. The sink capacity was taken to be the larger of the calculated catchment pump station capacity from the GHD spreadsheet or 5 m^3/s. Note that no changes have been made to the 2D surface levels at or around the point sources.

- Each sink is paired with a point source within the stopbank alignment which transfers the pumped flows into the river corridor. A list of the sink-source pairs is provided in Appendix A: Table A-6.

In this way the model simulates a new pump station arranged to drain the existing local stormwater network and capture any overland flow or ponding in the vicinity of the pump station. We note however, that the simulated pumped flow in the model may be limited by network capacity or overland flow paths to less than the calculated pump discharge, derived from catchment runoff estimates.

5. Example model results

Snapshots of results for the Avondale, Wainoni and Bexley areas for the 2060 50R07T18hr event are presented below as an example of the effects of the stopbanks and pumps as they have been represented in the model. We have compared the results to both the 2060 50R07T18hr with existing stopbanks and the 2020 'max of max' results, comprising the overall maximum depths for all the 50 Year ARI events simulated for 2020 conditions with the baseline model (1 hour, 3 hour, 9 hour, 18 hour, 36 hour storm durations for pluvially dominated events plus a tidally dominated event).

For Avondale the results (Figure 3) show that the new stopbanks alone improve flooding (compared to 2060 50R07T 18hr with existing stopbanks). With the addition of the pumps the flooding is reduced to less flooding than the 2060 existing stopbanks scenario and to close to the present day (2020 max of max) flood extent. Figure 5 shows the effects of the simulated unrestricted drawdown in the pipe long section, the peak level is the same as with the existing stopbanks, however with the existing stopbanks this level is still remaining when the model run finished, 24 hours after the peak, while it is only maintained for a short period at the peak of the event in the pumped scenario.

In the Wainoni area (Figure 4) near Torlesse St there is an increase in flooding with the new stopbanks compared to the 2060 50R07T 18hr with existing stopbanks due to an increase in river levels and additional impedance of drainage. The pumping scenario improves flooding to a very similar flood extent to the 2060 existing stopbanks scenario, but there is a small increase in flood extent when compared to the 2020 max of max results. Further away from the river (near Woodham Road) there is no change in flooding with the new stopbanks compared to the 2060 50R07T 18hr with existing stopbanks. The pumping scenario shows a reduced flood extent compared to the 2060 existing scenario, and the extent is very similar compared to the 2020 max of max results.

In the Bexley area (Figure 5) along Pages Road there is a large reduction in flooding with the addition of the new stopbanks. The pumping provides a small additional reduction flooding. The flood extent with the new stopbanks and pumping shows a small improvement compared to the 2020 max of max results.

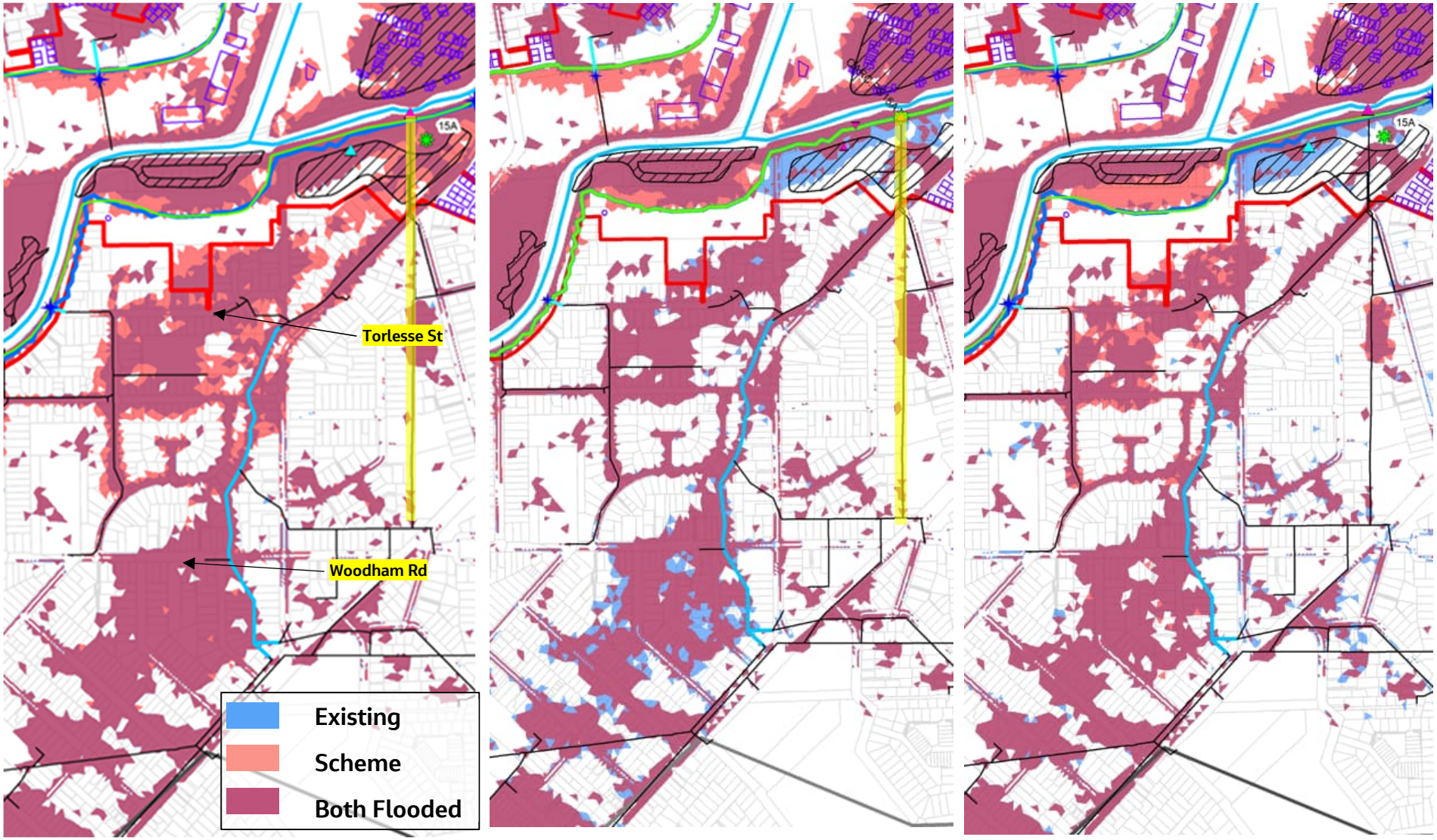
Table 3 shows the GHD calculated pumping capacity for the catchments, the adopted capacity for the sinks in the 2D model and the approximate actual discharge into the 2D modelled pumps (calculated as the 2D flow across a line around the pump). Figure 9 presents the discharge hydrographs for selected 2D point sinks, which show that some remove water at close to capacity for much of the event, while others are operating only near the event peak. It should be noted that since the pumps have generally been modelled as a combination of a Mike URBAN pump and a 2D point sink-source, the total pumped flow at each new pump station location will corresponds to the sum of these two flows.

Long section profiles and pipe discharge comparisons for selected pipes illustrate the pump operation in the model.

Results for the 200 Year ARI were also reviewed to ensure that the modelled changes were appropriate.

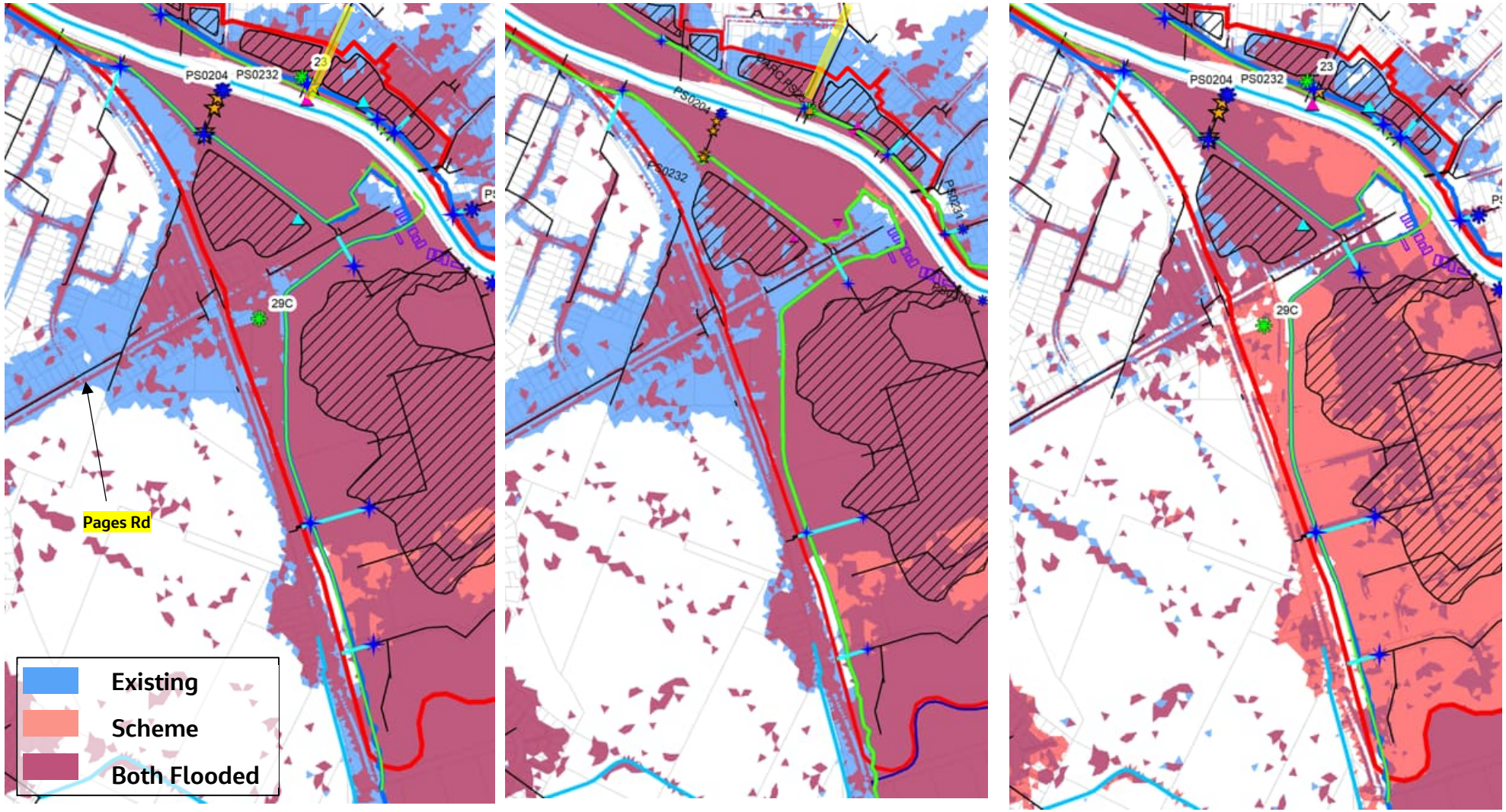
2060 50R07T 18Hr – Existing vs. New SB | 2060 50R07T18Hr – Existing vs. New SB +Pumps | 2020 Max of Max vs. 2060 50R07T 18Hr New SB +Pumps

Figure 3. Comparison of flooding with stopbanks and pumping in the Avondale area (long section for the yellow highlighted pipe is provided in Figure 6)



2060 50R07T 18Hr – Existing vs. New SB | 2060 50R07T18Hr – Existing vs. New SB +Pumps | 2020 Max of Max vs. 2060 50R07T 18Hr New SB +Pumps

Figure 4. Comparison of flooding with stopbanks and pumping in the Wainoni area (long section for the highlighted pipe is provided in Figure 7)



2060 50R07T 18Hr – Existing vs. New SB **2060 50R07T18Hr – Existing vs. New SB +Pumps** **2020 Max of Max vs. 2060 50R07T 18Hr New SB +Pumps**

Figure 5. Comparison of flooding with stopbanks and pumping in the Bexley and New Brighton areas (long section for the highlighted pipe is provided in Figure 8)

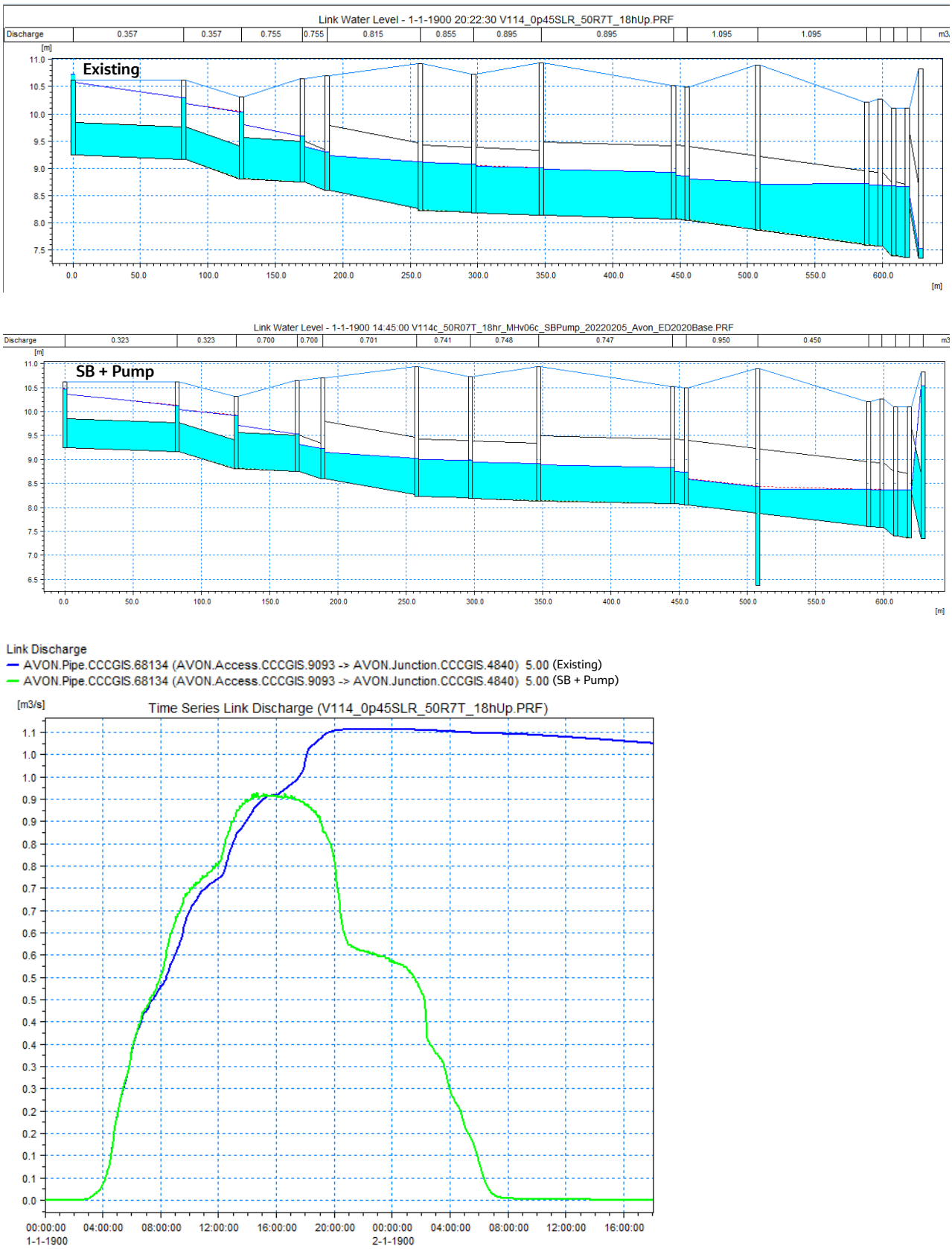


Figure 6. Avondale Area (Pump Station 17) Long Section profile (above) and pump discharge

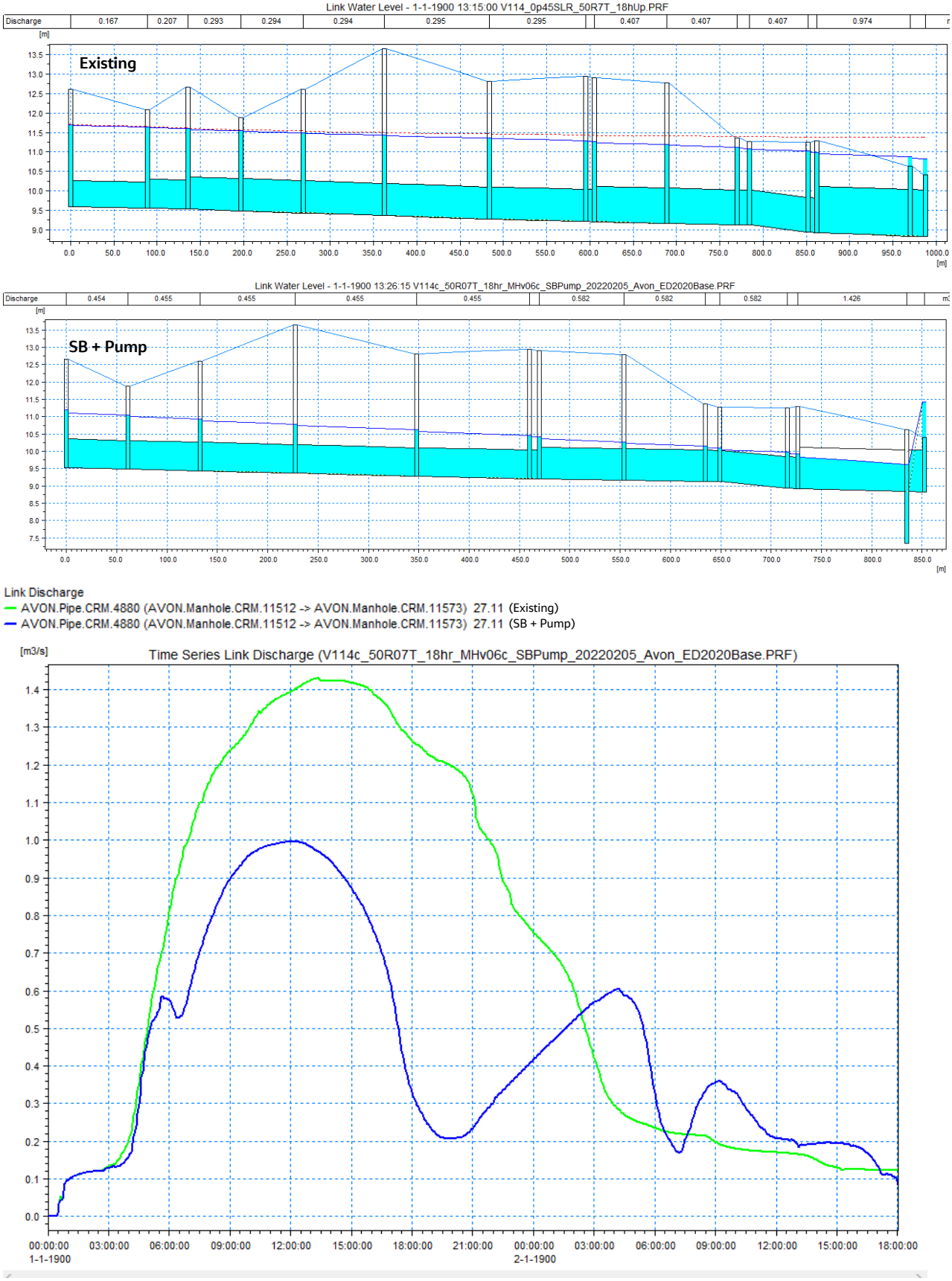
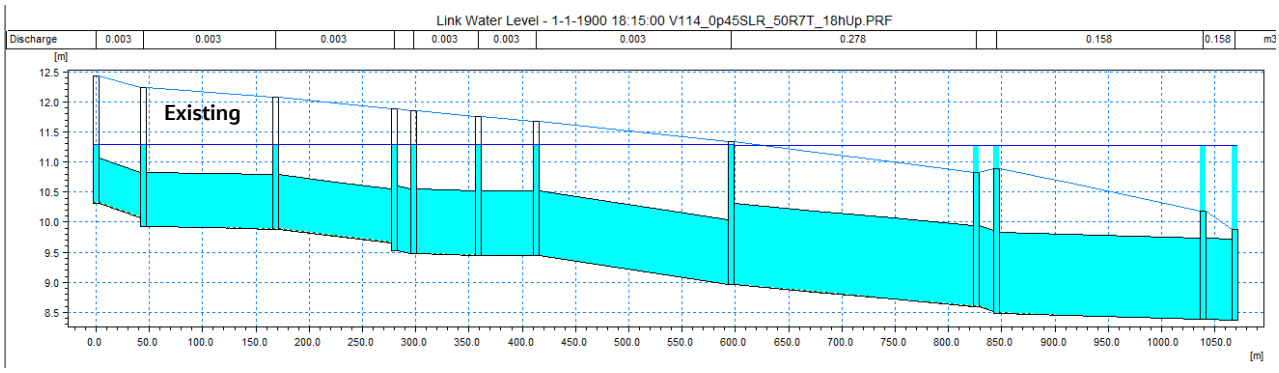
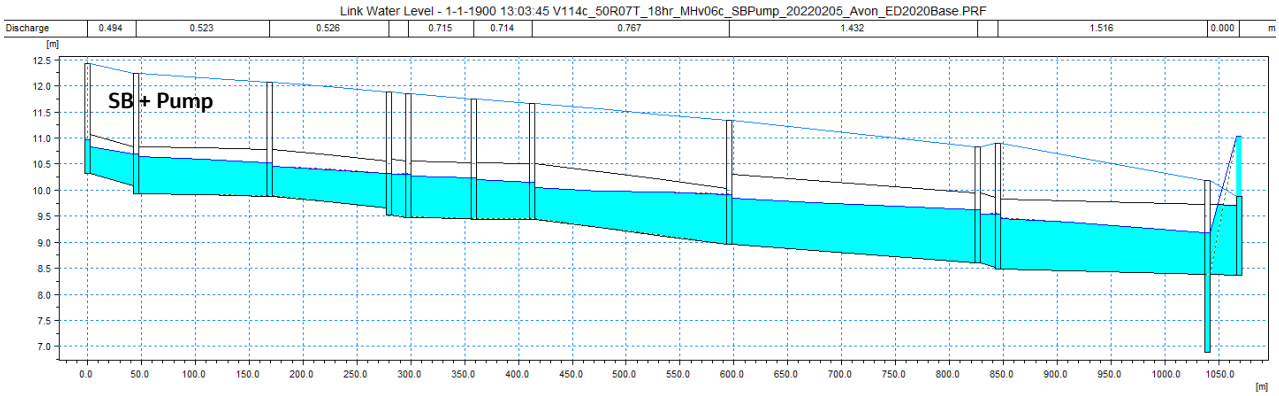


Figure 7. Wainoni Area (Pump Station 15A) Long Section profiles (above) and pump discharge


Link Water Level - 1-1-1900 18:15:00 V114_0p45SLR_50R7T_18hUp.PRF
Discharge
0.003
0.003
0.003
0.003
0.003
0.003
0.278
0.158
0.158
m3
[m]
Existing
[m]


Link Water Level - 1-1-1900 13:03:45 V114c_50R07T_18hr_MHv06c_SBPump_20220205_Avon_ED2020Base.PRF
Discharge
0.494
0.523
0.526
0.715
0.714
0.767
1.432
1.516
0.000
m
[m]
SB + Pump
[m]

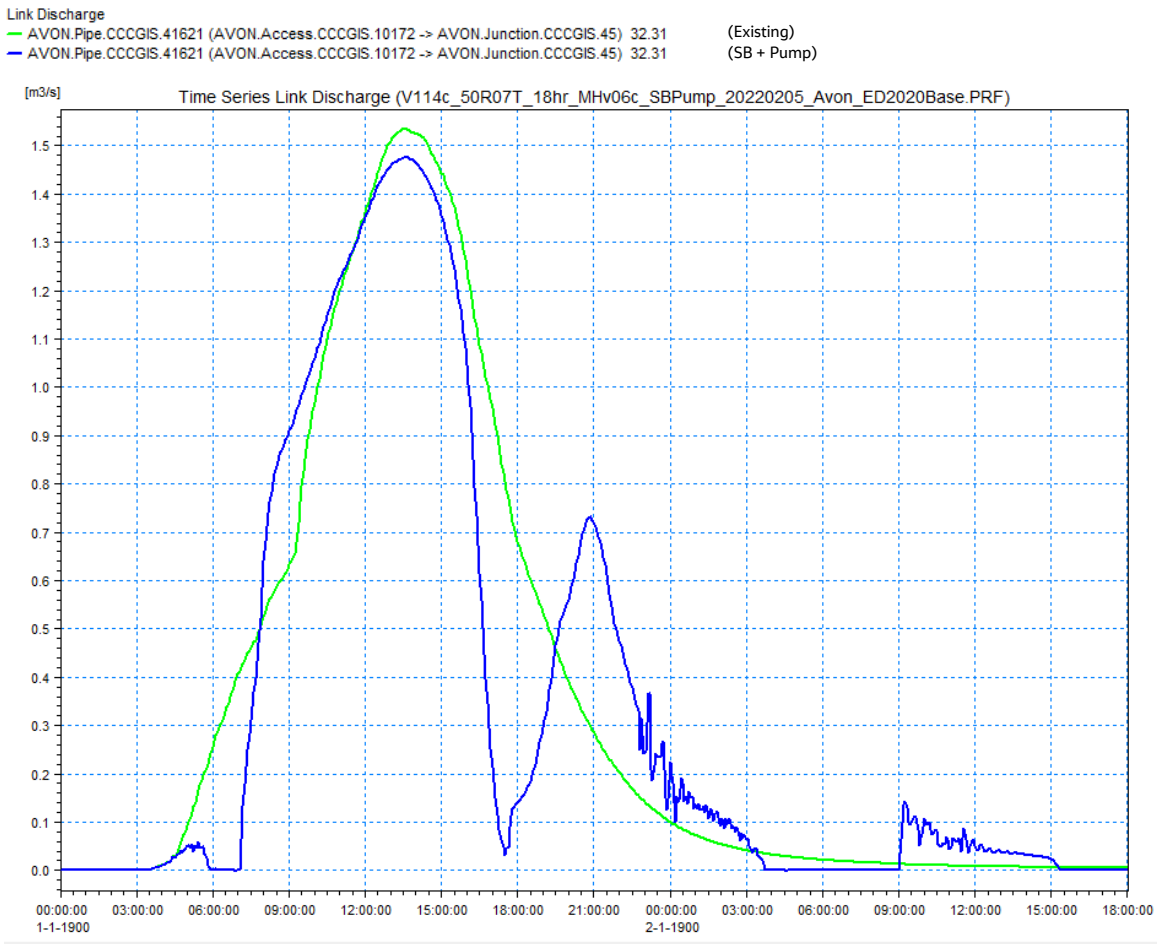

Link Discharge
AVON.Pipe.CCCGIS.41621 (AVON.Access.CCCGIS.10172 -> AVON.Junction.CCCGIS.45) 32.31 (Existing)
AVON.Pipe.CCCGIS.41621 (AVON.Access.CCCGIS.10172 -> AVON.Junction.CCCGIS.45) 32.31 (SB + Pump)
[m3/s]
Time Series Link Discharge (V114c_50R07T_18hr_MHv06c_SBPump_20220205_Avon_ED2020Base.PRF)
1-1-1900
2-1-1900

Figure 8. New Brighton Area (Pump Station 23) Long Section profile (above) and pump discharge

Table 3. Pump capacity and modelled flow (1D/2D)

Pump Name	GHD assessed capacity for catchment	Modelled maximum capacity (m^3/s)	Model maximum discharge -2060 50 Yr. ARI 18 hr.		
			2D (m^3/s)	1D (m^3/s)	Total (m^3/s)
Pump Station 10	1.669	3.01	0.025	0.468	0.493
Pump Station DC	N/A	3.01	0.800	-	0.800
Pump Station 11A	0.624	3.01	0.109	-	0.109
Pump Station MP	N/A	3.01	0.001	-	0.001
Pump Station 14B	5.871	3.01	1.321	1.809	3.130
Pump Station 15A	4.564	3.01	0.810	1.451	2.261
Pump Station 16A	0.435	3.01	0.016	0.307	0.323
Pump Station 17	5.097	3.01	0.109	0.597	0.706
Pump Station 18	4.855	3.01	0.004	-	0.004
Pump Station 19	15.055	3.01	0.034	-	0.034
Pump Station 20	0.286	3.01	0.011	0.256	0.267
Pump Station 22	1.605	3.01	0.026	0.233	0.259
Pump Station 23	8.867	3.01	0.278	1.536	1.814
Pump Station 24	0.738	3.01	0.053	0.415	0.468
Pump Station 25	0.14	3.01	0.065	0.121	0.186
Pump Station 31	3.053	3.01	1.269	-	1.269
Pump Station 29C	1.544	3.01	-	1.232	1.232
Pump Station 30B	0.19	3.01	0.081	0.531	0.612
Pump Station 31	3.05	3.01	-	0.407	0.407
Pump Station 32	0.83	3.01	0.013	0.240	0.253
Pump Station 33	0.570	3.01	0.109	0.028	0.137
Pump Station 8	0.250	3.01	0.025	0.468	0.493

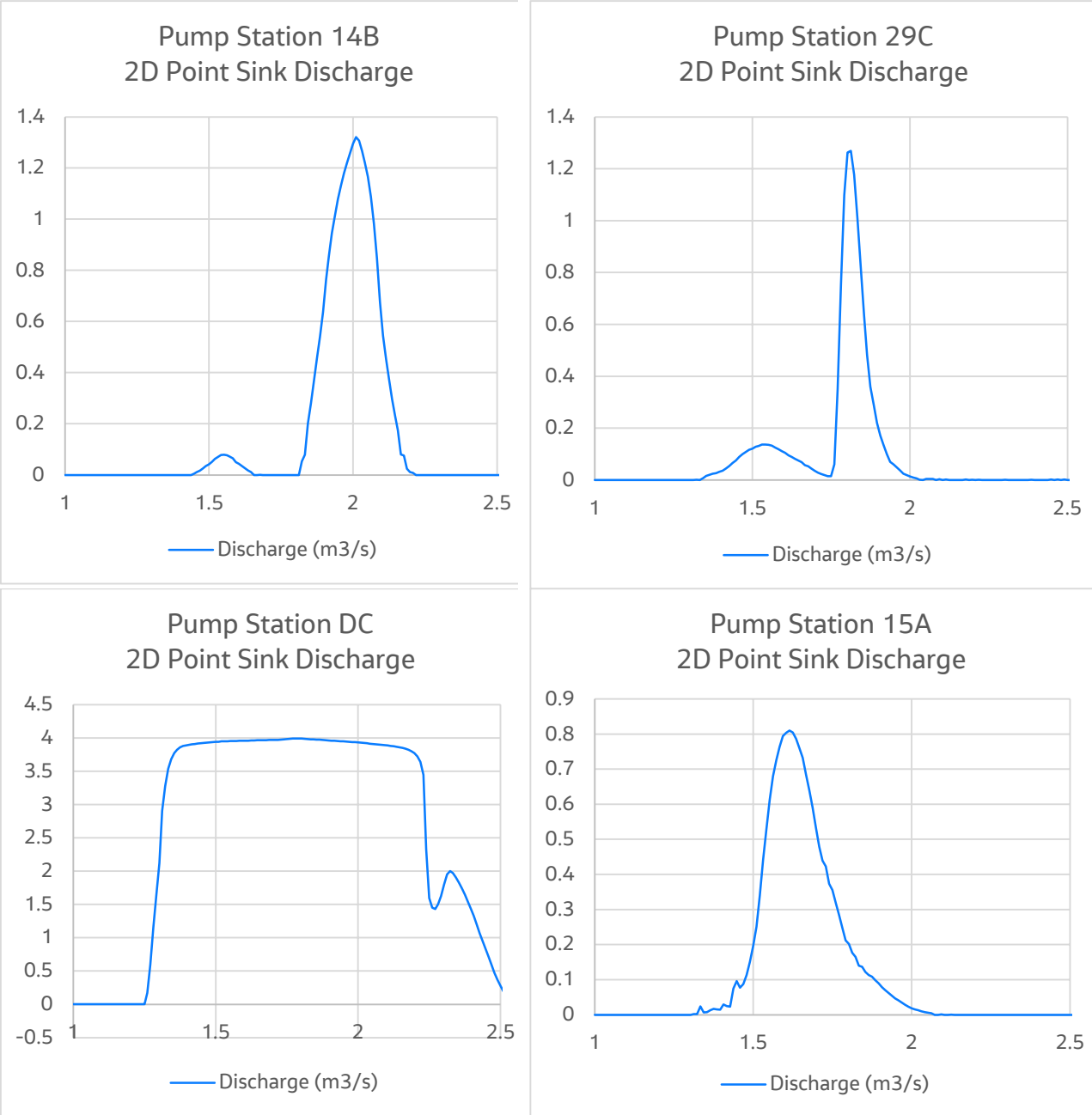


Figure 9. 2D sink modelled discharge hydrographs at 4 pump station locations

6. Limitations of the approach

The model will provide an understanding of the impacts of the new stopbanks and pump stations on flooding compared to the existing infrastructure and the overall benefits of these elements without any other additional flood management measures. The results will also indicate areas where additional infrastructure or network upgrades are required in order for the benefits of additional stormwater pumping to be realised more fully.

Our modelling uses the 'stopbanks down' version of the model, i.e. we assume that the existing stopbanks are fully removed. There is a risk that if the stopbanks are not fully removed the scheme might perform differently and this should be taken into account when using the results of this modelling schematisation.

While there are limitations to the representation as noted above, the model represents the scheme to a level suitable to proceed to the next phase:

- to simulate a selection of the scenarios previously modelled with the baseline model, as outlined in our proposal under Stage 1 modelling

The current version of the model as described in this memo may be suitable for Stage 2 and Stage 3 model runs. Review of the Stage 1 results is required to confirm this.

7. Peer Review

A peer review of the model schematisation has been carried out. The peer review comments and Jacobs' responses are provided in Appendix D. Jacobs met with the peer reviewer on 1st November 2023 to discuss our approach to schematisation of the pumps and basins and agree an approach appropriate for our study objectives.
We have updated this memo to reflect the changes made after the peer review and will complete the recommended changes to the model and provide these to the peer reviewer.

8. Stage 2 and Stage 3 Model Schematisation

The model has been peer reviewed by DHI and the changes as proposed in Appendix D and documented in this revision (C) of the memo have been made to the model to enable modelling of Stage 1: to meet the required performance from 2020 to 2060 (up to 0.45 m SLR). The Stage 1 schematisation includes all the pumps proposed for the OARC scheme in the model, there are no limits on the pumping (free outflow), and the stop banks are glass walled.
Stage 2 modelling is to meet the required performance from 2060 to 2100 (0.45 to 1.06 m SLR), while Stage 3 modelling is to meet the required performance from 2100 to 2150 (1.06 to 1.88 m SLR). Jacobs recommends that this model schematisation, developed for the Stage 1 modelling is also appropriate for assessing Stages 2 and 3. The model and results from it can be used to understand at a high level the potential benefits of stopbanks and pumping, assuming there are no network upgrades. This allows an understanding of where network upgrades are also required to realise additional benefits outside the scheme boundary and will allow comparison of the potential performance of the pump stations and stop banks for the Stage 2 and 3 future epochs.

9. Vertical land movement (VLM) modelling

We have undertaken additional modelling work to simulate the effects of VLM on flooding within the catchment. This follows the availability of new data indicating that VLM rates are higher than previously understood and therefore could affect residual flood risk with the OARC Scheme, as well as the timing and location of Project Response Indicators for flooding and groundwater.

Three plausible scenarios of VLM have been considered for modelling flooding in two of the future dates considered in the project model scenarios (2060 and 2100) as illustrated in Figure 10.

VLM Scenario 1: Post-seismic VLM for 10 years (2020 to 2030) followed by inter-seismic VLM thereafter (considered a less likely scenario)

VLM Scenario 2: Post-seismic VLM for 30 years (2020 to 2050) followed by inter-seismic VLM thereafter (considered a more likely scenario)

VLM Scenario 3: Earthquake "shock" scenario with long term VLM: post-seismic VLM for 30 years (2020 to 2050) followed by inter-seismic VLM from 2050 to 2060; 'instantaneous' liquefaction induced settlement from a seismic event at 2060; post-seismic VLM for 30 years after that event (2060 to 2090) followed by inter-seismic VLM

For post-seismic VLM we have used the spatially varying estimates of current rates of VLM following the 2010-11 and 2016 earthquake sequence as estimated by GNS (Figure 11).

For inter-seismic VLM we have adopted a uniform average rate of -1 mm/year over the whole Avon model and project area based on the NZ SeaRise estimates of ongoing VLM, excluding the effects of seismic events.

For liquefaction induced settlement we have used the same estimated ground settlement in an earthquake event as for the other model scenarios (without VLM), as derived by T+T in Stage 2 of the Multi-Hazards project.

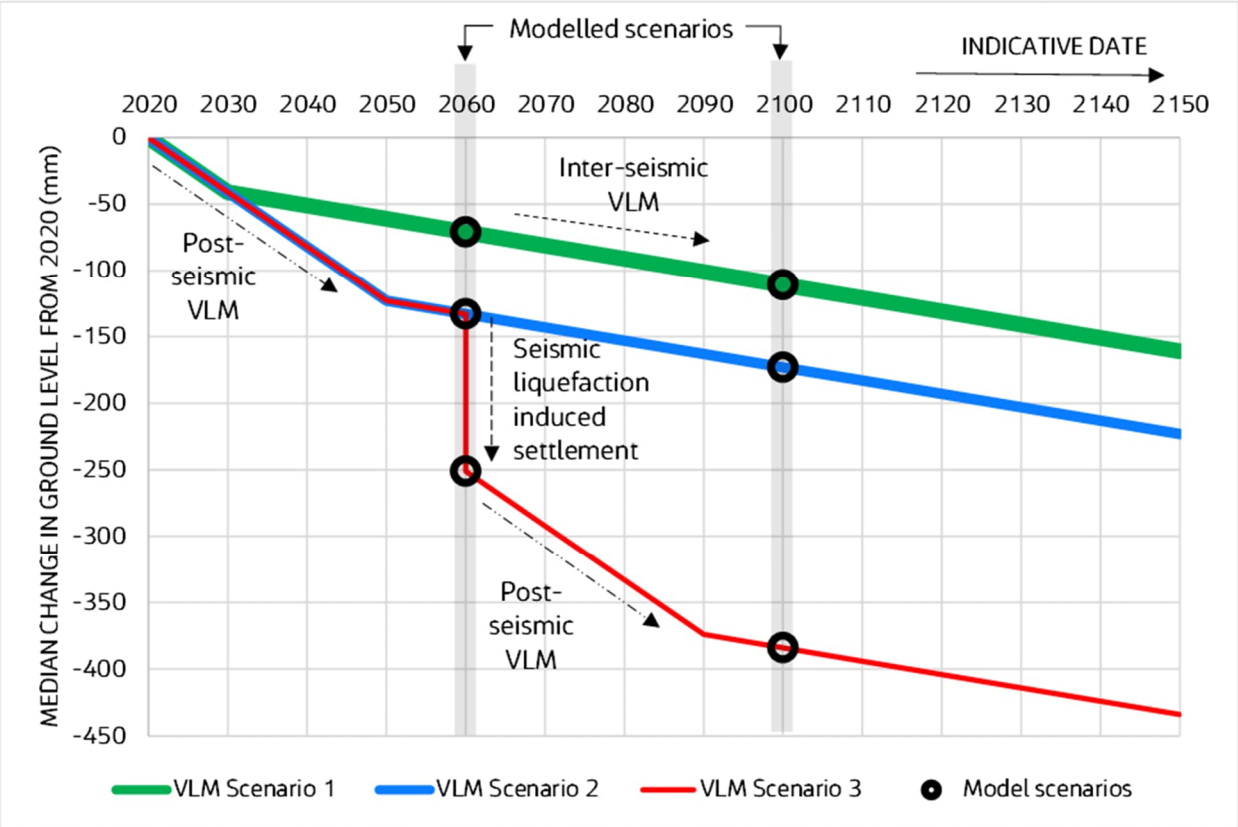


Figure 10. Diagrammatic illustration of the three scenarios of future VLM considered in Stage 3 of the project.

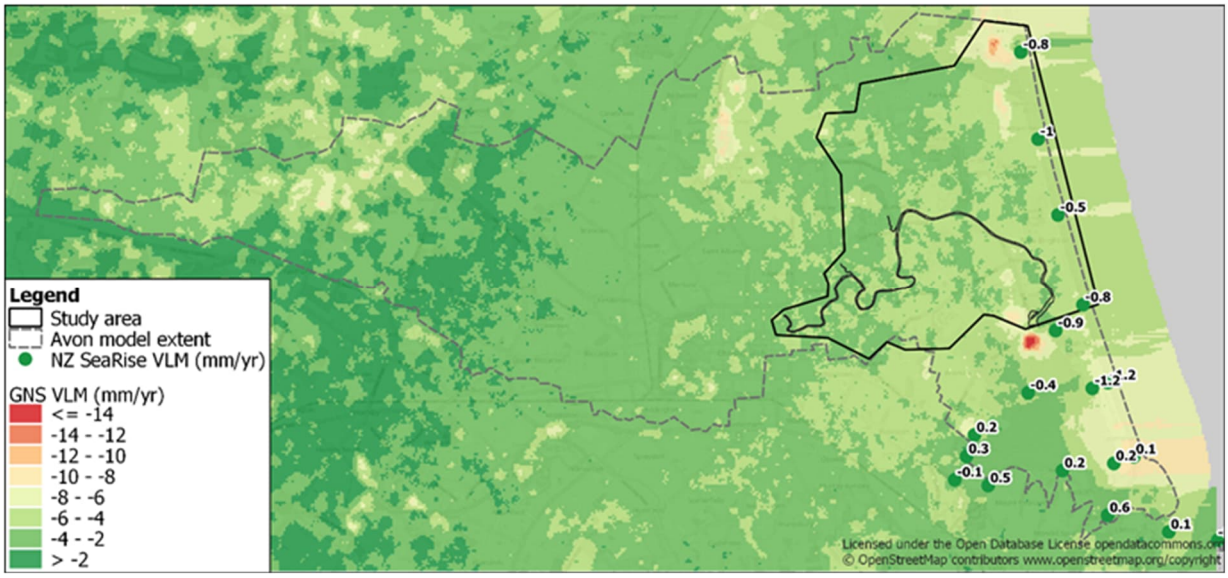


Figure 11. NZ SeaRise inter-seismic VLM values (2025) and post-seismic VLM rates derived by GNS.

We have adopted a simplified approach to incorporate VLM in the model. We have done this by incorporating the scenario-specific VLM values to adjust ground levels in the 2D model for surface flow and the associated linkages to the 1D model of the sub-surface pipe drainage model and the 1D model of the open channels (including the Avon River).

The following steps were undertaken to represent VLM in the baseline and the OARC scheme models:

1. Generate surfaces of total change in ground levels for each of the 3 VLM scenarios

   We derived a surface representing change in ground level from GNS data for spatially varying post-seismic movement, combined with a uniform rate of -1 mm/year informed by NZ Searise data along the coastline for each scenario.

2. Update model input files to reflect projected changes in ground surface due to VLM

   MIKE 21 model

   - The surfaces of change in ground level were then added to the original model ground level mesh files to create new ground level meshes for use in the VLM models.
   - Groundwater depths were updated by adding the scenario-specific VLM values (negative values representing reduction in ground levels) to the existing DFS2 files for groundwater depth below ground value (positive values), generating new groundwater level DFS2 files for each scenario.

   MIKE URBAN model

   - The manhole ground levels were updated using the ground surfaces generated in Step 1.
   - The invert levels were also updated for shallow manholes where the incorporation of VLM caused the invert level to exceed the updated ground level. This adjustment was made by applying the average vertical offset between and invert levels across these affected shallow manholes.

MIKE11 model

- The cross-section markers were updated by adding the scenario-specific VLM values to the .xns11 cross-section files for both the baseline and with OARC scheme models. This is to ensure that lateral links to M21 capture the modified ground levels.
- New hotstart models were set-up and rerun using the updated .xns11 cross-section files.

The VLM models were used to simulate the same combinations of rainfall and storm tide for the same three AEPs as the original models for climate states (SLR and change in rainfall) in 2060 and 2100.

Appendix A. Tables of Modelled Infrastructure

Table A-1. Dike Modelled Parameters

Dike Name	Specification type	Crest Level (m)	Changed from Banks Down
Beachville Road Sea Wall	Constant	100	Y
Monks Bay East Sea Wall	Constant	100	Y
Monks Bay West Sea Wall	Constant	100	Y
PS205 Dike	Constant	100	Y
South Shore Central	Constant	100	Y
South Shore Jellicoe Marsh	Constant	100	Y
South Shore North	Constant	100	Y
South Shore South	Constant	100	Y
Stopbank East 1	Constant	100	Y
Stopbank East 2	Constant	100	Y
Stopbank East 3	Constant	100	Y
Stopbank North	Deactivated	N/A	Y
Stopbank West	Constant	100	Y
Avon RB 1	Constant	100	Y
Avon RB 2	Constant	100	Y
Avon RB 3	Constant	100	Y
Avon RB 4	Constant	100	Y
Avon LB 1	Constant	100	Y
Avon LB 2	Constant	100	Y
Avon LB 3	Constant	100	Y
Avon LB 4	Constant	100	Y
Avon LB 5	Constant	100	Y
Avon LB 6	Constant	100	Y
Avon LB 7	Constant	100	Y
Avon LB 8	Constant	100	Y
Alpine View East	Varying	Specified	N
Alpine View South	Varying	Specified	N
Alpine View West	Varying	Specified	N
Applecross	Varying	Specified	N
Birkdale	Varying	Specified	N
Blake Street	Varying	Specified	N
Burwood Hospital	Varying	Specified	N

Cameo Drive	Varying	Specified	N
Clearbrook	Varying	Specified	N
Cole Porter	Varying	Specified	N
Cranford	Varying	Specified	N
Ellington	Varying	Specified	N
Knights	Varying	Specified	N
Prestons North	Varying	Specified	N
Prestons South	Varying	Specified	N
Prestons South Internal N	Varying	Specified	N
Prestons South Internal S	Varying	Specified	N
Wainoni	Varying	Specified	N
Winters	Varying	Specified	N

Table A-2. Additional Sealed Manholes

MUID	MUID	MUID
AVON.Access.ARM.10084	AVON.Access.CCCGIS.8609	AVON.Junction.ARM.18
AVON.Access.ARM.9737	AVON.Access.CCCGIS.8635	AVON.Junction.ARM.19
AVON.Access.CCCGIS.10404	AVON.Access.CCCGIS.9121	AVON.Junction.ARM.4648
AVON.Access.CCCGIS.10407	AVON.Access.CCCGIS.9718	AVON.Junction.CCCGIS.106
AVON.Access.CCCGIS.10409	AVON.Access.CCCGIS.9834	AVON.Junction.CCCGIS.107
AVON.Access.CCCGIS.11138	AVON.Bend.CCCGIS.710	AVON.Junction.CCCGIS.1559
AVON.Access.CCCGIS.20548	AVON.Bend.CCCGIS.711	AVON.Junction.CCCGIS.2273
AVON.Access.CCCGIS.20551	AVON.Bend.CCCGIS.712	AVON.Junction.CCCGIS.2274
AVON.Access.CCCGIS.20552	AVON.Inlet.ARM.982	AVON.Junction.CCCGIS.45
AVON.Access.CCCGIS.20553	AVON.Inlet.CCCGIS.1816	AVON.Pump.ARM.13
AVON.Access.CCCGIS.20554	AVON.Inlet.CCCGIS.20698	AVON.Pump.CCCGIS.19
AVON.Access.CCCGIS.8537	AVON.Inlet.CCCGIS.44850	

Table A-3. Additional non-return Valves on pipes/ flap gates on culvert

MUID	MUID	MUID
AVON.Pipe.CCCGIS.4886_1	AVON.Pipe.CCCGIS.5143	AVON.Pipe.CCCGIS.8038
AVON.Pipe.ARM.1081	AVON.Pipe.CCCGIS.4855	AVON.Pipe.CCCGIS.80702
AVON.Pipe.ARM.3402	AVON.Pipe.CCCGIS.6442	AVON.Pipe.CCCGIS.80858
AVON.Pipe.ARM.1154	AVON.Pipe.CCCGIS.66777	AVON.Pipe.CCCGIS.8087
AVON.Pipe.ARM.1895	AVON.Pipe.CCCGIS.57087	AVON.Pipe.CCCGIS.861
AVON.Pipe.ARM.64189	AVON.Pipe.CCCGIS.57109	AVON.Pipe.CCCGIS.864
AVON.Pipe.ARM.64195	AVON.Pipe.CCCGIS.57359	AVON.Pipe.CCCGIS.867
AVON.Pipe.ARM.962	AVON.Pipe.CCCGIS.57386	AVON.Pipe.CCCGIS.904
AVON.Pipe.ARM.2099	AVON.Pipe.CCCGIS.66792	AVON.Pipe.CCM.8005

AVON.Pipe.ARM.2123	AVON.Pipe.CCCGIS.4818	AVON.Pipe.CCM.8029
AVON.Pipe.ARM.2126	AVON.Pipe.CCCGIS.4828	AVON.Pipe.CCM.38249
AVON.Pipe.CCCGIS.2136	AVON.Pipe.CCCGIS.4984	AVON.Pipe.CCM.57835
AVON.Pipe.CCCGIS.2073_M	AVON.Pipe.CCCGIS.5108	AVON.Pipe.CCM.7824
AVON.Pipe.CCCGIS.2074	AVON.Pipe.CCCGIS.5151	AVON.Pipe.CCM.8194
AVON.Pipe.CCCGIS.3428	AVON.Pipe.CCCGIS.68313	AVON.Pipe.INFW.56
AVON.Pipe.CCCGIS.3460	AVON.Pipe.CCCGIS.68533	AVON.Pipe.INFW.204
AVON.Pipe.CCCGIS.3469	AVON.Pipe.CCCGIS.67694	AVON.Pipe.CCCGIS.86361
AVON.Pipe.CCCGIS.27698	AVON.Pipe.CCCGIS.6560	AVON.Pipe.CCCGIS.86335
AVON.Pipe.CCCGIS.3496	AVON.Pipe.CCCGIS.6657	AVON.Pipe.CCCGIS.1008_1
AVON.Pipe.CCCGIS.42726	AVON.Pipe.CCCGIS.69378	AVON.Pipe.CCCGIS.8038

Table A-4. Mike URBAN disconnected pipe network outlets (1D pumps)

MIKE URBAN Boundary ID	Outlet Name	Diameter (m)	Water Level Boundary (m)
PUMP_10_AVON.Outlet.CCM.679	AVON.Outlet.CCM.679	0.6	12.32
PUMP_14b_AVON.Access.CCCGIS.8555	AVON.Access.CCCGIS.8555	1.35	10.31
PUMP_15a_AVON.Outlet.CRM.2165	AVON.Outlet.CRM.2165	1.2	11.24
PUMP_16a_AVON.Outlet.CCCGIS.2156	AVON.Outlet.CCCGIS.2156	0.6	11.91
PUMP_17_AVON.Outlet.CCCGIS.260	AVON.Outlet.CCCGIS.260	1.35	10.27
PUMP_20_AVON.Outlet.ARM.255	AVON.Outlet.ARM.255	0.825	11.55
PUMP_22_AVON.Outlet.ARM.4099	AVON.Outlet.ARM.4099	0.525	11.18
PUMP_23_AVON.Outlet.CCCGIS.126	AVON.Outlet.CCCGIS.126	1.35	10.78
PUMP_24_AVON.Outlet.CCCGIS.189	AVON.Outlet.CCCGIS.189	0.9	10.48
PUMP_25_AVON.Outlet.CCCGIS.200	AVON.Outlet.CCCGIS.200	0.6	12.26
PUMP_30b_AVON.Outlet.CCCGIS.512	AVON.Outlet.CCCGIS.512	1.075	11.05
PUMP_31_AVON.Outlet.CCCGIS.14303	AVON.Outlet.CCCGIS.14303	1.2	10.99
PUMP_32_AVON.Outlet.CCCGIS.43	AVON.Outlet.CCCGIS.43	0.6	10.87
PUMP_33_AVON.Outlet.CCCGIS.69	AVON.Outlet.CCCGIS.69	0.675	11.45
PUMP_8_AVON.Outlet.CCCGIS.2137	AVON.Outlet.CCCGIS.2137	0.6	12.01

Table A-5. Mike URBAN Pumps

MIKE URBAN Pump Name	Connected Manhole	Start Level (m)	Stop Level (m)
AVON.Pump.OARC.PS10	AVON.Access.CCM.7517	10.32	10.02
AVON.Pump.OARC.PS14B	AVON.Access.CCCGIS.8442	8.31	8.01
AVON.Pump.OARC.PS15A	AVON.Manhole.CRM.11573	9.24	8.94
AVON.Pump.OARC.PS16A	AVON.Access.CCCGIS.11134	9.91	9.61
AVON.Pump.OARC.PS17	AVON.Junction.CCCGIS.108	8.27	7.97
AVON.Pump.OARC.PS20	AVON.Access.ARM.9346	9.55	9.25
AVON.Pump.OARC.PS22	AVON.Access.ARM.9687	9.18	8.88
AVON.Pump.OARC.PS23	AVON.Junction.CCCGIS.45	8.78	8.48
AVON.Pump.OARC.PS24	AVON.Access.CCCGIS.9834	8.48	8.18
AVON.Pump.OARC.PS25	AVON.Access.CCCGIS.9718	10.26	9.96
AVON.Pump.OARC.PS30B	AVON.Access.CCCGIS.8086	9.05	8.75
AVON.Pump.OARC.PS31	AVON.Junction.CCCGIS.5732	8.99	8.89
AVON.Pump.OARC.PS32	AVON.Access.CCCGIS.10479	8.87	8.57
AVON.Pump.OARC.PS33	AVON.Access.CCCGIS.10448	9.45	9.15
AVON.Pump.OARC.PS8	AVON.Junction.CCCGIS.1559	10.01	9.71

Table A-6. Mike 21 Point sink-source pairs

Sink Name	Max Flow	X	Y	Paired sink	X	Y
PS_8	-5	1574538.916	5182659.198	PS_8_Out	1574484.018	5182680.488
PS_10	-7	1572915.693	5181304.795	PS_10_Out	1572911.363	5181371.235
PS_DC	-5	1573196.423	5182082.44	PS_DC_Out	1573190.626	5182050.666
PS_11A	-5	1572712.964	5181627.959	PS_11A_Out	1572823.429	5181631.611
PS_MP	-5	1573293.131	5181445.269	PS_MP_Out	1573327.129	5181456.622
PS_14B	-7	1574137.325	5182950.136	PS_14B_Out	1574254.385	5182956.357
PS_15A	-7	1574387.708	5181634.92	PS_15A_Out	1574411.469	5181676.915
PS_16A	-5	1574219.877	5182694.038	PS_16A_Out	1574274.137	5182688.591
PS_17	-7	1574776.324	5183392.423	PS_17_Out	1574912.943	5183431.668
PS_18	-7	1575443.08	5183660.169	PS_18_Out	1575400.448	5183470.483
PS_19	-20	1576122.441	5183475.967	PS_19_Out	1576137.301	5183455.084
PS_20	-5	1575608.878	5183425.654	PS_20_Out	1575598.224	5183447.332
PS_22	-7	1576102.149	5183351.505	PS_22_Out	1576124.594	5183387.642
PS_23	-10	1577362.336	5182770.228	PS_23_Out	1577351.142	5182752.097
PS_24	-5	1576502.882	5183208.003	PS_24_Out	1576498.14	5183179.361
PS_25	-5	1576224.242	5183410.285	PS_25_Out	1576231.757	5183386.821
PS_29C	-5	1577230.428	5182535.842	PS_29C_Out	1577319.636	5182564.57
PS_31	-7	1578023.991	5181271.14	PS_31_Out	1578020.249	5181277.81
PS_33	-5	1577974.22	5181826.076	PS_33_Out	1577911.946	5181830.011

Appendix B. Model Amendments

The figures in Appendix B show the changes made to the model to implement the Ōtākaro Avon River Corridor (OARC) Regeneration Plan in the Avon River City Wide Model . A description of each of the items in the figure legends is provided below.

Modelled Pumps 2D - point sink-source pair transferring with negative flow to represent capture of overland flow or ponding in the vicinity of the pump station

Modelled Pumps 1D - Mike URBAN outlet disconnected from the 1D river branch with a static water level boundary level at the pipe centreline level to simulate unrestricted network discharge at the outlet

Additional non-return Outfalls - pipes modelled with non-return valves to prevent backflow from the river into the floodplain

Proposed Pump Stations - spatial locations of the pump stations from the OARC geopackage

Culvert Updates - culvert with valve regulations set to 'only positive flow' to prevent backflow through 'Avon.Cowlstiv' 1D channel

Sealed Manholes - manholes were set to Cover Type 'sealed' within MIKE URBAN and links were removed from the couple file to prevent backflow from the river into the floodplain

Additional non-return Outfalls Pipes - shows the pipe alignment for the Additional Non-Return Outfalls location

Proposed Stop Banks - spatial locations of the pump stations from the OARC geopackage

Modelled Stop Banks - The stop banks alignment as modelled

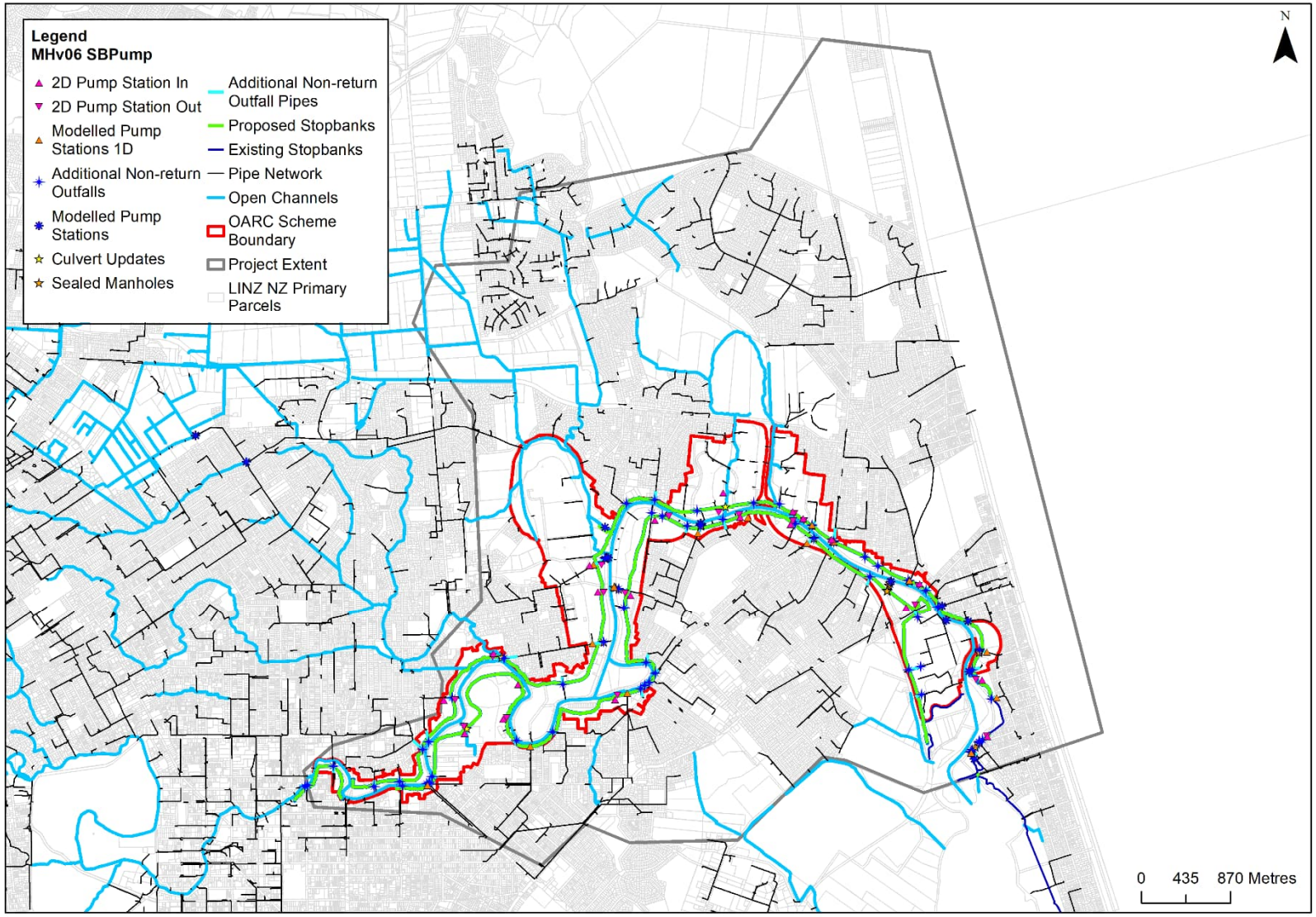


Figure B-1. Overview of Model Amendments

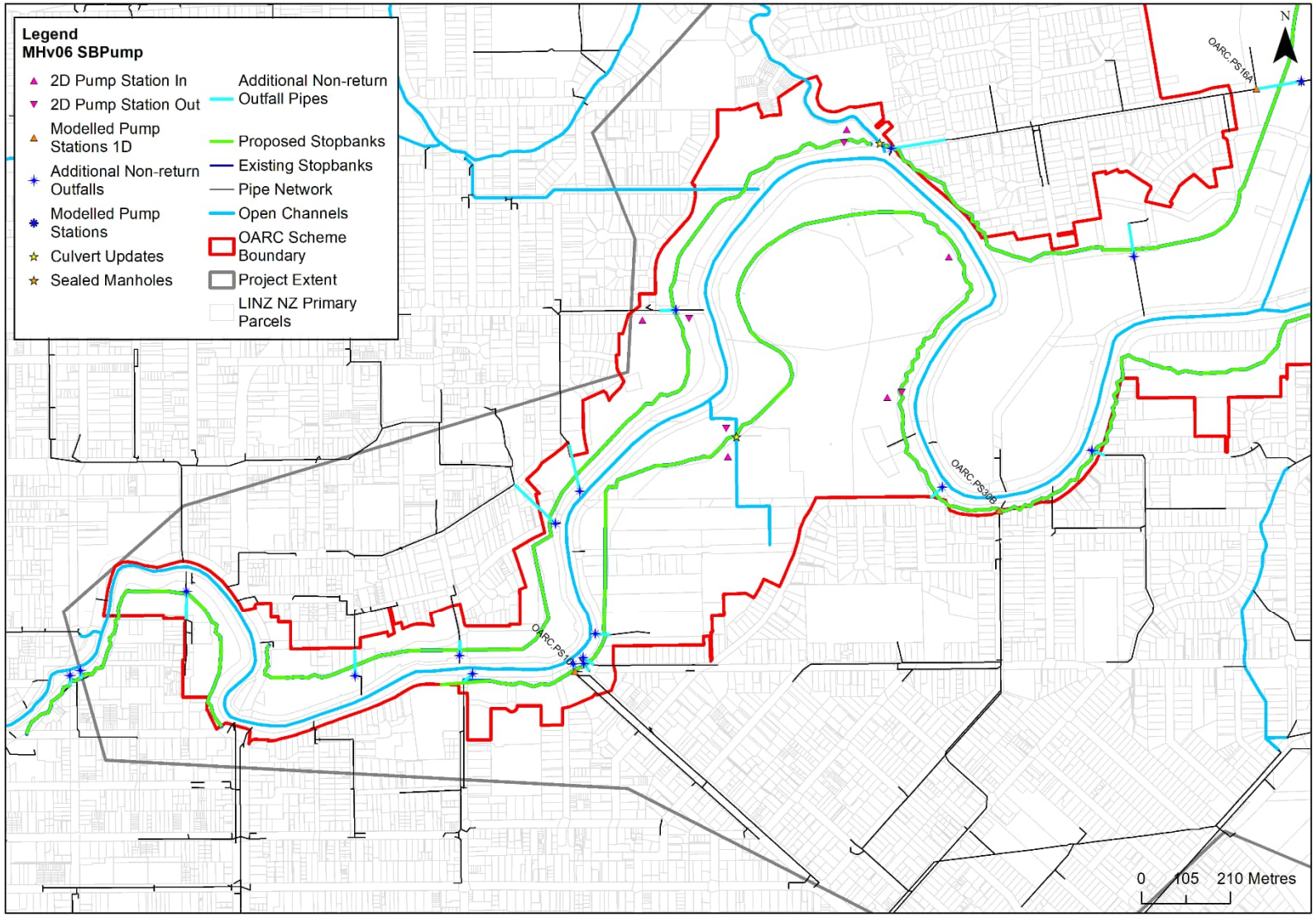


Figure B-2. Model Amendments -Barbadoes St to Avon Rowing Club

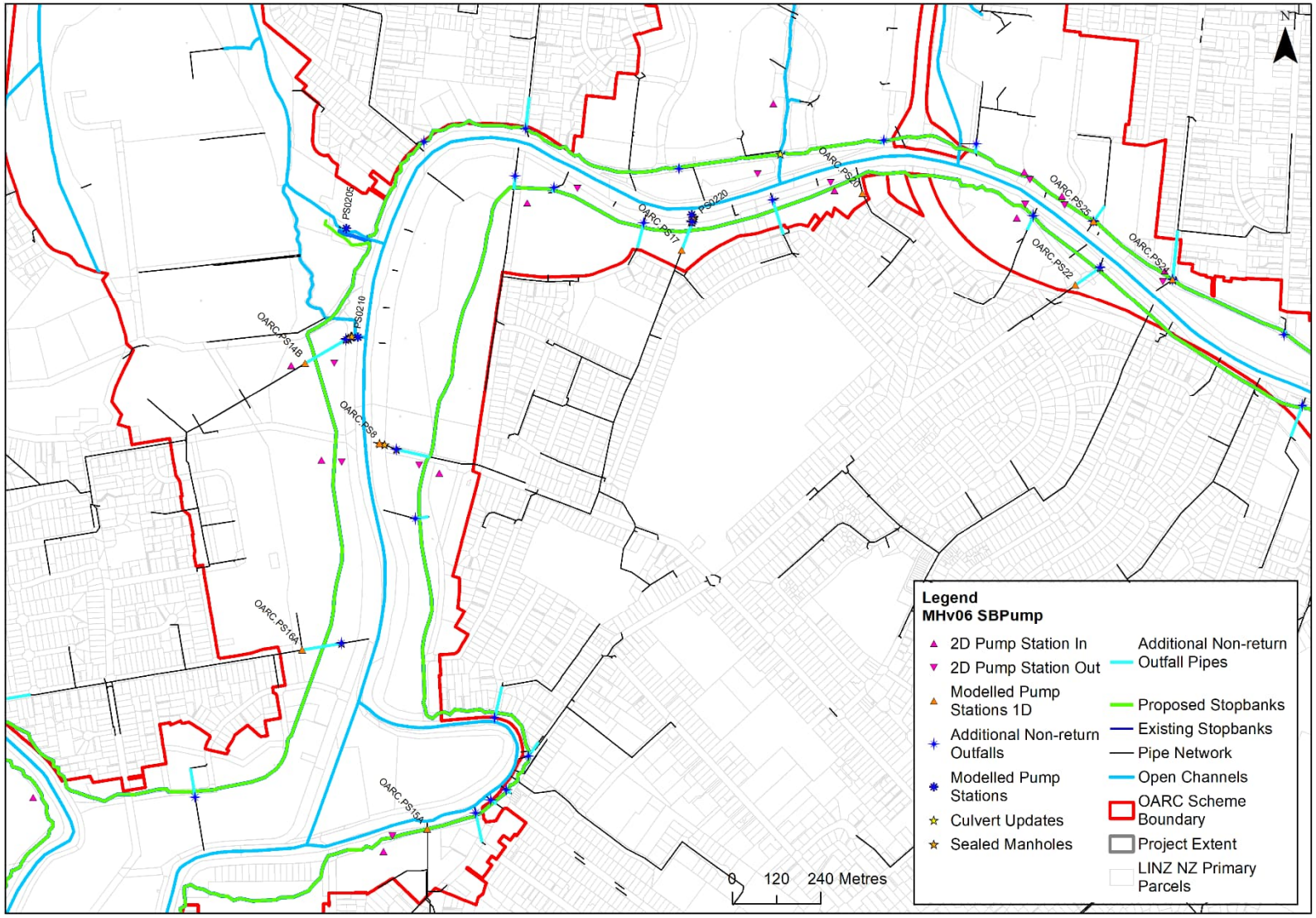


Figure B-3. Model Amendments - Avon Rowing Club to Palmers Rd

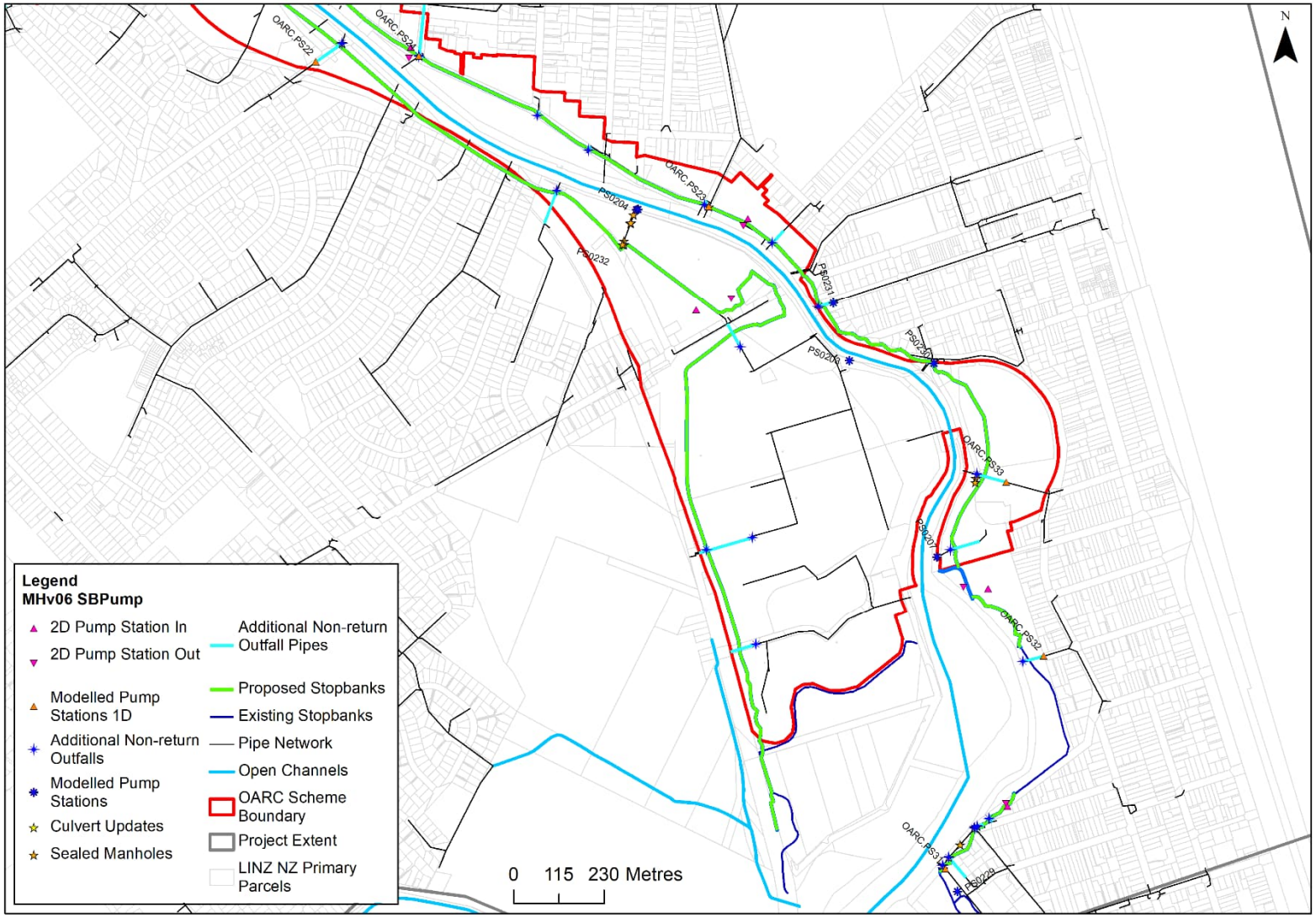


Figure B-4. Model Amendments - Palmers Rd to near Bridge St

Appendix C. Scenarios to be Modelled

Table C-1. List of Scenarios to be modelled (from Task 3 Scope)

Stage	Timeline and SLR	Earthquake	Stopbanks	Groundwater levels
Stage 1	2020 0 m SLR	no	Up	85th percentile
	2030 0.19 m SLR	no	Up	85th percentile
	2060 0.45 m SLR	no	Up	85th percentile
	2060 0.45 m SLR	yes	Up	85th percentile
Stage 2	2100 1.06 m SLR	no	Up	85th percentile
	2100 1.06 m SLR	yes	Up	85th percentile
	2100 1.06 m SLR	no	Up	50th Percentile
Stage 3	2150 1.88 m SLR	no	Up	85th percentile
	2150+ 2.4 m SLR	no	Up	85th percentile

Table C-2. List of Events and Durations to be modelled for each Scenario in Table C 1

Event	Rainfall	Tide
10-year	10-year ARI 3-hour duration	2- year ARI
	10-year ARI 9-hour duration	2- year ARI
	10-year ARI 18-hour duration	2- year ARI
	10-year ARI 36-hour duration	2- year ARI
	10-year ARI 1-hour duration (2020/2060 Up /no scenarios only)	2- year ARI
50-year	50-year ARI 3-hour duration	5- year ARI
	50-year ARI 1-hour duration (2020/2060 Up/no scenarios only)	5- year ARI
	50-year ARI 9-hour duration	7- year ARI
	50-year ARI 18-hour duration	7- year ARI
	50-year ARI 36-hour duration	7- year ARI
	7-year ARI 18-hour duration	50- year ARI
200-year	200-year ARI 3-hour duration	7-year ARI
	200-year ARI 9-hour duration	13-year ARI
	200-year ARI 18-hour duration	13-year ARI
	200-year ARI 36-hour duration	13-year ARI
	13-year ARI 18-hour duration	200-year ARI

Appendix D. Peer Review Comments and Jacobs Response

Catchment: Avon City Wide Model
Software used: MIKE FLOOD FM 3-way coupled
Objective of revie QA/QC of MIKE FLOOD model development and results
Checks by: ANT

Task	Description	Observation	DHI comment	Jacobs Response	Action	Closeout comment
		Design Model Setup	Design Model Setup			
1	Requirements of model					
1.1	Purpose of the model					
2	Input data					
2.1	MIKE 21 data files		All input files provided.			No Action required
2.2	MIKE FLOOD data files	V116e_Avon_2060_0p45SLR_50R07T_09hr_CC14p86_Up.couple, V116e_Avon_2060_0p45SLR_50R05T_03hr_CC17p6_Up.couple, V116e_Avon_2060_0p45SLR_50R07T_18hr_Pump.couple, V116e_Avon_2060_0p45SLR_50R05T_01hr_CC18p9_Up.couple	All input files provided.			No Action required
2.3	MIKE URBAN data files		All input files provided.			No Action required
2.4	MIKE 11 data files		All input files provided.			No Action required
2.5	Time series files		All input files provided.			No Action required
2.6	Summary files		All input files provided.			No Action required
2.7	Result data files		All input files provided.			No Action required
2.8	File naming	example scenario name: V116e_Avon_2060_0p45SLR_50R05T_03hr_CC17p6_Up.couple	File refers to the "stopbanks Up" scenario of the Avon, but I think this is misleading, as this is a different type of scenario altogether. The model files also reflect the stopbanks down, so it is additionally confusing. I think instead of using the "Up" in the filename this needs to be replaced with some other scenario identifier that you can use which says 1) that you are doing specific scenarios that don't match with the standard Avon scenarios and 2) any individual differences between these scenarios. In addition the base scenario number, i.e. the V116e needs to match back to any base model you are comparing back to. This should only be updated when the base scenario number is updated.	Agreed, we will update the naming convention to reflect our Multihazard Scenarios	Jacobs will update model naming convention- Version - use the same version number as the base model that we are comparing to. i.e. v114c Scenario - use a Multihazards version number ('MHvXX' where 'XX' is the version from 01-99) and a scenario identifier for the stopbanks + pump scenario ('SBPump') e.g *V116e_Avon_2060_0p45SLR_50R07T_09hr_CC14p86_Up.couple* becomes *V114c_Avon_2060_0p45SLR_50R07T_09hr_CC14p86_MHv01_SBPump.couple* Network version will revert to previous version number with a suffix MHvXX_SBPump	Updated naming convention adopted in models Described in Section 2 of Modelling Methodology Memo (Rev D)
3	Reporting					
3.1	Report	*A report was provided covering the model changes made: IZ084400-NW-MEM-0008 Task 3 Model Method Statement_Rev A.pdf*	The report is comprehensive and provides the information necessary to undertake the review. Some minor comments: 1. It would be useful when referring to the tables, that it is also indicated that these are in the Appendix A. 2. Section 2 indicates 200yr ARI scenarios which were not provided for review. Perhaps the report needs updating? 3. Section 3, Instead of using a 0m crest level it is recommended that the dike is disabled instead (by unchecking it in the M21 setup).	We will update report to address Comments 1 and 2. Comment 3 also covers a major comment – stopbank dikes - see reponse to 7.11 Structures.	Update table references in the memo. Update report to discuss 200 yr ARI scenario (or remove if not relevant). Provide full list of future scenarios to be run in report. For comment 3 see Action for 7.11 Structures.	Updated table references in Modelling Methodology Memo (Rev D) to say e.g. "*Appendix A: Table A-1* " For comment 3 see Action for 7.11 Structures
4	General					
4.1	Software Version	MIKE 2020 update 1, version 18.1.0.14122	This matches the version used for the previous Avon modelling by GHD			No Action required
4.2	Schematisation	The model has been modified to represent the design for the realignment of the Avon stopbanks. The stopbanks are represented by shifting and adding Dikes to the 2D domain, to block all water. Pump stations to drain any water ponding upstream of the stopbanks are represented as a combination of sink points in the M21 model and open water level boundaries in the 1D model. So that water is removed upstream of the stopbanks but not added back to the river downstream. The proposed stormwater ponds were not represented at all with the assumption that this would not impact on the flooding.	1. Assuming the modelled river levels will be used to set the stopbanks levels, it would be necessary to transfer any "pumped" flow, that is extracted upstream of the stopbanks, into the Avon River. Otherwise the river levels will be underestimated, and any stopbanks levels derived from this. Transferring the flow to the river could be done in a variety of ways, e.g. using source sink pairs in the M21 model or a pump structure in the 1D model. 2. Omitting the stormwater basins would only be appropriate when looking at this as a very high level design. The basins would allow for the accumulation of runoff from surrounding areas making the pumping more efficient, but also potentially allowing for a slower release of the stored water. It is not clear if these have been omitted due to lack of data or other project constraints. By omitting the basins, the flood extent and levels upstream of the stopbanks cannot be relied on as accurate. 3. The GHD pump capacity appears to vary significantly from the resulting capacity from the model simulation. However without modelling the ponds, which would likely increase the potential pumped volume, it is not clear how useful the analysis of the modelled maximum discharge would be. Especially considering that the pumps are essentially doubled up by using both a "free" outfall and a sink point at the same location. 4. A discussion on the model schematisation to help explain the reasoning for how the model is setup, along with explaining what the model results will be used for, is needed.	To be discussed in meeting. Our high level schematisation had been discussed and agreed with CCC as we felt the changes to river levels would be minor however pumping volumes are large enough that they may have some impact.	Outcomes of meeting with Peer reviewer to discuss: 1. Jacobs will alter model to transfer flow from pumps into the river, Kristin and Antoinette to meet to confirm the best way to do this 2. Agreed that for our purposes omitting the storage basins is appropriate as – design is not yet available, our assessment will be conservative because we are using the model to understand residual flooding and where additional network improvement is required to get further flooding improvements Recommended that Jacobs carry out a sensitivity run to test the response of river levels to additional pumped flow to cover the risk that additional pumping to mitigate flooding could impact on the required stopbank levels. This needs to be confirmed with CCC) The sensitivity run with additional 'pumped' flows into the river (for example the total estimated pumping capacity estimated by GHD) would provide confidence that the adopted methodology is not underestimating river levels (or provide an understanding of how sensitive these are to any additional pumped flow)	Pumps were updated by connecting to the river. The pump set up is described in Section 4 of the Modelling Methodology Memo (Rev D). No sensitivity run required as pumps were connected to river for all model runs.
5	Adjustments to MIKE URBAN model					

5.1	Network model	Flap gates added at new stopbank alignment, sealed manholes (and disconnected links to surface).	These appear to have been added correctly			No Action required
5.2	Head losses	No changes	N/A			No Action required
5.3	Boundary items	Added water level boundaries at outlets to the river, where pump stations are located, so that water will drain "relatively freely". Water level set to mid point of pipe.	These appear to have been setup correctly			No Action required
5.4	ini file	No changes	N/A			No Action required
5.5	Results		Spot checks on results indicate these appear stable and are working as intended.			No Action required
6	Adjustments to M11 model					
6.1	Network model	No significant changes made to the network model except the structures as discussed below	N/A			No Action required
6.2	Structures	Culverts added where the structure is being modelled as a closed cross section and a flap gate needed to be included. Flap gates added at new stopbank alignment.	Non return valves added. Note that it may also be necessary to update the weir levels at some of these structures to ensure that these also don't overtop. The weirs are located at the same location as some of these culverts and don't appear to have been raised up to a "glass wall" level.	We will review weir levels and update as required. While there is no flow over weirs in the results for the 2060 epoch we agree that this could be an issue with the later epoch events.	Jacobs to review weir levels and rasie them to an appropriate 'glass wall' elevation. Noted that some weirs into the Travis Wetland are one way - double check that it is appropriate for these weirs to be raised.	Three weirs were set to 'no flow' to prevent backflow. Detailed in Section 3 of Modelling Methodology Memo (Rev D).
6.3	Cross sections	Only minor changes made	N/A			No Action required
6.4	Boundary items	No changes	N/A			No Action required
6.5	HD parameters	No changes	N/A			No Action required
6.6	Mike11.ini	No changes	N/A			No Action required
6.7	Initial conditions	Hotstart rerun to account for changes to network	Hotstart generated appears consistent with previous model. Note that because the 1hr and 3hr sims are not starting at the same time as the GHD model, this changes the starting levels, and may not fit with the hotstart	Would like to confirm start times with peer reviewer. Jacobs calculated start timesusing Table 28 (p.52 GHD Avon Model Status Report Rev 7) values for duration from rainfall start to tide peakand pre-start time. Jacobs calculation time of 9:24pm for the 18h duration was 1h different to the time used in the model files which was 8:24pm.	Antoinette will confirm model start times used by GHD to ensure consistency with their model runs.	Start times were reviewed and updated as per log files provided by Antoinette.
6.8	Results		Spot checks on results indicate that they are stable and are producing the expected results.			No Action required
7	Adjustments to M21 model					No Action required
7.1	Bathymetry	No changes	N/A			No Action required
7.2	Simulation parameters	No changes	N/A			No Action required
7.3	Boundary conditions	Added sink points to represent pump stations.	Points appear to have been added correctly.			No Action required
7.4	Rainfall	No changes	N/A			No Action required
7.5	Infiltration	No changes	N/A			No Action required
7.6	Initial conditions	Simulation start time adjusted for the 1hr and 3hr which will alter the initial state.	Simulation start time adjusted slightly for the 1hr and 3hr simulations. It looks like the start time for the 9hr or 18hr was used. Modeller needs to be aware that the start times are not the same for all durations due to some adjustments made to align the initial conditions with a lower starting level.	Would like to confirm start times with peer reviewer. See response to 6.7 Initial Conditions	See Action for 6.7 Initial Conditions	Model start times adjusted as per peer reviewer comments.
7.7	Flood and dry	No changes	N/A			No Action required
7.8	Eddy Viscosity	No changes	N/A			No Action required
7.9	Roughness	No changes	N/A			No Action required
7.11	Structures	Additional dikes have been added to the model to represent the stopbanks as "glass walls"	The added dike "Avon RB 4" is overlapping the existing dike "Stopbank West". This is creating model issues in the form of very high velocities. This is because the software does not support overlapping structures. The high velocities are forcing the timestep very low and making the simulation approx.. 4 times longer than it should be. " Stopbank North" should be deactivated instead of set to zero, to keep things tidier, as this is also very close to the new stopbank position.	Agreed that we will remove any overlaps and deactivate unused dikes, (previously using crest level of 0m). The approach to set crest level to 0 was adopted to be consistent with GHD approach	Set unused dikes (using crest level of 0m)to deactivated (unticked). Review active dikes and remove any remaining overlaps.	Overlapping dikes (Stopbank North) unticked. Other dikes edited to remove overlaps. Details are provided in Section 3 of the Modelling Methodology Memo (Rev D).

7.12	Results		Overlapping dikes are causing high velocities, as discussed above. Also recommend adding inundation statistics for saving max velocity and depth (this is a new requirement for the CCC models). In addition where you require discharge calculations around the pump stations, these should be defined within the M21 model results, before you run the simulation for the most accurate output.	Agreed, RE: overlapping dikes see reponse to 7.11 Structures. We will update results outputs to include inundation statistics for max velocity and depth, and define discharge calculations for pump station '2D sinks'.	RE: overlapping dikes see reponse to 7.11 Structures. Save additional inundation results for max velocity and depth. Save additional dischsrge results for pump station '2D sinks'.	Overlapping dikes (Stopbank North) unticked. Other dikes edited to remove overlaps. Details are provided in Section 3 of the Modelling Methodology Memo (Rev D).
8	Adjustments to MIKE FLOOD model					
8.1	Lateral Links	Links are using M21 or a specified spill level in the stopbanked area. This will ignore the stopbank levels as defined in the MIKE 11 cross section. This way the flow can be stopped by the dike structures which are placed further out from the lateral links.	M21 for the lateral links appears to be the correct method to use here. The EXT link appears to have been setup correctly.			No Action required
8.2	Standard Links	No changes				No Action required
8.3	Urban Links	Some links removed	spot checks indicate that the links were removed where sealed manholes were applied			No Action required
8.4	River/Urban Links	Some links removed	spot checks indicate the links were removed as intended			No Action required
8.5	Volume Balance		Volume error appears to be within reasonable limits			No Action required
8.6	Running Flood model	The 9hr 50yr simulation is taking 4 days to run. Comparing this to the GHD work, this same simulation took 1 day to run on an only slightly better GPU card.	The high velocity errors caused by the dike overlap is the most likely cause of the increase in simulation time. Simulation time can also be improved by using fast storage and by storing files and results locally on the PC and not on the network. Using faster CPU and GPU cards will also speed up the simulation.	Noted, we had not found significant speedups from saving locally, however once we fix the dike overlap, we can review this. Our network storage location is optimised for fast saving.	RE: overlapping dikes see reponse to 7.11 Structures. Review model run speed for saving network vs local and with the upgraded GPU/CPU	Addressed - see closeout comment for 7.11 Structures.

Colour legend:

Not done at all or still not at a satisfactory level
Addressed partially, still room for improvements but not critical
No action necessary

Appendix I. Alternative options memo

Christchurch Multi-Hazards (LDRP97) - Other Flood Risk Management Options for the Lower Ōtākaro Avon River

Date:	7 April 2026
Project name:	LDRP97 Multi-Hazard Analysis
Project no:	IZ084400
Attention:	Martin Densham, Tom Parsons
Company:	Christchurch City Council
Prepared by:	Charlotte Doogue, Ian Wiseman, Damian Debski
Document no:	IZ084400-NW-MEM-0012

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Scope

The work reported in this memo was commissioned by Christchurch City Council (Council) as Task 1 of Variation 16 of the Christchurch Multi-Hazards project. The purpose is to identify, conceptually, a selection of other possible options for managing flood risk in the lower Ōtākaro Avon catchment and to make an initial, high level, assessment of the potential performance of these options relative to the flood management measures planned as part of the Ōtākaro Avon River Corridor Regeneration Plan (the OARC Scheme).

The work addresses a question raised by the Project Control Group (PCG) in response to comments from the Peer Review Panel relating to the change in scope of Stage 3 of the project. That is, from considering a broad range of flood management options and pathways for managing flood risk to only assessing the OARC Scheme pathway of setback stopbanks and stormwater pumpstations.

Importantly, this work is not expected to recommend a preferred option to the OARC Scheme for managing flood risk. Instead, the outputs are intended to provide Council with further high-level information to support their decisions on whether other complementary or alternative flood risk management options to the OARC Scheme have merit and would be worth investigating further in more detail.

Council revised their concept design for the OARC Scheme stopbanks following completion of flood modelling of the OARC Scheme (which informs this assessment) and commencement of this alternative options assessment. The change in design is primarily to reduce the design life, and hence cost, of the new stopbanks as follows:

A. Original Stopbank Concept Design

   Engineered long term stopbanks with a 100-year design life and a 1% Annual Exceedance Probability (AEP) crest level including freeboard and sea level rise allowance with provision to further raise the crest level by up to 0.5 m in the future to accommodate additional future sea level rise if this is required.

B. Revised Stopbank Concept Design

   Narrower "interim" stopbanks with a 50-year design life, less reinforcement and designed to allow a longer term stopbank to be constructed over the landward side of the interim stopbank. It is intended that this design will provide for existing tidal flood levels up to the 1% AEP with 0.3 m freeboard and allowance for 30 years of sea level rise and vertical land movement. The design adopts a shorter 50-year design life in accordance with NZS1170.5 for seismic design.

For completeness, both stopbank designs are considered in this assessment. However, the performance of the alternative options is considered only in relation to the revised OARC Scheme stopbank concept design, which now supersedes the original design.

Method

We have identified a selection of options commonly adopted to manage flood risk and made an initial, high-level assessment of the performance of these options in comparison to the OARC Scheme to understand whether there are other options which may be viable alternatives to the OARC Scheme and so would be worth considering in greater detail.

The results of this analysis will be included in the final Stage 3 report for the Multi-Hazards project. The report will consider the performance of the OARC Scheme and residual risks in detail together with this high-level review of potential alternative options, how they may perform and their residual risks for comparison, using the information presented in this memo.

The approach taken was:

1. Workshop with the Christchurch City Council project team to develop and refine a longlist of possible alternative options to the OARC Scheme based on the 'protect', 'avoid', 'retreat' and 'accommodate' types of option often considered in adaptation planning. For each type, there are a range of specific potential options. Development of this longlist of options was guided by the Catalogue of Coastal Hazard Adaptation Options (Christchurch City Council, 2021), both in the options considered and the factors and criteria for assessing the suitability of options for shortlisting in terms of feasibility, effectiveness, and environmental impact (detailed in Table 1 below).
2. Screen the longlist of options to develop shortlist of up to six options to be quantitatively evaluated. (Table 5 of this memo)
3. Develop a high-level description of each of the shortlisted options to provide a clear understanding of the basis of the option and the intended approach to derive the indicative option cost and damages. (Table 4 of this memo)
4. Develop a high-level results matrix (Table 3 of this memo) to assess the performance of these options in comparison to the OARC. The factors considered are the indicative residual damages, indicative cost, likely environmental factors, residual flood risks, performance under multi-hazards, and adaptive capacity of each shortlisted option, relative to the proposed OARC Scheme. For comparative purposes, each option is assessed as a sole means to addressing flood risk.
   a. Residual damages were derived by inspection of existing available data from the Multi-Hazards project for the number of properties flooded and financial flood damages calculated using the FloodFX[1] tool in terms of estimated Annual Average Damage (AAD) for individual model scenarios ('without' the OARC Scheme and 'with' the OARC Scheme[2]) and Present Value[3] Damages for a set of potential future pathways of climate change.

[1] FloodFX is a Christchurch City Council tool (developed by Jacobs). It uses flood model outputs and a database of house floor levels and types to identify properties at risk of flooding and estimate damages (based on intangible and tangible factors).

[2] Jacobs (June 2024) *Ōtākaro Avon River Corridor Regeneration Plan flood model results.*

[3] A discount rate of 5% has been used for illustrative purposes

Flood damages were calculated from the results of flood modelling previously completed for the Multi-Hazards project. In the model, river levels are contained by the stopbanks in all the future scenarios considered, including those beyond the initial design life of the revised stopbank concept. The resulting damage values are considered to be applicable to both the original and revised concept designs since both are intended to be adapted to accommodate the effects of climate change over time. Further commentary is provided in the Results Matrix (Table 2) to indicate how the performance of the two design concepts may differ.

It should be noted that in the model for the OARC Scheme, river levels are contained by the stopbanks for all probabilities of flooding simulated (10% AEP to 0.5% AEP). Although the stopbanks will only be designed to contain the 1% AEP river level, the difference in water levels between the 0.5% and 1% AEP is expected to be much less than the freeboard allowed for in the design (e.g., 1% and 0.5% AEP storm tide levels at Bridge Street differ by less than 100 mm) such that the model results are still considered applicable for the purpose of this assessment.

b. Costs for each option are based on readily available pricing information (e.g., average house prices, benchmark costs for other council projects).

5. This version (Draft B) of this document includes an additional option that combines two of the shortlisted options together into a single pathway over time. For this option we have also indicated the potential effect of Vertical Land Movement (VLM) on indicative costs and damages avoided (the lower values of costs and damages are without VLM and higher values are with VLM), reflecting our increased understanding of the VLM hazard since the assessment was originally undertaken.

Table 1 Assessment criteria for alternative options

Factor	Element Criteria	"Traffic Light" Definitions		
Environmental factors	Considers ecological impacts on the surrounding area, geomorphological impacts to the system, resource requirements for implementation, and the severity or duration of disruption to the natural environment during implementation.	Positive environmental impacts associated with the implementation of this option.	Negligible or neutral environmental impacts associated with the implementation of this option.	Negative or unacceptable environmental consequences associated with the implementation of this option.
Residual flood risk	The potential risk of flooding that remains after the implementation of the alternative option in terms of unmanaged hazards or potential for failure of the option.	Minimal residual flood risk	Moderate residual flood risk	High/critical residual flood risk
Performance under multi-hazards	Considers how the option addresses the impacts of multi-hazards including: • Coastal storm events and coastal erosion • Tsunami • Regional flood (Waimakariri River) • Earthquake and liquefaction • Vertical land movement (VLM) • Climate change and sea level rise • Future increases in groundwater levels Note that whilst all the above hazards have been considered in result matrix scoring, the accompanying commentary addresses key points only.	Addresses multiple sources of hazard	Addresses more than one sources of hazard	Does not well address multiple sources of hazard, or is undermined by other hazards
Adaptive capacity	Considers how flexible the option is to being adjusted and accommodate variability in climate change or changes in other sources of hazard.	The option can be easily adapted as conditions change	The option can be partially adapted as conditions change	The option cannot be adapted as conditions change

Results

Table 2 provides a summary of our high-level assessment of the performance of the selected alternative options in relation to that of the OARC Scheme. Further details are provided in Table 3. The results suggest that of the options considered, the following options could be worth considering further as complementary or alternative measures to the OARC scheme:

- Short design life stopbanks: An alternative arrangement of stopbanks with a short design life (~20-30-year design life) – this might have a similar level of performance as the OARC Scheme in the short to medium term and could more readily allow for a change in option in the longer term.
- Managed retreat (partial): Widescale retreat is very much more costly than the OARC Scheme for a similar reduction in damages but a more targeted approach could be beneficial in reducing damages at a lower cost, noting that other factors not considered in the assessment such as social impacts could influence the relative viability of this option, than widescale retreat. Retreat addresses exposure of multiple land use elements to groundwater hazards and other multi-hazards in a single management option.
- Accommodate (range of options possible): This is probably relatively low cost but is not as robust as the OARC Scheme, has greater residual damages and does not address flood impacts to public and private assets other than buildings. Assets not addressed include damage to roads, pump stations and cars, for example. These damages become particularly significant in the long term (i.e. more frequent and prolonged on-street flooding resulting in street-level or community-level isolation). In the short term, where flood depths are shallow, costs to waterproof houses are high relative to damages avoided as the costs to for instance waterproof a house are fairly fixed irrespective of the depth of flooding/damages avoided for that investment.
- Combined option - protect then retreat: This option is generally assessed favourably against the assessment criteria, having similar damages avoided to the OARC Scheme, lower costs than a retreat-only option and potential to provide protection from a range of other hazards.

Options which compare less favourably are:

- Planning controls: These do not address the risk to existing properties which results in the majority of flood damages – except through re-building – or risk to other elements so do not reduce damages as much as other measures. However, this is viewed as a complementary option that sits alongside all other options, in order to minimise future risk.

- Damages under a 'tolerate' or 'do minimum' approach with no new flood management measures of some form are considered unlikely to be acceptable to the community.

All the alternative options considered would likely require some changes to the flood management infrastructure and land use development currently envisaged under the OARC Regeneration Plan.

Table 2 Alternative Options Assessment Results – Summary

Type of Option	Specific Option (See Table 4 for detailed descriptions)	Costs		Indicative PV Residual Damages (2030-2120)	Reduction in PV Damages from Tolerate	Other assessment factors			
		Indicative cash cost (2030-2100)	Indicative PV cost (2030-2100)			Environmental factors	Residual flood risks	Performance under multi-hazards	Adaptive capacity
Tolerate	Do minimum	Low	Low	$1,010 M					
Protect	OARC Scheme - original	$579 M	$579 M	$272 M	$738 M				
Protect	OARC scheme – revised (current)	$579 M	$469 M	$272 M	$738 M				
Protect	Short design life stopbanks	$342 M	$150 M	$374 M	$636 M				
Avoid	Planning controls	$1-2 M	$1-2 M	$957 M - $1,010 M	$0 - $53 M				
Retreat	Managed retreat	$5,700 M – 21,600 M	$1,500 M - $16,600 M	$126 M - $547 M	$463 M - $884 M				
Accommodate	Hybrid – floodproofing and floor raising	$360 M	$40 M	$625 M	$385 M				
Protect then Retreat (Combined option)	Short design life stopbanks then managed retreat	$8726 M to $9578 M	$1154 M to $1222 M	$250 M to $254 M	$756 M to $760 M				

Colour Coding Key:

Costs

Indicative cash and PV costs have been colour categorised by comparison to the revised OARC stopbanks approach i.e. Orange as broadly equivalent to the cost of the revised OARC, Red as notably more expensive, and Green as notably cheaper.

Other assessment factors

Environmental factors, residual flood risks, performance under multi-hazards and adaptive capacity are as defined in Table 1.

Table 3 Alternative Options Assessment Results – Full Matrix

	Option (See Table 4 for option descriptions)	Indicative Option Cost[4]			Indicative PV Damages from 2030[5]			Environmental factors	Residual flood risks	Performance under multi-hazards	Adaptive capacity
Protect (OARC Scheme)	OARC Scheme - Revised (current) stopbank concept with narrower, shorter design life interim stopbank and provision for future raising		Cash Cost	PV Cost		Per epoch	Cumulative	The revised OARC Scheme will constrain the river ecologically and limit natural river movement. The setback from the existing stopbank alignment will provide more room for morphological processes than the present day stopbanks but not as much as if there were no stopbanks at all. The OARC Scheme incorporates measures to promote sustainable development i.e., habitat expansion and restoration projects, green corridors to link habitats and the prioritisation of critical areas and species. However, the physical works involved, including maintenance and possible future renewals, will pose an impact. Overall likely positive compared to present day.	There are still pockets of residual stormwater flooding in the catchment where water exceeds network capacity and ponds. In the short term, underfloor damages will comprise a large proportion of direct flood damage, reflecting the general shallow nature of flooding outside the OARC Scheme area. A smaller proportion are likely to experience above floor flooding, particularly for the more frequent events (e.g., 10% AEP). The Scheme actively manages flood risk over the long term, though climate change will increase the amount of residual risk over time. Some additional risk compared to the original OARC scheme due to the lower design heights	The revised OARC Scheme will perform relatively well under multi-hazards – however the stopbanks as currently proposed will still be damaged under future earthquakes but will be more effective than present day or short design life stopbanks. They will be more effective against a tsunami than the existing stopbanks and will manage anticipated rates of VLM and SLR. The scheme does not address the risk of dune breaching (erosion and subsequent flooding). However, the performance of the pumpstations under multi-hazards is limited by the inletting and conveyance capacity of the pipe network serving the pumpstation. The OARC Scheme will not explicitly manage existing shallow groundwater levels within the project area, nor future groundwater level rise.	Climate resistant and adaptive design principles have been incorporated into all new OARC Scheme elements (e.g., raising stopbank levels over time). However, only the individual new elements themselves are adaptable rather than the scheme as a whole. This means committing to one risk management approach in the long term or risk not realising the full value of the infrastructure investment.
		2030	$436 M	$436	2030	$11.3 M	$11.3 M				
		2060	$144 M	$33 M	2060	$189.8 M	$ 201.1 M				
		2100	$0	$0	2100	$63.1 M	$264.2 M				
		Total to 2100	**$579 M**	**$469 M**	2120	$7.8 M	$272.0 M				
					Cumulative reduction in Damages over whole assessment period from 'Tolerate': $738 M						
	OARC Scheme - Original concept Stopbanks + Pumpstations (all Stages)		Cash Cost/ PV Cost					The original concept would be expected to perform as the revised concept as the footprint is very similar over time.	A longer build time than the revised OARC scheme may result in slightly more short term flood risk, higher design heights and stronger design can reduce residual risk. However over the long term this option has a similar residual risk to the current OARC scheme.	The original OARC scheme would perform better than the revised scheme for earthquakes but may still be damaged needing repair (albeit less severely). Risk of overtopping and breaching would be lower. Other multi-hazard impacts including groundwater effects would be the same, hence this option is ranked the same as the revised (current) OARC Scheme concept. .	The original concept was similarly adaptable by staging top up's and upgrades and is ranked the same. However the extra cost may make deciding to change adaptation approach harder.
		2030	$579 M								
		2060	$0								
		2100	$0								
		Total to 2100	**$579 M**								

[4] The costs associated with the alternative options in this assessment are considered in addition to (above and beyond) the cost of a 'Do Minimum' approach. Therefore, the 'Do Minimum' approach is assigned a relative cost of $0.00

[5] PV = Present Value (Calculated with a discount factor of 1 / (1 + r)^t) where r is the discount rate

	Option (See Table 4 for option descriptions)	Indicative Option Cost[4]			Indicative PV Damages from 2030[5]			Environmental factors	Residual flood risks	Performance under multi-hazards	Adaptive capacity
Protect	Short design-life stopbanks (~20-30-year design life) along the proposed OARC stopbank alignment then rebuilt in 2060 and 2080 (Table 4)		Cash Cost	PV Cost		Per epoch	Cumulative	Short design-life stopbanks would have similar environmental outcomes to those of the OARC Scheme i.e. constrain the river ecologically and prevent natural river movement. The physical works involved, including maintenance and possible future renewals, will pose an impact. However, the setback from the existing stopbank alignment will provide a more positive environmental impact (but still worse than if no stopbanks were there).	Any flood event > 0.5% AEP over the design life will risk overtopping, noting that the residual flood risk will increase over time due to sea level rise and vertical land movement (The stopbanks will have future allowance for SLR and VLM, though only over the ~20-30 yr stopbank design life). Overtopping of the stopbanks would likely result in extensive flooding along the river corridor. Flood hazard outside the stopbanks will be primarily due to rainfall over the catchments draining to the river. Emergent groundwater, in some places (over longer timeframes), will further contribute to surface ponding.	The short design-life stopbanks will manage flood risk well until 2080 (when the standard of protection provided by the option drops away) but will adapt poorly to multi-hazards – the stopbanks will not be engineered to perform under an earthquake and since they will be engineered to a lower standard than long term stopbanks they are likely to sustain more damage in the event of a tsunami than the OARC Scheme.	For the purposes of this assessment it is defined that they cannot be relied upon or adapted for longer term protection. The standard of protection will reduce over time from 2080 to 2100 due to sea level rise and vertical land movement - by 2100 this type of stopbank is not considered feasible (i.e. not feasible to be built higher). By being short term and cheaper they make it easier to change pathway to a different element if required.
		2030	$114 M	$114 M	2030	$11.3 M	$11.3 M				
		2060	$114 M	$26 M	2060	$189.8 M	$201.1 M				
		2080	$114 M	$10 M	2080	$43.7 M	$244.8 M				
		2100	$0	$0	2100	$75.3 M	$320.1 M				
					2120	$53.6 M	$373.7 M				
		Total to 2100	$342 M	$150 M	Reduction in Damages from 'Tolerate': $636 M						
Avoid	Planning Controls – Avoidance measures to reduce damage to new development by controlling (or preventing) development in areas of high flood risk.		Cash Cost	PV Cost	Cumulative				Ineffective at managing exposure to existing infrastructure but can limit compounding of risk from extensions of existing property. New developments will remain susceptible to overfloor flooding for flood events > 0.5% AEP (though this will comprise a small component of the AAD). Flood risk remains in the short term. Areas of the Lower Avon at risk of flooding in the immediate-short term will remain susceptible.	Planning Controls as an avoidance measure will perform well under multi-hazards for new development. The area boundary used to control (or prevent) development can be defined by and adapted to the spatial co-existence and likely temporal coincidence of multi-hazards. Does not perform well for existing development but complements other options very well to reduce the increase in residual risks over time.	Controlling (or preventing) development in areas considered to be high flood risk can be adapted (area boundary expanded/changed) over time as SLR/VLM etc. conditions change. No adaptive capacity for existing development. This option is best used in conjunction with other options.
		2030	$1-2 M	$1-2M	Development scenario[6]	2030	2060	2100	2120		
		Total to 2100	$1-2 M		0%	$27.0 M	$583.7 M	$903.7 M	$957.3 M		
					10%	$27.7 M	$596.8 M	$920.6 M	$974.7 M		
					20%	$28.5 M	$609.8 M	$937.6 M	$992.1 M		
					30%	$29.2 M	$622.9 M	$954.5 M	$1,009.5 M		
					Per epoch						
					Development scenario[6]	2030	2060	2100	2120		
					0%	$27 M	$556.7 M	$320 M	$53.6 M		
					10%	$27.7 M	$569.1 M	$323.8 M	$54.1 M		
					20%	$28.5 M	$581.3 M	$327.8 M	$54.5 M		
					30%	$29.2 M	$593.7 M	$331.6 M	$55 M		
					Reduction in Damages from 'Tolerate': $0 - $53 M						

[6] Consideration for alternative development scenarios (e.g., 0%, 10%, 20%, 30% increase in current building footprints) in AAD totals. Note that lower bound (0%) corresponds to baseline modelling and upper bound (e.g., 30%) corresponds to the scenario proposed for SL04 ('Tolerate/ Do Minimum').

	Option (See Table 4 for option descriptions)	Indicative Option Cost[4]	Indicative PV Damages from 2030[5]	Environmental factors	Residual flood risks	Performance under multi-hazards	Adaptive capacity
Retreat	**Managed Retreat –** Retreat of properties where flood impacts exceed a defined severity at each future climate scenario.	a) **Retreat Criteria -** 10% AEP under floor and/or 2% AEP over floor flooding Cash Cost[7] / PV Cost 2030: $16.1 B / $16.1 B 2060: $1.6 B / $363 M 2100: $4.0 B / $131 M **Total to 2100: $21.7 B / $16.6 B**	a) **Retreat Criteria -** 10% AEP under floor and/or 2% AEP over floor flooding **Properties retreated -** 2030 = 3,874; 2060 = 826; 2100 = 1,782 Per epoch / Cumulative 2030: $27.0 M / $27.0 M 2060: $53.6 M / $80.6 M 2100: $44.5 M / $125.1 M 2120: $0.8 M / $125.9 M	For the purposes of this assessment, it is assumed that subsequent land use decisions following managed retreat would act to conserve or enhance the natural environment i.e. Parks which provide buffer zones for natural river processes to occur and greater ecological value.	High short-term residual flood risk which becomes negligible over time. Properties which do not meet the criteria for retreat at any given point in time remain susceptible to flooding. Council-owned assets will remain susceptible to flood risk.	Managed retreat eventually prevents the potential impacts of all multi-hazards including flood risk and groundwater level rise. Although the criteria for managed retreat in this instance does not explicitly consider the spatial co-existence or temporal coincidence of multi-hazards, it does incorporate cascading impacts i.e. earthquake induced land raising/ collapse will likely proportionately impact when a property meets criteria for retreat.	Managed retreat can be a highly adaptive option as the criteria for retreat can be adapted in real time as SLR/VLM etc. conditions change. However, the community and Council are unlikely to have the same adaptive capacity. Continued revision of the criteria for retreat could be burdensome to community wellbeing and Council resources.
		b) **Retreat Criteria -** 2% AEP over floor flooding Cash Cost / PV Cost 2030: $2.6 B / $2.6 B 2060: $1.4 B / $330 M 2100: $3.7 B / $121 M **Total to 2100: $7.7 B / $3.1 B**	b) **Retreat Criteria -** 2% AEP over floor flooding **Properties retreated -** 2030 = 917; 2060 = 632; 2100 = 1,659 Per epoch / Cumulative 2030: $27.0 M / $27.0 M 2060: $159.6 M / $186.6 M 2100: $87.2 M / $273.8 M 2120: $3.2 M / $277.0 M				
		c) **Retreat Criteria -** 10% AEP over floor flooding Cash Cost / PV Cost 2030: $1.1 B / $1.1 B 2060: $1.1 B / $263 M 2100: $3.5 B / $114 M **Total to 2100: $5.7 B / $1.5 B**	c) **Retreat Criteria -** 10% AEP over floor flooding **Properties retreated -** 2030 = 307; 2060 = 515; 2100 = 1,455 Per epoch / Cumulative 2030: $27.0 M / $27.0 M 2060: $356.9 M / $383.9 M 2100: $154.4 M / $538.3 M 2120: $8.9 M / $547.2 M **Reduction in Damages from 'Tolerate':** $463 M - $884 M				

[7] *Costs for retreat include consideration of all buildings meeting the documented criteria for retreat in each epoch. This includes some higher value non-residential buildings that can influence the overall magnitude of the cost. Depending on the approach developed with the community for retreating infrastructure actual costs could be lower.*

	Option (See Table 4 for option descriptions)	Indicative Option Cost[4]			Indicative PV Damages from 2030[5]			Environmental factors	Residual flood risks	Performance under multi-hazards	Adaptive capacity
Tolerate	**Do Minimum –** Existing stormwater drainage infrastructure is maintained, and rules/decisions under the current Christchurch District Plan remain operative	$0.00 (relative cost[4])				Per epoch	Cumulative	Limited opportunity to have positive environmental impact	Necessitates the acceptance of a higher and increasing level of residual risk and reduced and degrading levels of service.	This option will perform poorly under multi-hazards, and climate change will further exacerbate this. Existing infrastructure such as stopbanks are not designed for multi-hazard resilience i.e. not engineered to perform under an earthquake, ineffective against a tsunami, and not designed to manage variability in relative rates of VLM and SLR.	The adaptive capacity of this option is negligible. It could be possible to change from this option in the future but would have an acceptance of high residual risks while on the pathway.
					2030	$29.2 M	$29.2 M				
					2060	$593.7 M	$622.9 M				
					2100	$331.6 M	$954.5 M				
					2120	$55 M	$1,009.5 M				
Accommodate	**Accommodate Hybrid –** Buildings will be eligible for either waterproofing or floor level raising where flood depth thresholds for either option are met		Cash Cost	PV Cost	2030 Eligible for waterproofing = 279 Eligible for house raising = 27	Per epoch	Cumulative	Limited opportunity to have positive environmental impact. Limited negative impacts.	This option leaves a number of residual risks (some of which could have significant impact) including underfloor flooding, damage to garage contents and cars, council infrastructure (roads, services etc) and peoples safety. Waterproofed buildings will remain at risk from damage when inundation is >0.5 m above floor level. Raised buildings will remain susceptible to flooding for flood events > 0.5% AEP, and underfloor damages. Existing developments/ specific building typologies are likely to remain disproportionately susceptible to flooding due to the onus being on homeowners and the feasibility of implementation.	House raising will perform well under multi-hazards (addresses structural issues - poor performance of residential foundations in past earthquakes, reduces severity/risk of damage from liquefaction and rising groundwater levels etc.). However, comparatively, the OARC Scheme provides a more integrated flood protection approach. 'Accommodate' is also unlikely to perform well under multi-hazards at a catchment scale. This option will perform best for marginal/ low risk properties to improve level of service on a case-by-case basis.	The accommodate option is by nature adaptive, but it needs to be, as waterproofing is not infallible and becomes ineffective with time – the adaptive capacity of this option lies with house raising and the potential for subsequent retreat if house raising also becomes ineffective. A risk that not all houses which need works can have works done. This option also addresses only part of the issue – access and servicing issues could degrade adaptive capacity with time.
		2030	$19.5 M [8] *($14.0 M for waterproofing and $5.5 M for house raising)*	$19.5 M [8] *($14.0 M for waterproofing and $5.5 M for house raising)*		$20.3 M	$20.3 M				
		2060	$44.7 M *($38.1 M for waterproofing and $6.6 M for house raising)*	$10 M *($9 M for waterproofing and $2 M for house raising)*	2060 Eligible for waterproofing = 761 Eligible for house raising = 30	$390 M	$410.3 M				
		2100	$296.0 M *($76.8 M for waterproofing and $219.3 M for house raising)*	$9 M *($3 M for waterproofing and $7 M for house raising)*	2100 Eligible for waterproofing = 1535 Eligible for house raising = 693	$186.2 M	$596.5 M				
		Total to 2100	$360.2 M	$40 M	2120	$28.4 M	$624.9 M				
					Reduction in Damages from 'Tolerate': $385 M						

[8] Burwood Hospital was eligible for raising but was removed from calculations as it would not be feasible to raise and the property's Capital Value drastically skewed the indicative cost of the option.

	Option (See Table 4 for option descriptions)	Indicative Option Cost[4]			Indicative PV Damages from 2030[5]			Environmental factors	Residual flood risks	Performance under multi-hazards	Adaptive capacity
Protect then Retreat	Combination pathway of short design life stopbanks followed by progressive managed retreat This considered two scenarios, with and without Vertical Land Movement (VLM). The range in costs and damages indicates the effect of VLM – lower values are without VLM and higher values are with VLM.		Cash Cost[9]	PV Cost	2030 to 2060 Short design life stopbanks Properties retreated = 0	In epoch	Cumulative	Short design-life stopbanks would have similar environmental outcomes to those of the OARC Scheme i.e. constrain the river ecologically and prevent natural river movement. The physical works involved, including maintenance and possible future renewals, will pose an impact. However, the setback from the existing stopbank alignment will provide a more positive environmental impact (but still worse than if no stopbanks were there). For the purposes of this assessment, it is assumed that subsequent land use decisions following managed retreat would act to conserve or enhance the natural environment. However the option allows for the residual protection of the short design life stopbanks which would limit the ability to further retreat the stopbanks for much of the assessment period	In the short term (till 2060) any flood event > 0.5% AEP over the design life will risk overtopping, noting that the residual flood risk will increase over time due to sea level rise and vertical land movement (The stopbanks will have future allowance for SLR and VLM, though only over the ~20-30 yr stopbank design life). Overtopping of the stopbanks would likely result in extensive flooding along the river corridor however from 2060 onwards the residual flood risk becomes negligible over time due to the retreating of properties most at risk. Properties which do not meet the criteria for retreat at any given point in time remain susceptible to flooding. Council-owned assets will remain susceptible to flood risk.	The short design-life stopbanks will manage flood risk well until 2060 (when the standard of protection provided by the option drops away) but will adapt poorly to multi-hazards – the stopbanks will not be engineered to perform under an earthquake and will be less effective against a tsunami than the OARC Scheme. Including retreat means that many houses vulnerable to the impacts of those other hazards would be removed but not all properties within the area potentially impacted by tsunamis. Hence some properties will remain at risk.	The short term stopbanks till 2060 provide a level of protection but being short term and cheaper they make it easier to change pathway to a different element. Within this example pathway retreat is identified as the next step. However in practice it will be for future community and council decisions to agree what the next step of the pathway is based on a range of values at that point in time. This combined pathway approach is adaptive as it recognizes that future decision point when the short design life stopbanks reduce effectiveness. The community have the option to choose different retreat criteria in the future among other options.
		2030	$114 M	$114 M		$201 M to $204 M	$201 M to $204 M				
		2060 to 2070	$3605 M to $3661 M	$668 M to $678 M	2060 to 2070 Properties retreated = 507 to 523	$19 M to $20 M	$220 M to $224 M				
		2070 to 2100	$5006 M to $5803 M	$371 M to $430 M	2070 to 2100 Properties retreated = 2414 to 2867	$23 M to $24 M	$244 M to $248 M				
		Total to 2100	$8726 M to $9578 M	$1154 M to $1222 M	2100 to 2120	$6 M	$250 M to $254 M				
					Reduction in Damages from 'Tolerate': $756 M to $760 M						

[9] *Costs for retreat include consideration of all buildings meeting the documented criteria for retreat in each epoch. This includes some higher value non-residential buildings that can influence the overall magnitude of the cost. Depending on the approach developed with the community for retreating infrastructure actual costs could be lower.*

Table 4 Shortlist of Alternative Options

Assumptions of the OARC Scheme (for both the original and revised/current concept design) made in this assessment are as follows:

Costing Approach: OARC scheme costs outlined in this assessment are programme level estimates provided by council for the purposes of this assessment (anticipated accuracy range of -50% to + 50%).

The estimation for the revised/current OARC scheme is formed of three components as follows:

1) Imminent construction of Stopbank Stage A, which comprises 22,980m in three types of stopbank, with an average height of 0.98m.
2) Imminent construction of 18 pumpstations
3) Construction of Stopbank Stage B at year 30 - comprising an additional earth embankment on top of Stage A Stopbanks

The estimation for the original OARC scheme is formed of two components as follows:

1) Imminent construction of the original engineered long term stopbanks and pumpstations

Damages - Damages for the with OARC scheme modelling are based on glass walled hydraulic modelling rather than a specific design. It is assumed that these damages reflect both concepts as overall design AEP's and adaptation to SLR would be similar in both original and revised concept over time.

Damages may differ because the revised concept would be built sooner thus potentially reducing damage in the earlier epoch, however the slightly lower design height may increase the risk of low probability events causing damage. However, given the freeboard this is a low probability so damage values may not differ greatly.

PROTECT
Short design-life stopbanks

OVERVIEW DESCRIPTION

- The short design-life stopbanks will be engineered to a lower standard than long term stopbanks to realise capital cost savings at expense of long-term risk management.
- The short design-life stopbanks would be constructed along the proposed OARC stopbank alignment (setback from the existing stopbanks).
- The stopbanks will not be engineered to perform under an earthquake.
- The short design-life stopbanks would be built to contain the same storm event but with less freeboard and lower future allowances to account for the shorter design life. The future allowance will provide for sea level rise and vertical land movement over the stopbank design life, and the standard of protection will reduce after this if modifications are not made.
- The short design-life stopbanks will have a ~20-30-year design life but can be adapted for longer term protection, although less readily than the long term stopbanks due to the narrower crest and limited foundation width. For the purposes of the assessment, replacement stopbanks will be built in 2030 and rebuilt in 2060 and 2080. At the end of the assessment period (2100), for the purpose of this assessment only, this type of stopbank is not considered effective given the height required. For this assessment this provides a point of difference to a fully engineered OARC stopbank.
- No new pump stations or other improvements to the stormwater network are included in this option. While it is not possible to assess damages for this option directly without further modelling, available results for the full OARC Scheme (stopbanks and pumps) indicate that the additional reduction in damages due to pumping (without other stormwater improvements) in the first part of the evaluation period is small. For the purposes of this assessment, we therefore use the damages for the full OARC Scheme to 2080 and then interpolate damages to the baseline (no stopbanks) damages for 2100.

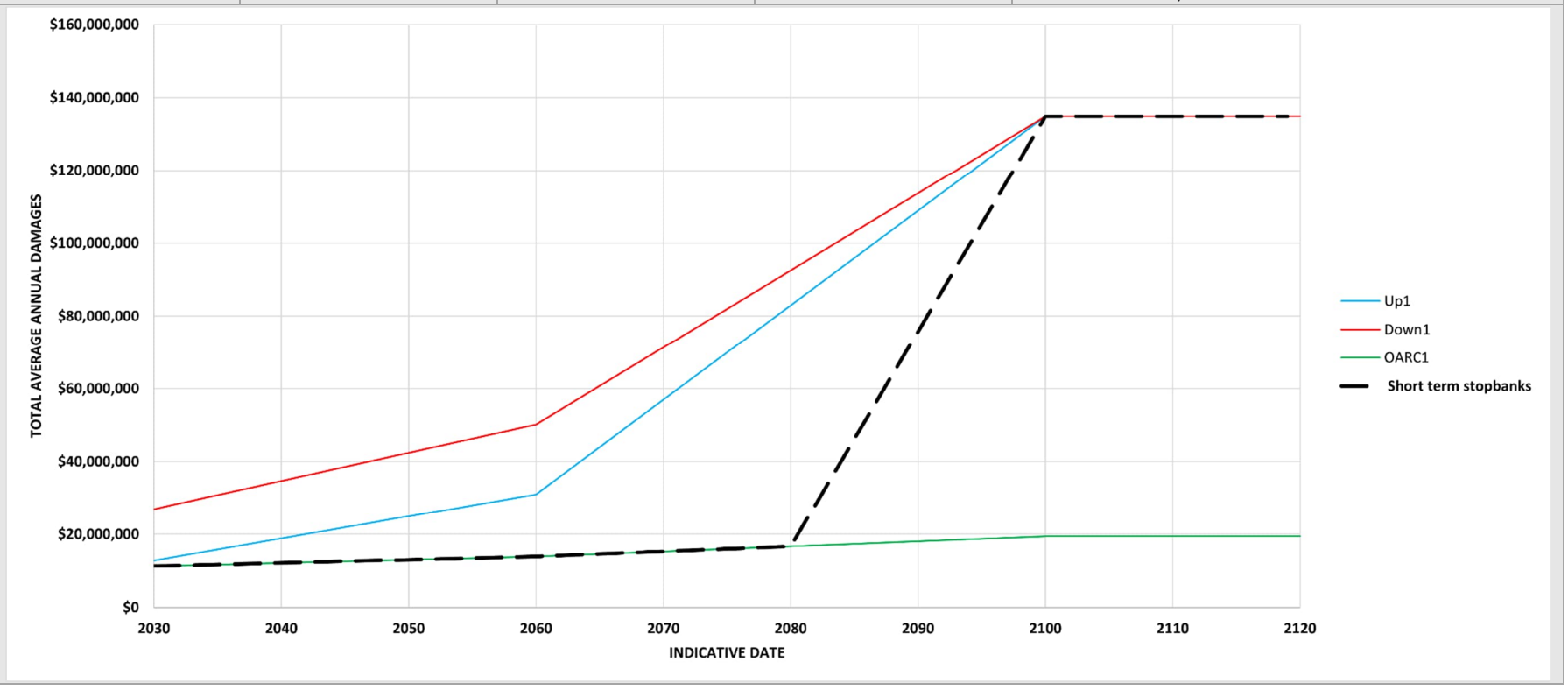
COSTING APPROACH

- The cost of existing CCC stopbanks is to be used (provided by council).
- Cost will be incurred in 2030, 2060 and 2080 as the stopbanks are built (2030) and rebuilt (2060 and 2080) at the end of each ~20-30-year design-life period.

DAMAGES

- Damages same as for OARC Scheme except for 2100 where baseline (without defences) are applied. Note that OARC Scheme results include the effect of new stormwater pumps as well as stopbanks. It is not possible to separate the contribution of the pumps to reduction in damages without additional model simulations. We expect that without network capacity and conveyance improvements the additional effect of the pumps in reducing damages is relatively small compared to the stopbanks and we therefore use OARC Scheme model results as a surrogate for purposes of this assessment.

	2030	2060	2080	2100
Damages calculation	OARC Scheme FloodFX damage outputs	OARC Scheme FloodFX damage outputs	Interpolated from 2060 and 2100 OARC Scheme FloodFX damage outputs	Baseline (without any stopbanks) FloodFX damage outputs Assumed that short term stopbanks are not feasible by this point in time due to rates of sea level rise, vertical land movement etc.



AVOID
Planning Controls

OVERVIEW DESCRIPTION

- Avoidance measures reduce damage to new development by controlling (or preventing) development in areas of high flood risk, and they provide buffer zones that allow for natural river and coastal processes to occur.
- This option consists of planning control policies be implemented to avoid flood risk, and will exist within the following context;
  - An absence of any new 'hard' engineered flood protection scheme from 2030 (design-life of existing stopbanks ends)
  - The current Christchurch District Plan remains operative - minimum floor levels for new developments are set above the 0.5% AEP flood, and development in high hazard flood zones is to be avoided. Generally, building platforms for new developments will be raised along with floor levels, limiting underfloor damages. However, for the purposes of this assessment, additional underfloor flooding will contribute to total damages for new developments (this may reduce damages reported).
- Options for avoiding flood risk through planning controls include;
  - Avoid intensification (zoning)
  - Setback controls
  - Trigger-based/time-limited land use consents
- Enabled through Council planning processes/policy development, and the existing direction in the 2010 New Zealand Coastal Policy Statement which advocates for the use of avoidance measures nationally.
- Assumes that services can still be provided in areas impacted by hazards and that residential land use remains tenable.

COSTING APPROACH

- CCC have provided an indicative cost for catchment scale policy development and implementation ($1-2 M). This cost will be incurred at the beginning of the assessment period in 2030.

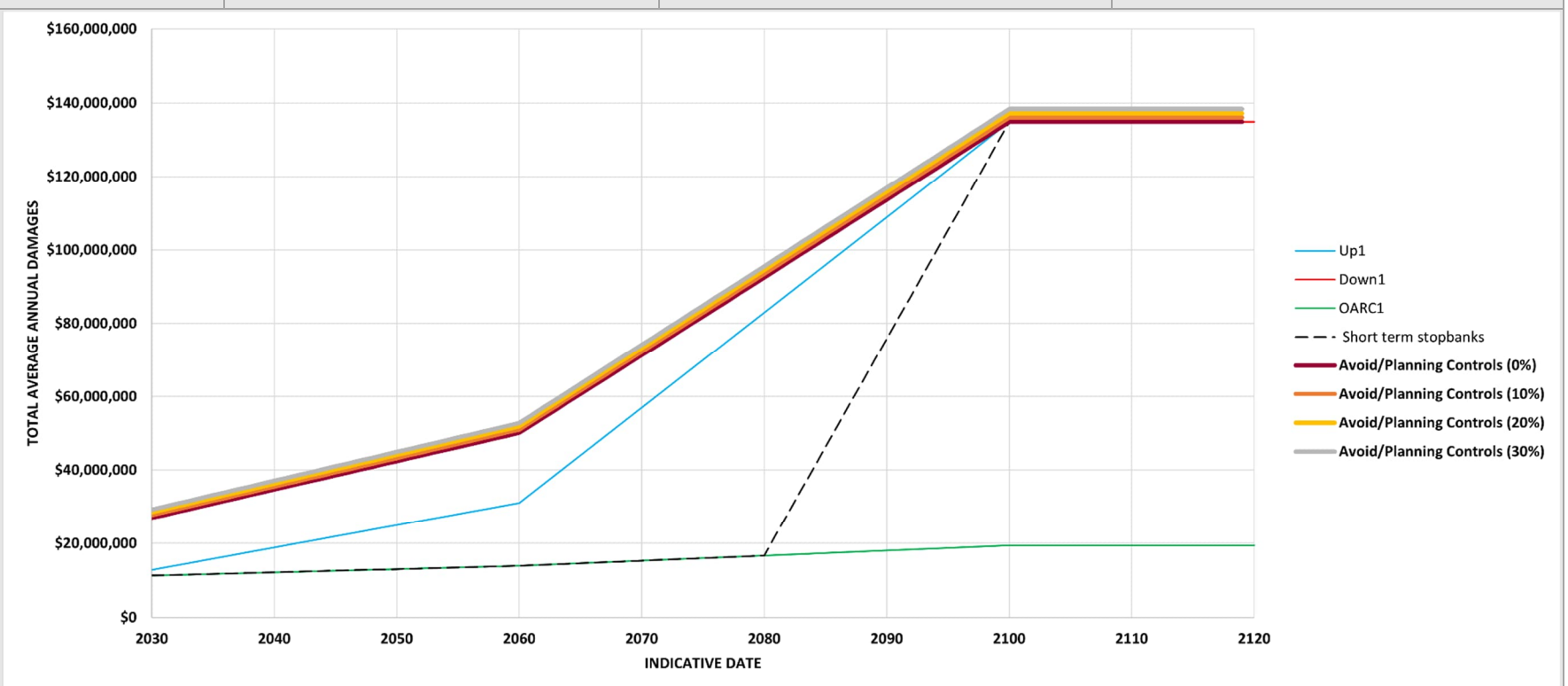
DAMAGES

Allowing for new development in damage calculations:

- Above floor flooding is avoided for new development (minimum floor levels set in the District Plan), but additional underfloor flooding will contribute to total damages, as well as additional indirect and intangible damages.
- Consider three alternative development scenarios: 0%, 10%, 20%, 30% increase in current underfloor damages to be included in AAD totals. Note that lower bound (0%) corresponds to baseline modelling (no further development) and upper bound (30%) corresponds to the scenario proposed for SL04 ('Tolerate').

	2030	2060	2100
Damages calculation	A % increase will be applied to FloodFX outputs for underfloor flooding for the 2030 baseline 'without any stopbanks' scenario and total damages recalculated	A % increase will be applied to FloodFX outputs for underfloor flooding for the 2060 baseline 'without any stopbanks' scenario and total damages recalculated	A % increase will be applied to FloodFX outputs, for underfloor flooding for the 2100 baseline 'without any stopbanks' scenario and total damages recalculated

ILLUSTRATION OF APPROACH



RETREAT
Managed Retreat

OVERVIEW DESCRIPTION

- Remove properties where flood impacts exceed a defined severity at each future climate scenario (a reactive approach to retreat)
- Estimate costs and residual damages for three alternative retreat criteria. Buildings will be removed from the damage calculation where the criteria are met in the 'without any stopbanks' scenario in 2030, 2060, and 2100. The criteria are as follows:
  1. Either of two of the predefined Project Response Indicators for buildings[10]
     a. Above floor damages at 2% AEP
     b. Underfloor flooding at 10% AEP (i.e., damages are accrued for the building)
  2. Above floor damages at 2% AEP
  3. Above floor damages at 10% AEP
- Retreat would be enabled through council planning processes (developing policy and local consultation).
- No new building will be permitted in flood vulnerable locations.
- Costs are based on properties being bought at ratable value.

COSTING APPROACH

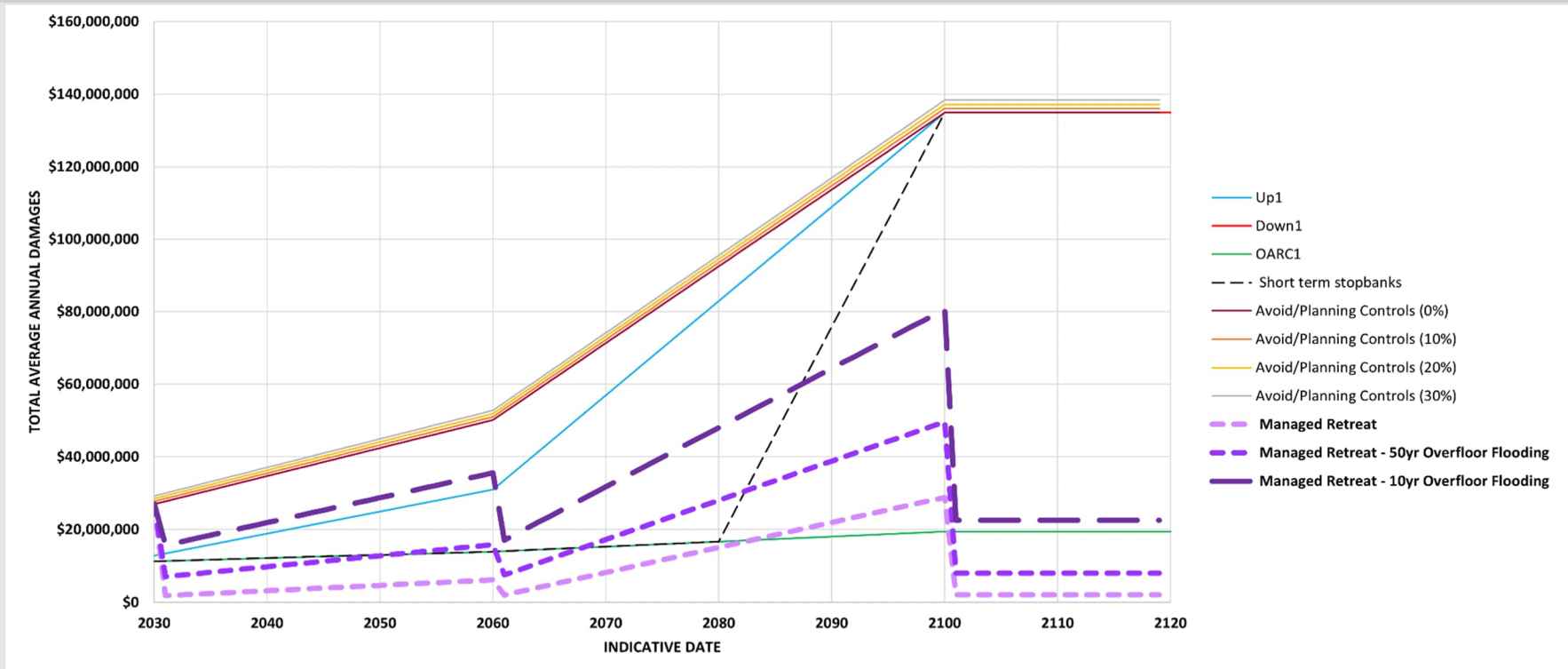
The costing approach has been adapted from the 'Hawke's Bay Coastal Strategy - Implementation approaches and indicative costs for planned retreat'[11]. Costs will be applied at the date of each assessment timeframe (no spreading of costs). No allowances for increased costs for maintaining utilities through the flood affected areas.

	Cost at time 2030	Cost at time 2060	Cost at time 2100
Costing approach	Calculated as 2.5 times the RV of each property identified for retreat at 2030	Calculated as 2.5 times the RV of each additional property identified for retreat at 2060	Calculated as 2.5 times the RV of each additional property identified for retreat at 2100

DAMAGES

Damages Calculation	2030	2060	2100
1. Either of ▪ Above floor damages at 2% AEP ▪ Underfloor flooding (damages) at 10% AEP	Properties which exceed the Project Response Indicators at 2030 will be removed from FloodFX Total AAD for the 2030 'without any stopbanks' scenario (applied at 2031 for PV calculation) and Total AAD for 2060.	Properties which exceed the Project Response Indicators at 2060 will be removed from FloodFX Total AAD for the 2060 'without any stopbanks' scenario (applied at 2061 for PV calculation) and Total AAD for 2100	Properties which exceed the Project Response Indicators at 2100 will be removed from FloodFX Total AAD calculations for the 2100 'without any stopbanks' scenario (applied at 2101 for PV calculation). Same damages applied at 2120 for PV calculation.
2. No above floor damages at 2% AEP 3. No over floor damages at 10% AEP	Properties which exceed the indicator at 2030 will be removed from FloodFX Total AAD for the 2030 'without any stopbanks' scenario (applied at 2031 for PV calculation) and Total AAD for 2060.	Properties which exceed the indicator at 2060 will be removed from FloodFX Total AAD for the 2060 'without any stopbanks' scenario (applied at 2061 for PV calculation) and Total AAD for 2100	Properties which exceed the indicator at 2100 will be removed from FloodFX Total AAD calculations for the 2100 'without any stopbanks' scenario (applied at 2101 for PV calculation). Same damages applied at 2120 for PV calculation.

ILLUSTRATION OF APPROACH



[10] Jacobs memo on this project - IZ084400-NW-MEM-0006-Final Task 2 Initial Project Response Indicators for Groundwater and Flood Hazards (15032024)

[11] Tonkin & Taylor Ltd (2022) Hawke's Bay Coastal Strategy - *Implementation approaches and indicative costs for planned retreat. tech.* Hawke's Bay Regional Council. The 2.5xRV value was calculated by comparing the calculated total cost of retreat in that report by the total cost (land value and capital value) of those houses identified as requiring retreating at 'present' day 2019/20 values. This indicated that retreat may cost approximately 2.5x the cost of the houses and land to be retreated, which accounts for a range of activities including, land clearance, consenting, professional services, project management etc.

TOLERATE
Do Minimum

OVERVIEW DESCRIPTION

- Existing stormwater drainage infrastructure is maintained, and rules/decisions under the current Christchurch District Plan remain operative, but no additional schemes or policies are implemented.
- No limit on new development/intensification provided it meets minimum floor level requirements.
- Floor levels of new buildings will be raised above more extreme flood levels (as governed by the District Plan) so no new above floor damages.
    - When old buildings are replaced the current District Plan would also require floor levels be raised above more extreme flood levels, thus further reducing above floor damages. However, this has not been included or costed within this assessment due to data availability.
- No additional capital cost – i.e. no replacement stopbanks of any kind, existing ones considered ineffective by 2030.
- Implications of residual flood risk include reduced level of service.

COSTING APPROACH

- The costs associated with the alternative options in this assessment are considered in addition to (above and beyond) the cost of a 'Do Minimum' approach. Therefore, the 'Do Minimum' approach is assigned a relative cost of $0.00 (cost in reality would comprise current stormwater drainage infrastructure maintenance and operation in the project area).
- No allowances for increased costs for maintaining utilities through the flood affected areas.

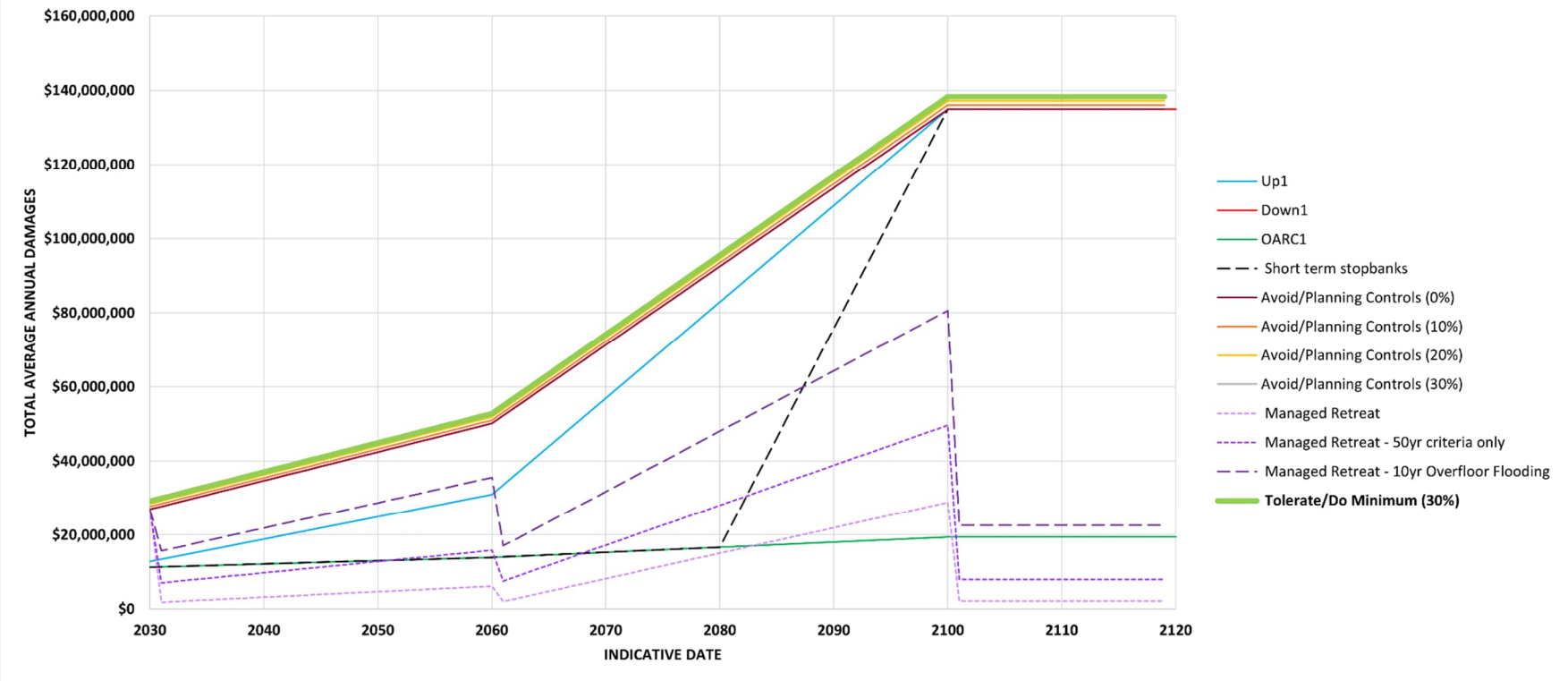
DAMAGES

Representing new development in damage calculations:

- Above floor flooding is avoided for new developments (minimum floor levels set in the District Plan), but underfloor flooding to new development would still occur, as well as additional indirect and intangible damages. A development scenario resulting in an increase in 30% to the existing underfloor flooding damages will be considered and the total damages including indirect and intangible recalculated.

	2030	2060	2100
Damages calculation	A 30% increase will be applied to FloodFX outputs for underfloor flooding for the 2030 baseline 'without any stopbanks' scenario and total damages recalculated	A 30% increase will be applied to FloodFX outputs for underfloor flooding for the 2060 baseline 'without any stopbanks' scenario and total damages recalculated	A 30% increase will be applied to FloodFX outputs, for underfloor flooding for the 2100 baseline 'without any stopbanks' scenario and total damages recalculated

ILLUSTRATION OF APPROACH



ACCOMMODATE
Accommodate Hybrid

OVERVIEW DESCRIPTION

- At risk properties can be protected via approaches which accommodate flooding. Buildings will be eligible for either waterproofing or floor level raising where the flood depth thresholds for either option below are met. Decision making will however consider other factors such as building typology and requirements for consent.

1. Waterproofing buildings
   - When the flood level is above floor in a 10% AEP flood event and no more than 0.5 m deep, properties are eligible to receive waterproofing protection.
   - Buildings will be waterproofed to be protected from damage for inundation up to 0.5 m above floor level (beyond which waterproofing is considered an ineffective option).

2. Raising floor heights
   - When the flood level is more than 0.5 m above floor level in a 10% AEP flood event, properties are eligible for raising.
   - Buildings will be raised to be protected from damage for flood events up to a 0.5% AEP flood event with freeboard.

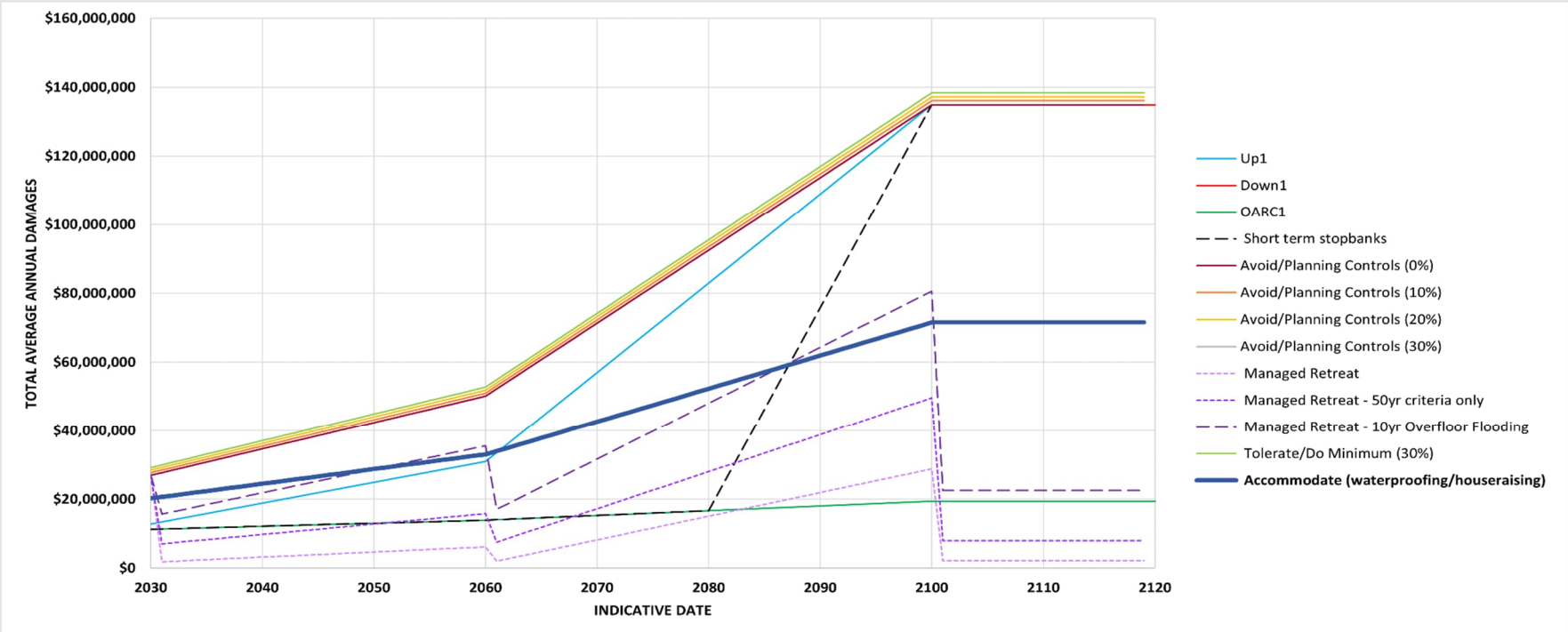
COSTING APPROACH

- Waterproofing buildings –
  - The cost of waterproofing will be calculated for all those properties eligible by 2030, 2060, and 2100.
  - For each eligible property, internal and external waterproofing will be costed at $50k (indic.).
- Raising floor heights –
  - The cost of building raising will be calculated for those properties eligible by 2030, 2060, and 2100.
  - For each eligible property, cost will be 50% of the value of the building RV to give an indication of a viable upper limit for the option.
- No allowances for increased costs for maintaining utilities through the flood affected areas for either option.
- This option does not consider individual building types and therefore assumes that all eligible houses are suitable for waterproofing/ floor raising

DAMAGES

		2030	2060	2100
Damages calculation	Waterproofing buildings	FloodFX outputs for the 2030 baseline 'without any stopbanks' scenario will be used. Damages for properties which experience over floor flooding in 10% AEP with <0.5 m max depth above floor in a 0.5% AEP event are removed.	FloodFX outputs for the 2060 baseline 'without any stopbanks' scenario will be used. Damages for properties which experience over floor flooding in 10% AEP and <0.5 m max depth above floor in a 0.5% AEP event are removed.	FloodFX outputs for the 2060 baseline 'without any stopbanks' scenario will be used. Damages for properties which experience over floor flooding in 10% AEP and <0.5 m max depth above floor in a 0.5% AEP event are removed.
	Raising floor heights	FloodFX outputs for the 2030 baseline 'without any stopbanks' scenario will be used. Over floor damages for properties which experience over floor flooding in a 10% AEP event are removed (underfloor damages retained).	FloodFX outputs for the 2060 baseline 'without any stopbanks' scenario will be used. Over floor damages for properties which experience over floor flooding in a 10% AEP event are removed (underfloor damages retained).	FloodFX outputs for the 2100 baseline 'without any stopbanks' scenario will be used. Over floor damages for properties which experience over floor flooding in a 10% AEP event are removed (underfloor damages retained).

ILLUSTRATION OF APPROACH



PROTECT THEN RETREAT (COMBINED OPTION)

Short design life stopbanks then progressive managed retreat

OVERVIEW DESCRIPTION

- This option is a combined pathway option considering staged implementation of the individual options considered originally in this work. It involves protecting through short design life stopbanks built to protect up till 2060 followed from that point in time by residual protection from those stopbanks and progressive managed retreat of properties at risk as they risk increase over time.
- Stopbanks taken to be partly effective for 10 years after design life with loss of freeboard. Provides time to implement initial stage of managed retreat. Aligns with adaptive approach – decision on pathway based on actual changes to flood risk by 2060, either retreat or enhance stopbanks for future flood levels.
- Damages and costs of initial managed retreat linearly varied from 2060 to 2070.
- Simple linear increase in costs and damages from 2070 to 2100 represents a gradual phased retreat of properties identified as needing to be retreated by 2100 to meet objective (above floor flooding in 10% AEP prevented).
- Planning controls inherent in damage calculations as no new properties added

COSTING APPROACH

Costs of short design life stopbanks are as for the short design life stopbanks option discussed above but only involve construction once in 2030.

Costing of retreat is as for the retreat option discussed above based on a cost per house retreated for the retreat on overflood flooding in a 10% AEP option.

DAMAGES

	2030	2060	2100
Damages calculation	Damages as for short design life stopbanks assessment	Properties which have above floor flooding in 10% AEP in the 'with Scheme' scenario at 2060 will be removed from FloodFX Total AAD for the 2060 'with Scheme' scenario. For PV calculations purposes, amended 2060 AADs applied at 2070 with linear interpolation from 'with Scheme' damages at 2060.	Properties which have above floor flooding in 10% AEP in the 'Stopbanks Down' scenario at 2100 will be removed from FloodFX Total AAD calculations. Damages will be applied at 2100 with linear interpolation from the 2070 damages. Same damages applied at 2120 for PV calculation.

ILLUSTRATION OF APPROACH

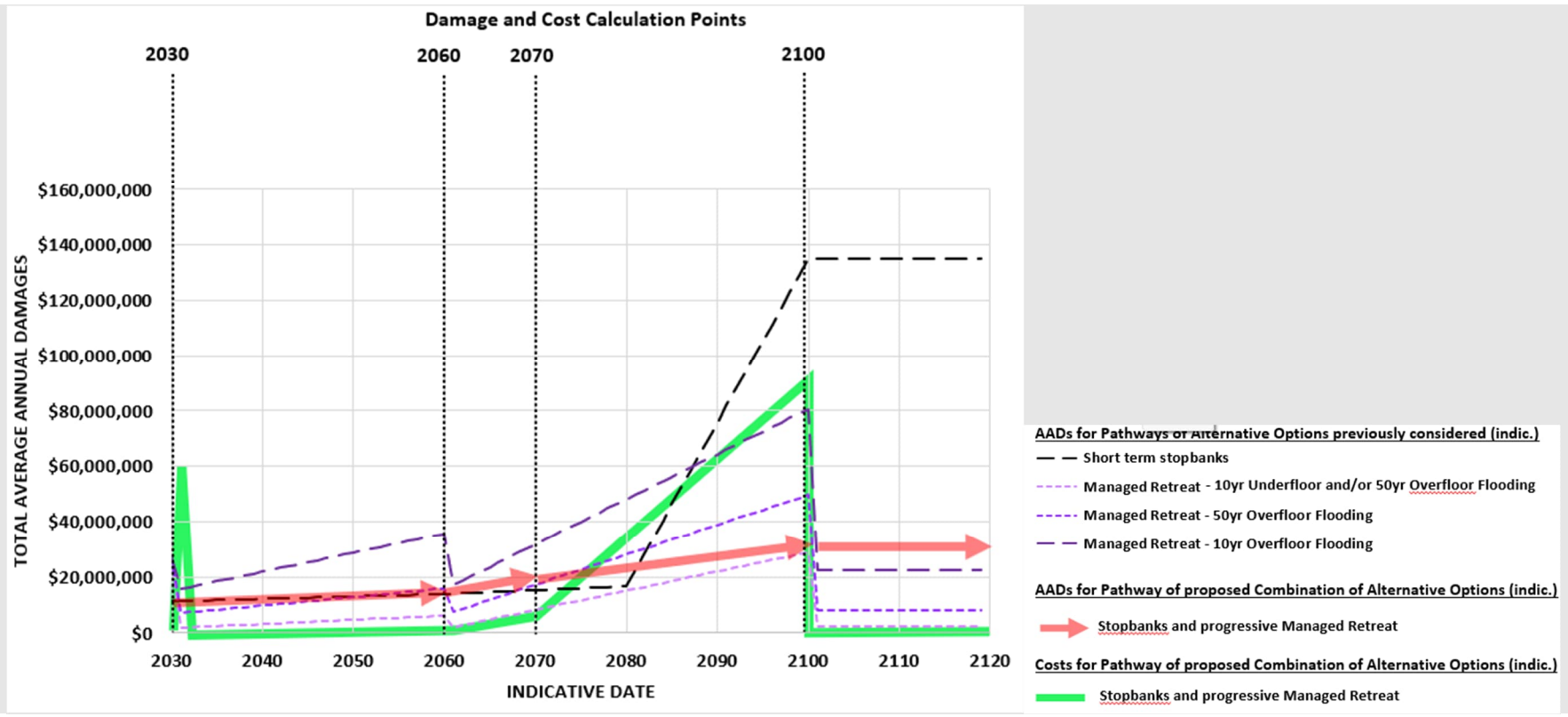


Table 5 Longlist of Alternative Options and Shortlist Screening Commentary

Category	Reference Number	Option	Feasibility	Effectiveness	Environmental	Comments	Workshop Discussion	Shortlisted?	Shortlist Option Number	Shortlist Option Name
PROTECT	LL01	Interim Stopbanks	Engineered to a lower standard than long term stopbanks to realise capital cost savings at expense of long term risk management	Effective over a short (fixed) time period – design life. But less effective/ can't be adapted for longer life	Impact highly dependent on selected alignment	Can manage the risk of both fluvial and tidal flooding. They cannot be relied upon or adapted for longer term protection. So have a shorter-term life after which new stopbanks or other measures may be needed. Limited earthquake reinforcement, and therefore less resilient.	Environmental and effectiveness ranking for stopbanks should be orange. The temporal element associated with the feasibility and effectiveness of stopbanks is important - somehow make provision for this consideration (another column which reflects timeframe?). Consider when making the assessment of options. Number of options could be considered going forward: • Interim reinforcement/replacement of stopbanks along existing stopbank alignment (river edge) • Interim stopbanks along OARC alignment (setback) • Further (than OARC) setback of stopbanks (both temporary and longer term)	Included	SL01	Interim/temporary stopbanks (alignment to be determined)
	LL02	Demountable defences	Problematic given length of defences. Passive performance desirable. Limited benefit in this location given space available for construction of stopbanks	Deployment lead times might make implementation challenging for some sources. Risk of false alarms. Short critical durations for catchments.	Offer little opportunity for enhancement.	Could manage the risk of both fluvial and tidal flooding. Requires forecasting and sufficient warning time to deploy. For the lower Avon, forecasting and warning of storm tide driven flooding, where there is good notice of high astronomical tides ('red tide' days) and atmospheric conditions to predict whether tide levels are likely to require defence mounting, is likely to be more reliable than for fluvially driven events where there is more uncertainty in forecasts.	Unlikely to be feasible for whole scheme due to length required. Demountable defences is not a lead option (could be part of another protect option for shorter sections). Exclude from shortlisted.	Excluded		
	LL03	Shoreline nourishment	Only addresses coastal hazards			This option does not provide focused management of fluvial/tidal flooding along the river corridor, thus is not relevant for comparison with the OARC Scheme. Whilst this option can help provide a temporary buffer zone (allowing waves to run up and dissipate energy) in the event of tidally induced flooding, it focuses on minimising the hazard of coastal erosion first and foremost.	Grey out as Not Applicable – this option is effective in addressing the tidal aspect of the flood hazard along the coastal shoreline, but not the fluvial aspect, or flooding from the river along the corridor which a major source of flood hazard. May be suitable as part of response to coastal hazards in combination with other measures	Removed		
	LL04	Dune reconstruction and regeneration	Only addresses coastal hazards			This option does not provide focused management of fluvial/tidal flooding, thus is not relevant for comparison with the OARC Scheme. This option primarily addresses the hazard of coastal erosion.	As above, grey out as Not Applicable – this option is effective in addressing flood hazard along the coastal shoreline, but not the fluvial aspect, or flooding from the river along the corridor which a major source of flood hazard. May be suitable as part of response to coastal hazards in combination with other measures	Removed		
	LL05	Interception drainage (inc. beach drains)	Intercepts overtopping flows and discharges to sea/river	Ineffective in this location due to likely volume of overtopping from river. In coastal setting likely to be inundated/submerged Relies on highly permeable foreshore which is not present in the Avon floodplain.		This option has been implemented to manage the hazard of coastal overtopping (for modest overtopping rates) and interception of limited stopbank overtopping. Case studies suggest beach drainage has not been significantly effective during larger storms. In this case overtopping rates likely to prevent effective functioning. Also levels may prevent gravity discharge from drains requiring significant storage or pumping.	Agreed	Excluded		
	LL06	Nature based solutions – *making space for the river, constructed wetlands, riparian management and living shorelines*	May require change in landuse	May be difficult to offer the same level of service as other protect options (stopbanks) and perhaps more likely as part of the solution (there are components incorporated in OARC)	Offer opportunity for enhancement and restoration	It is likely that this option alone cannot manage the scale of flooding the Lower Avon is susceptible to. These areas act as a buffer to inundation, and to reduce wave action. Could be implemented in conjunction with another option.	This option is not really a separate option to be compared against the OARC – it is an element of the OARC scheme. It will provide some wave dampening, potentially reducing freeboard requirements, though it is being used more for ecological benefits than flood protection. Could be moved out of the 'Protect' general option type and into retreat, as in the context of the OARC scheme, land will need to be made vacant to implement this option.	Excluded		
	LL07	Groynes and attached breakwaters	Only addresses coastal hazards			This option does not provide focused management of fluvial/tidal flooding, thus is not relevant for comparison with the OARC Scheme. This option primarily addresses the hazard of coastal erosion.	Green feasibility ranking for Groynes is generous (change to orange)	Removed		

PROTECT	LL08	Detached breakwaters and artificial reefs	Only addresses coastal hazards			This option does not provide focused management of fluvial/tidal flooding, thus is not relevant for comparison with the OARC Scheme. This option primarily addresses the hazard of coastal erosion.	Feasibility to orange. Environmental to orange.	Removed		
	LL09	Armouring of existing stopbanks and of riverbanks and coastline as required	Could preserve current crest heights but would need to be strengthened with time to maintain LoS in the context of VLM and climate change influences.	Primarily addresses erosion risk. May extend life of existing assets	Likely to have negative impact on habitat in these areas	This option does not provide focused management of fluvial/tidal flooding, thus is not relevant for comparison with the OARC Scheme. This option primarily addresses the hazard of erosion. Short term solution with ongoing management costs – Structures require height increases overtime to adjust for sea level rise.	OARC may need to include a component of this to address erosion of stopbanks along the river corridor. Desire for this to not be considered a standalone option.	Excluded		
	LL10	Storm surge barriers	A barrier could feasibly be constructed to control estuary water levels, however it is ikely to require significant capital and operational expenditure.	Could reduce tailwater levels but doesn't address shortage in conveyance capacity upstream. A barrier would need to be implemented as part of a catchment wide flood management strategy, taking into account future scenarios on land development and climate change, in conjunction with other engineering considerations (GHD & NIWA, 2015).	Likely to have negative impact on habitat	This option comes with significant caveats related to cost, ongoing management and required side car systems (flood warning systems for barrier closure etc.). Also, it addresses tidal flooding only. However, storm surge barriers could be devised as one component of a larger flood prevention program. Can provide some fluvial benefit if the estuary is used as a storage basin. Reduces reliance on flood protection defences inland (creates space between communities and the hazard)	Agree with the rankings/removal from options list. The 'Avon-Heathcote Tidal Barrier Pre-Feasibility Study' (GHD & NIWA, 2015) concluded that a barrier could feasibly be constructed to control estuary water levels, however a tidal barrier would not resolve Christchurch's flood risk challenges in isolation.	Excluded		
	LL11	Conveyance and storage improvements (utilizing Nature Based Solutions (NBS))	Likely to require significant disposal of fill (offsite)	Could require significant maintenance of sediment and vegetation	Offers good opportunity for enhancement	Would comprise lowering and widening of the river corridor to make more space for the river without need for stopbanks (or with limited need). Would not address tidal flood risk. Could build on Nature Based Solutions to make more space for the river. May require change of landuse (retreat of some assets?).	Not discussed at workshop (developed since)	TBC	SL06	
AVOID	LL12	Avoid intensification (zoning)	Feasibility dependent on related council policy and public appetite.	Avoids placing new infrastructure at risk. Ineffective at managing exposure to existing infrastructure.	Protects from further impact but does not offer opportunity to restore	Manages both tidal and fluvial flooding. Phasing out development through zoning takes time. May not be the appropriate approach to address flooding in areas of the Lower Avon at risk in the immediate-short term. Could be employed in conjunction with other more 'hard and fast' options.	'Avoid' land use change options are absolutely needed to manage future development in a way that is appropriate. It is assumed that land use control/change policy will be included in parallel to whatever flood management option/scheme is implemented in future. These three avoid options are to be amalgamated and shortlisted as one 'Land use change/controls' option.	Included	SL02	Avoid through planning controls (hybrid)
	LL13	Tighter land use controls (trigger-based or time-limited land use consents)	Feasibility dependent on related council policy and public appetite	Could reduce future exposure and control risk to new assets. Perhaps ineffective in short term?	Could offer opportunity to restore depending upon replacement for retired assets/ landuses	Manages both tidal and fluvial flooding. Requires land restoration and long-term management (costly, prolonged process). This land use change may entail implementing protection measures or creating a natural buffer zone etc. which offers additional flood protection. Equally, it allows for utilisation of residual asset life of utility infrastructure and defers construction of replacement services elsewhere.				
	LL14	Setback controls / Relocation of assets *(Development restricted to outside of 1% AEP flood extent or minimum elevation for development etc.)*	Already implemented and reduces exposure to new infrastructure & assets	Avoids placing new infrastructure at risk. Ineffective at managing exposure to existing infrastructure & assets.	Protects from further impact but does not offer opportunity to restore	Manages both tidal and fluvial flooding. Instating setback controls is effective in minimising damage to future developments but does not as effectively minimise risk to existing areas of development (i.e. compared to the extent the OARC scheme does).				

RETREAT	LL15	Proactive whole community retreat / Removal of assets *(Agree a date for retreat or set flooding tolerance threshold and extent of properties/assets affected as trigger for retreat)*	Economic feasibility untested. Some may be unwilling or unable to retreat.	Effective provided exposed assets & properties participate	Opportunity to restore land following retreat	A highly effective approach to managing both tidal and fluvial flooding. However, although this option may be practical to implement, it is complex and burdensome (to community wellbeing, council resourcing, financially etc.) Likely a lengthy process. Expensive option - Costs and benefits would need to be carefully weighed.	Roll up retreat options listed here into one option with the following sub options to be considered during assessment – proactive retreat, reactive retreat, area wide retreat, or puzzle piece retreat based upon asset/property risk.	Included	SL03	Managed Retreat (hybrid)
	LL16	Reactive retreat following future flood (or earthquake)	Uncertainty around government policy & funding	Effective provided exposed assets & properties participate	Opportunity to restore land following retreat	Separated out response following an event for clarity. Need to consider how we develop a retreat alternative to OARC for comparison in this task.				
	LL17	Reactive at change in ownership		Implementation timeframes long (at change in ownership) and no guarantee of being able to purchase all exposed property on the open market	Opportunity to restore land following retreat	Manages both tidal and fluvial flooding. Being reactive at change in property ownership will take time - May not be the appropriate approach to address flooding in areas of the Lower Avon which are at risk in the immediate-short term.				
	LL18	Insurance/finance triggered retreat		No control on the timeframes or scope of retreat. No guarantees of all exposed properties retreating		In part, this option takes a 'do nothing' approach - How effectively flood risks are managed in Ōtākaro/Avon River will influence the scale and timing of any insurance/finance issues. These communities will remain vulnerable to occurrences of tidal/fluvial flooding up until these triggers are reached (already in harm's way).		Excluded		
	LL19	Acquisition *Various acquisition tools including: Buyouts, Land swamps, Leasebacks, Future interests, Conservation easements, and Transferable development rights*				Repeat of above options (not distinctly different to other retreat options rather a mechanism to achieve proactive or reactive retreat)		Removed		
ACCOMMODATE	LL20	Tolerate risk / reduced levels of service *Implementation – regular risk perception assessments, assisting communities to prepare and recover from large events, funding science communication, providing weather forecasts/warnings*	May be possible to accept higher residual risk in exchange for reduced investment in risk management.	Not as effective as OARC given reduce Level of service	Limited opportunity to have positive environmental impact	Entirely dependent on community perception and tolerance of risk. For this reason, the feasibility and effectivity of this option cannot be categorized prior to community engagement. Relatively easily implemented and has the potential to increase community resilience to fluvial/tidal flooding, with no major change witnessed by the wider community. Thus, should be considered further.	Tolerate risk/reduced levels of service - the 'do minimum' baseline option . Though not comparable with the OARC scheme, it helps us see and show what the baseline impact is.	Included	SL04	Do minimum
	LL21	Adaptable buildings (i.e., house raising)	Feasibility depends on depth of flooding, form of construction etc. May not work for all vulnerable properties	House raising may be effective for some properties. May not address access and indirect risks	Limited opportunity to have positive environmental impact	Comparatively, the OARC provides a more integrated flood protection approach Realistically, this option isn't easily implemented in existing developments. Particularly onerous for homeowners.	May be worth being given more consideration - look at building typology during our assessment. Shortlist it. It is important to note that adaptable buildings (i.e., house raising) refers to raising floor levels in the context of it being a general flood management approach across the city for greenfield or redevelopment rather than retrofit. Effective only against fluvial hazard (change to orange)			
	LL22	Emergency management - Improved flood warning.	Some technical challenges with enhances flood warning given complexities of sources of risk	May be limited opportunity to improve outcomes (reduce losses).	Limited opportunity to have positive environmental impact	Addresses both tidal and fluvial flooding. Effectively allows for planning ahead and can help to increase community resilience and reduce the risk of fluvial/tidal flood hazards.				

ACCOMMODATE	LL23	Flood proofing property level	Plausible to explore ring bunds, door guards, airbrick covers, etc. Also consider flood proof materials (no carpets on ground floor) and raising electrical points etc.	Best suited to marginal/low risk properties to improve LoS on case-by-case basis. Perhaps unlikely to be effective at catchment scale	Limited opportunity to have positive environmental impact	Helps to prevent or provide resistance to flood damage (both tidal and fluvial flooding) Requires no extra land It can be carried out by individual property owners This option is less easily implemented in existing developments.		Included	SL05	Accommodate (hybrid)
	LL24	Flood proofing infrastructure	Could be prioritized based on criticality/exposure	Could be effective in reducing impact of flooding on critical infrastructure	Limited opportunity to have positive environmental impact	Only suitable in areas where flood depths are low				
	LL25		Usually raising of flood vulnerable assets (electrical switchgear, telecoms infrastructure etc.)							
	LL26	Raising land levels	May be prohibitively expensive/implausible depending on current and proposed landuse. Likely to be more expensive than smaller footprint stopbanks Could displace floodwater to other vulnerable areas	Difficult to implement this option in areas with existing developments.	Limited opportunity to have positive environmental impact	Difficult to implement this option in areas with existing developments. Edges of raised land may require ongoing protection from fluvial etc. erosion May increase flood hazard in adjoining areas where the water is redirected Material used will likely be subject to earthquake induced vertical land movement in future - how much it will subside is unknown, thus may need to be reworked at an unknown time in the future. May create access issues i.e. surrounding roads remain at a lower level and are flooded for periods of time				
	LL27	Groundwater management	Wells/Pumping of groundwater to lower levels is not usually a long term risk management approach. Cost and carbon could be prohibitive. Cut-off walls and other measures also unlikely to be feasible.	Unlikely to be long term effective risk management approach. Would be compounded by other risks (coastal, pluvial & fluvial)	Limited opportunity to have positive environmental impact. Further these kinds of interventions could be harmful to the aquifer	This option does not manage fluvial and tidal flooding, thus is not relevant for comparison with the OARC scheme.	Groundwater management is being considered in the OARC scheme, though it would not be permitted under current plan. However, it is assumed this will change in the future.			
	LL28	Enhanced stormwater management	Increased storage, conveyance and pump capacity could manage some risks and perhaps even deal with multihazard events to a certain point.	Unclear if these measures would be as effective as other measures.	Plausible to explore some enhancement (using constructed wetlands for example).	Manages both tidal and fluvial flooding. Stormwater Management Plans have already been prepared for the Ōtākaro/Avon River catchment. These plans consider both changes in climate and changes in development patterns. Thus, will likely minimise fluvial/tidal inundation impacts on the area.				
	LL29	Diversifying energy and water supply	Potentially plausible to live with higher flood risk with increased resilience to water and energy supplies.	Ineffective at materially reducing flood risk and perhaps therefore not a suitable candidate for ORAC alternative	Limited opportunity to have positive environmental impact.	Whilst this option increases community resilience during hazard events, it does not provide focused management of fluvial/tidal flooding as the OARC Scheme does. Thus, it is not relevant to the comparison being made in this assessment.				

Appendix J. Source data for assessment of PRIs and method of application

Project Response Indicators for Groundwater Hazards ***Indicators refer to the 85th percentile groundwater level in metres below ground level (mbgl)***			
Element	***Proposed PRI value***	***Source***	***Application***
Local ponding/flooding	Emergent groundwater (<0 mbgl)	Data provided by Aqualinc and reported in Aqualinc 2020. *LDRP45: Impacts of Earthquakes and Sea Level Rise on Shallow Groundwater Levels*. Report prepared for Christchurch City Council. Reference C17054. 14 August 2020 J:\IE\Projects\02_New Zealand\IZ084400\05 Incoming\20231219 Aqualinc DTW Rasters	[Raster grid, all cells exceeding PRI]
Buildings	New builds 0.3 m, older buildings 0.3 m (sandy soils) and 0.7 m (silty soils)	Buildings: OARC Scheme FloodFX outputs Soils: Begg, J.G.; Jones, K.E.; Barrell, D.J.A. (compilers) 2015. *Geology and geomorphology of urban Christchurch and eastern Canterbury.* GNS Science geological map 3. 1 DVD-ROM. Lower Hutt, New Zealand: GNS Science.	0.3 m (sandy soils) and 0.7 m (silty soils) [discrete buildings, >10% building area exceeds PRI]
Contaminated Sites	0 mbgl - surface exposure at site 0.5 mbgl - services within 50 m of contaminated site	Listed land use register (LLUR) – Environment Canterbury. Accessed 31/05/2024.	0 mbgl - surface exposure at site 0.5 mbgl - within 50 m of contaminated site [Raster grid, all cells exceeding PRI]
Parks and Reserves / Sports Fields	0.3 mbgl sandy soils 0.5 mbgl silty soils	*Formed from a combination of:* Park (OpenData) – Christchurch City Council NZ Facilities – Land Information New Zealand	[Raster grid, all cells exceeding PRI]

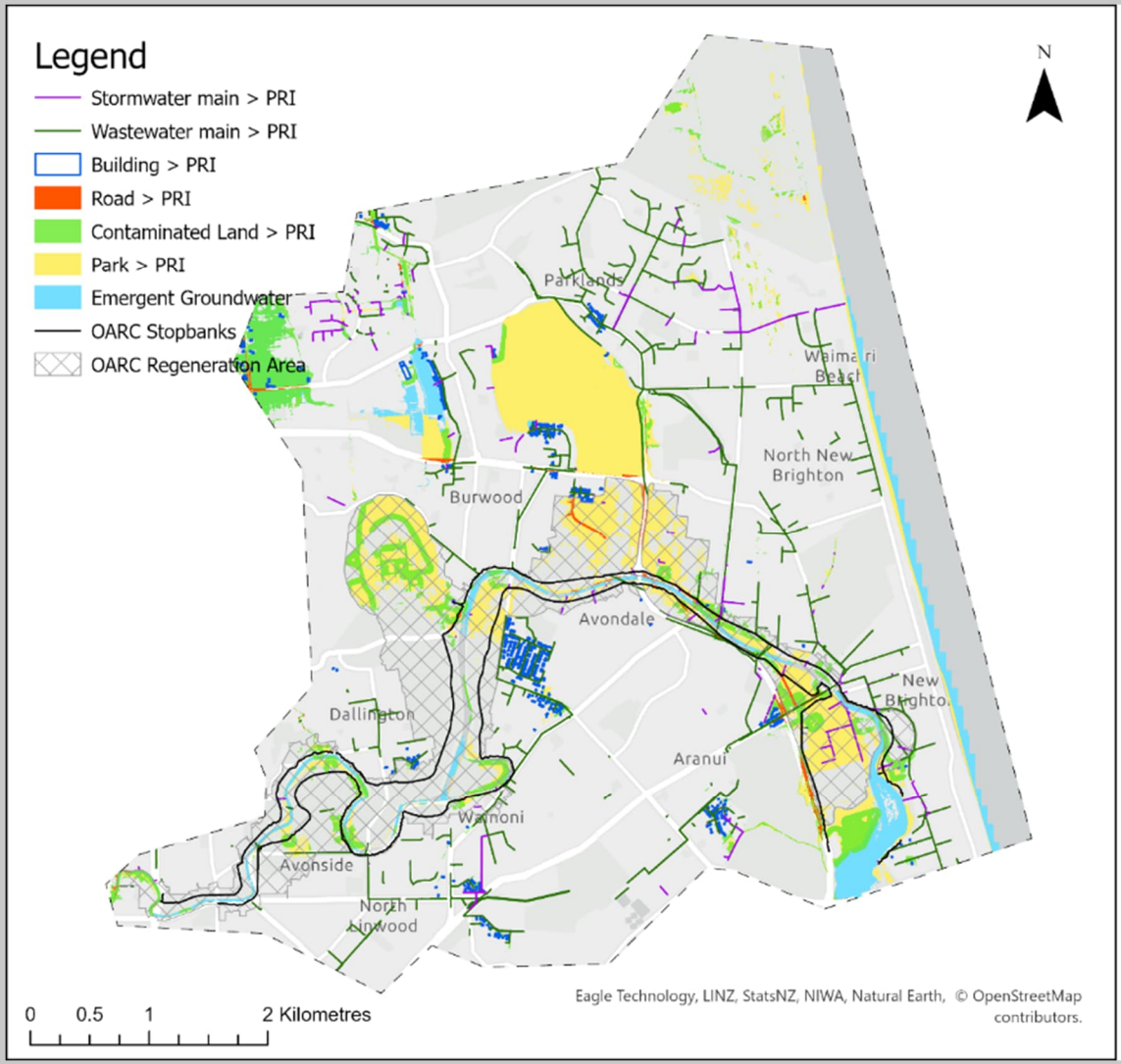
		DistrictPlanOperative - Christchurch City Council	
Roads	0.1 mbgl for local roads, 0.3 mbgl main arterial routes	NZ Primary Road Parcels - Land Information New Zealand	[Raster grid, all cells exceeding PRI]
Service Stations	0.5 mbgl – buoyancy of underground storage tanks	Bespoke layer created to show service stations within area from publicly available online sources	[discrete service station areas, any cell in area exceeds PRI]
~~Stormwater / Wastewater Laterals~~	~~Dependent on pipe depth – groundwater at mid-level of pipe~~		Omitted from analysis due to lack of differentiation of laterals and limited depth data.
Stormwater / Wastewater Mains	Dependent on pipe depth – groundwater 1 m above top of pipe for buoyancy	Stormwater mains: exported from Multihazards City Wide Model Wastewater mains: WwPipeType – Christchurch City Council	Stormwater: Groundwater 1 m above depth of downstream node plus pipe height/diameter. Wastewater: Groundwater 1 m above depth of pipe plus pipe diameter. [discrete pipes, any cell a pipe touches exceeds PRI]
Project Response Indicators for Flood Hazards ***Indicators refer to the depth of water in metres (m) above ground level or Damage Ratio[69] (DR) for a specified likelihood of flooding in terms of Annual Exceedance Probability (AEP)***			
Element	***Proposed Indicators***	***Source***	***Application***
People's safety (roads and properties)	0.4 m at 0.5% AEP	NZ Primary Road Parcels - Land Information New Zealand NZ Primary Parcels - Land Information New Zealand	[Raster grid, all cells exceeding PRI]

[69] As defined in Table 3 of RiskScape: Flood fragility methodology, NIWA Client Report: WLG2010-45, August 2010

		DistrictPlanOperative - Christchurch City Council	
Buildings	No underfloor damages at 10% AEP, No above floor damage at 2% AEP, DR<0.1 at 0.5% AEP	Buildings: OARC Scheme FloodFX outputs	No underfloor damages at 10% AEP, No above floor damage at 2% AEP [discrete buildings, any cell in area exceeds PRI]
Contaminated Sites	0 m at 0.5% AEP (i.e., no flooding for all AEPs considered)	Listed land use register (LLUR) – Environment Canterbury. Accessed 31/05/2024.	0.05 m at 0.5% AEP (i.e., no flooding for all AEPs considered) [Raster grid, all cells exceeding PRI]
Roads	Use people's safety threshold (lower than hazard to roads themselves)	See *People's safety* PRI NZ Primary Road Parcels - Land Information New Zealand	[Raster grid, all cells exceeding PRI]
Service stations	As for buildings	Bespoke layer created to show service stations within area from publicly available online sources	No underfloor damages at 10% AEP, No above floor damage at 2% AEP [discrete buildings, any cell in area exceeds PRI]
Stormwater Laterals / Mains	None		
Wastewater Laterals / Mains	None		
Water Supply Laterals / Mains	None		
Stormwater Pump Station	0.3 m at 0.5% AEP	SwPump (OpenData) – Christchurch City Council	[points, exceeding PRI]
Wastewater Pump Station	0.3 m at 0.5% AEP	SwPump (OpenData) – Christchurch City Council	[points, exceeding PRI]
Wastewater Monitors	None		
Water Supply Station	None		

Parks and Reserves / Sports Fields	0.2 m at 10% AEP	*Formed from a combination of:* Park (OpenData) – Christchurch City Council NZ Facilities – Land Information New Zealand DistrictPlanOperative - Christchurch City Council	[Raster grid, all cells exceeding PRI]

Appendix K. Groundwater hazard PRI mapping

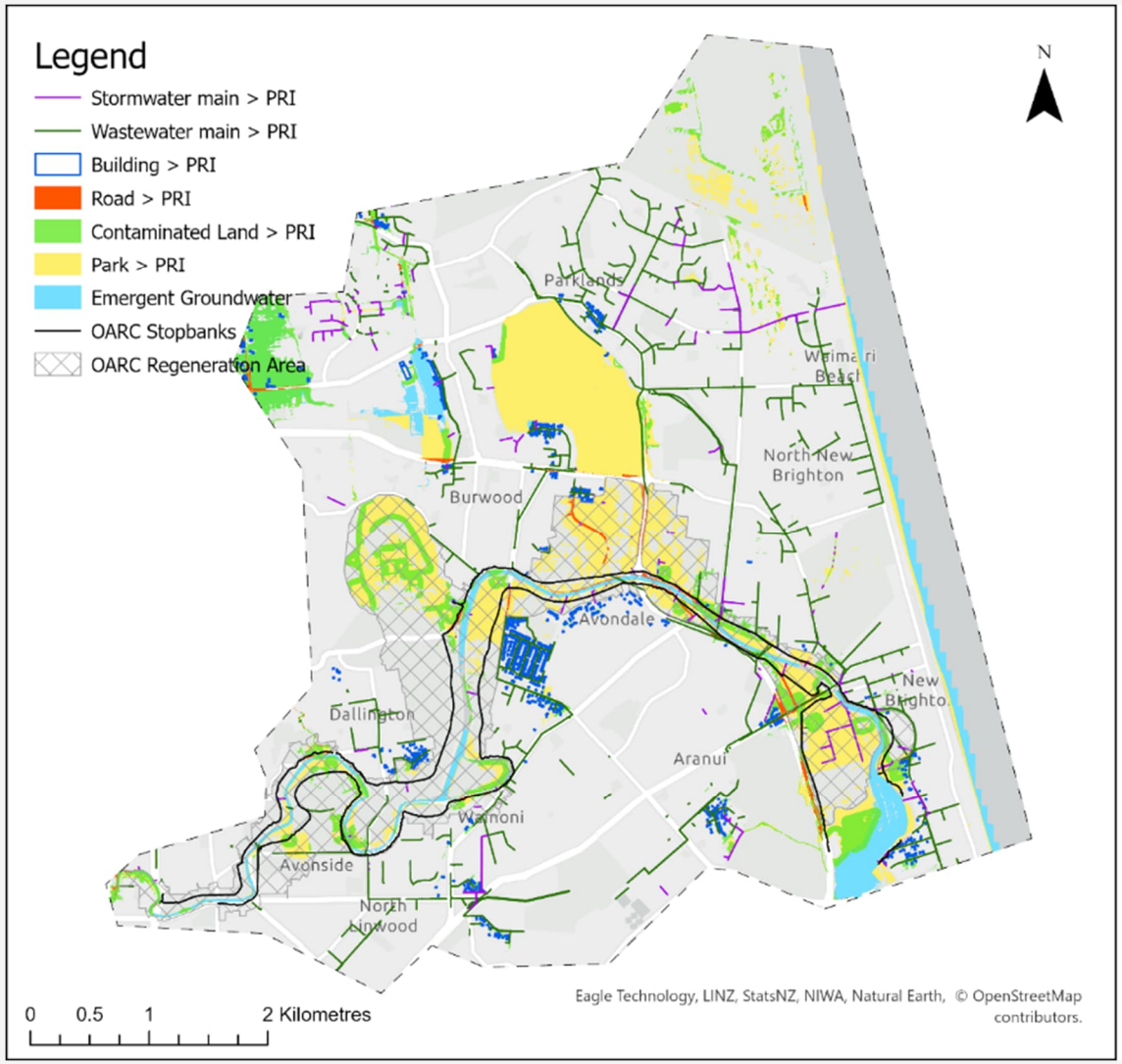


Groundwater - All PRIs

0.19 m SLR [2030]

Scenario: 4+ Scheme

- **Exceedance of PRIs is mainly for pipe infrastructure (stormwater and wastewater mains) and parks.**
- **Pipes exceeding PRIs are mainly in Wainoni, North Linwood, Avondale, to the east of the OARC flood defences in New Brighton, Parklands, North New Brighton and Prestons. Exceedances are mostly for wastewater mains.**
- **Exceedances of pipe infrastructure PRIs in Parklands, North New Brighton and Prestons areas are likely to be in areas far enough from the proposed OARC flood defence to not gain direct flood protection by the scheme.**
- **Very few exceedances of roads** PRIs outside the OARC Regeneration area. **Building PRIs exceeded mainly in western Avondale.**
- **Travis wetland area and Clare Park are key park areas exceeding PRIs, however with these being wetland area it is an expected result.**
- **Emergent groundwater is largely confined to parks and wetlands.**

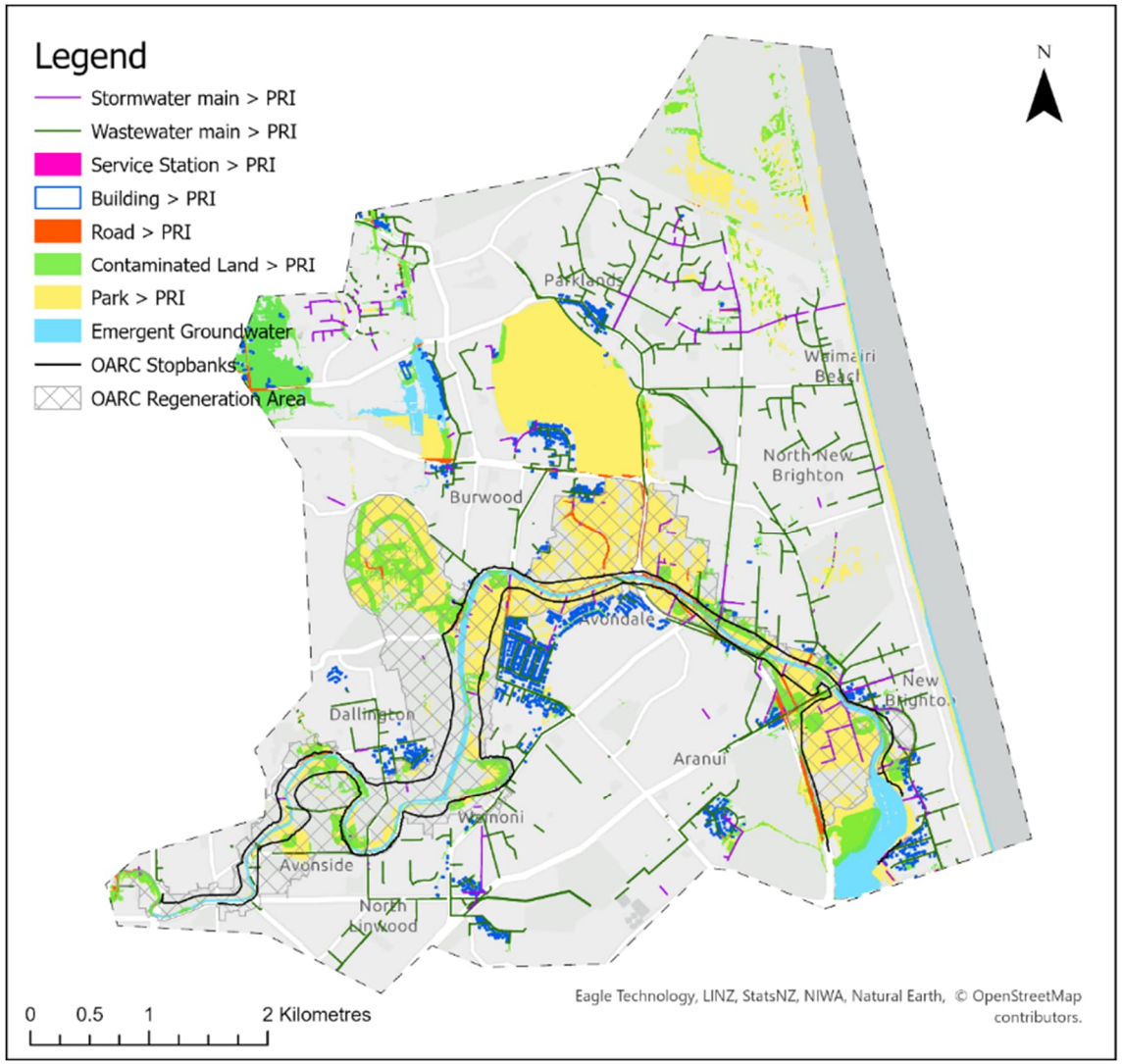


Groundwater - All PRIs

0.45 m SLR [2060]

Scenario: 6+ Scheme

- By ~2060 with 0.45 m SLR there is little change in the overall spatial distribution of PRI exceedances from 0.19 m SLR but a small increase in the density of exceedance – i.e. more elements exceeding in the same areas.
- Outside of the OARC Regeneration areas exceedances within parks are again Clare Park and Travis Wetland with some in Bottle Lake.
- Emergent groundwater is largely confined to parks and wetlands.

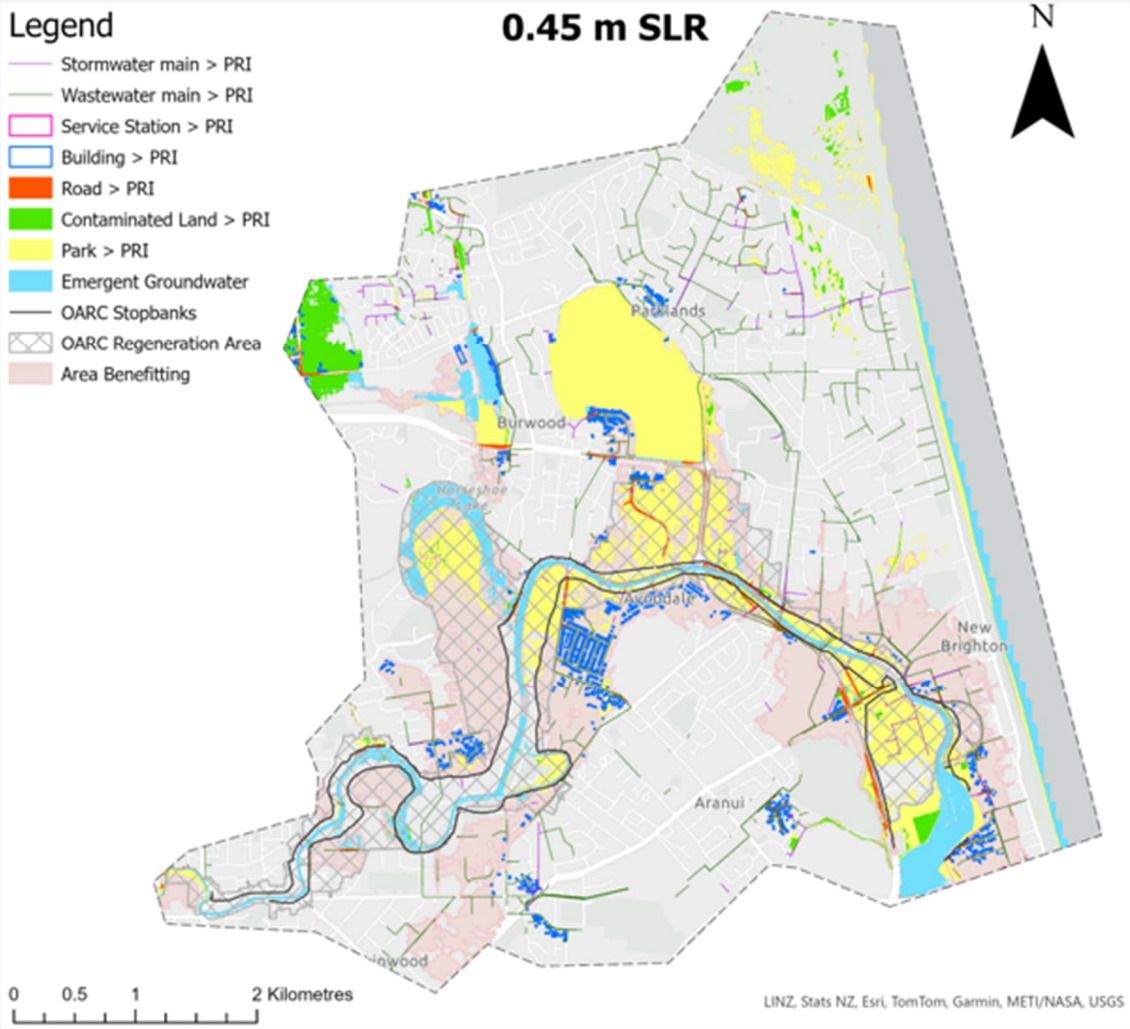


Groundwater - All PRIs

0.45 m SLR [2060] with earthquake settlement

Scenario: 8+ Scheme

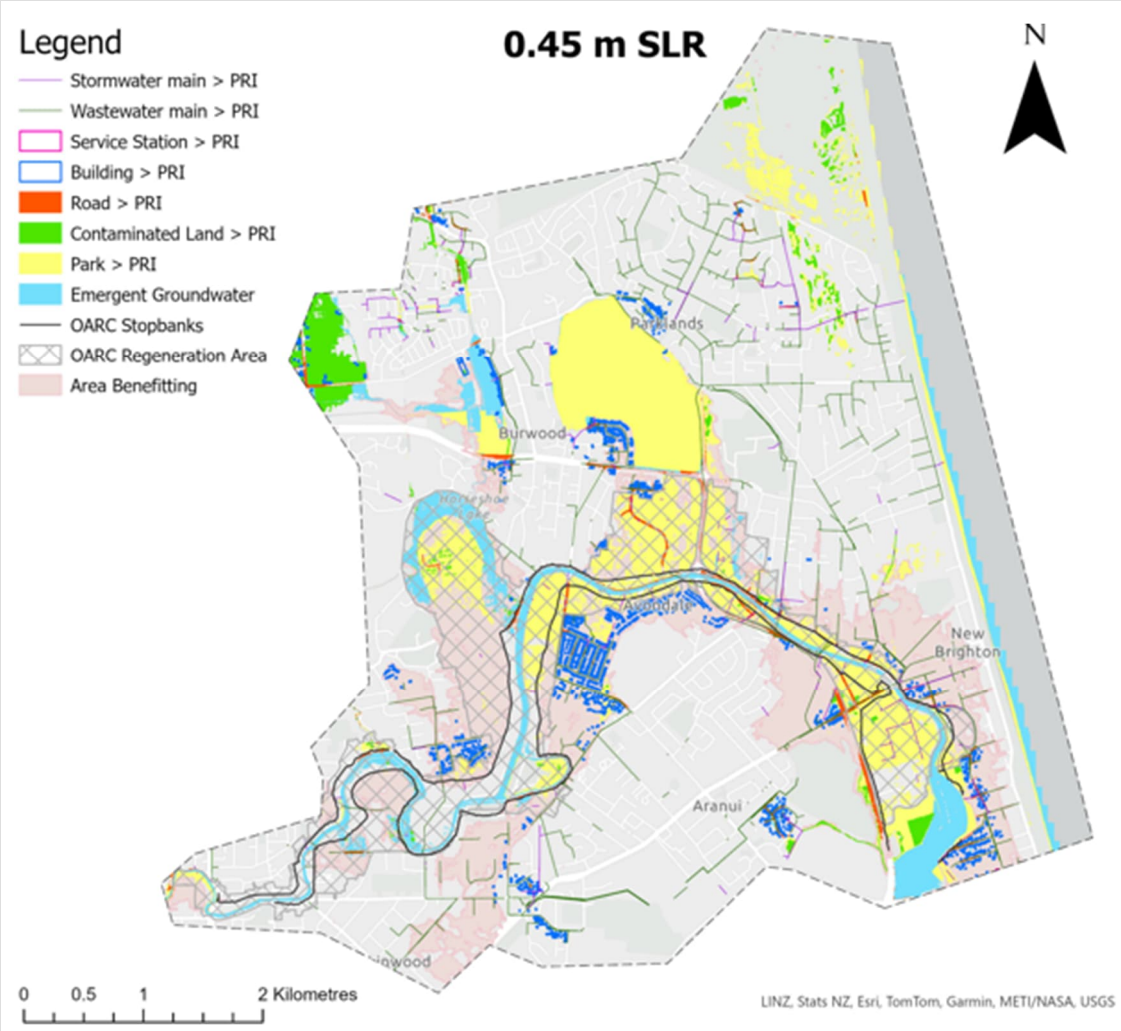
- The change in addition of earthquake induced land settlement in 2060 with 0.45 m SLR appears to make a small change in exceedance of PRIs only.
- There is a slight increase in exceedance of pipe infrastructure PRIs and an area of buildings exceeding PRIs by Travis Wetland in Burwood.
- The number of exceedances of building PRIs within the Avondale area is starting to increase and exceedances of building PRIs in Dallington are starting to be observed as are exceedances of the wastewater network PRIs in that area.



Groundwater – all PRI's

0.45m SLR (~2060) with S1 VLM

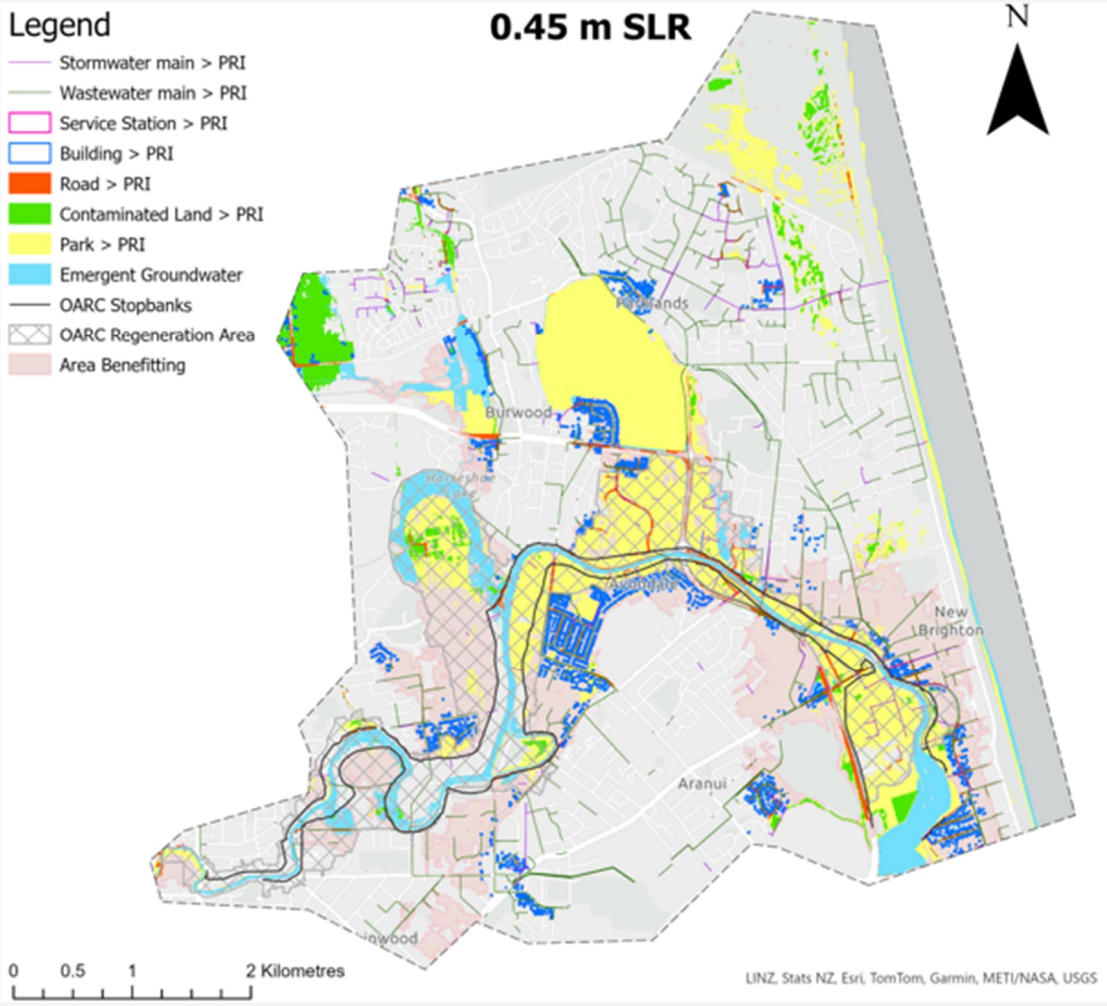
- The change in addition of scenario 1 VLM in 2060 with 0.45 m SLR appears to make a small change in exceedance of PRIs only compared to with no VLM.
- The number of exceedances of building PRIs within the Avondale area is starting to increase and exceedances of building PRIs in Dallington are starting to be observed.



Groundwater – all PRI's

0.45m SLR (~2060) with S2 VLM

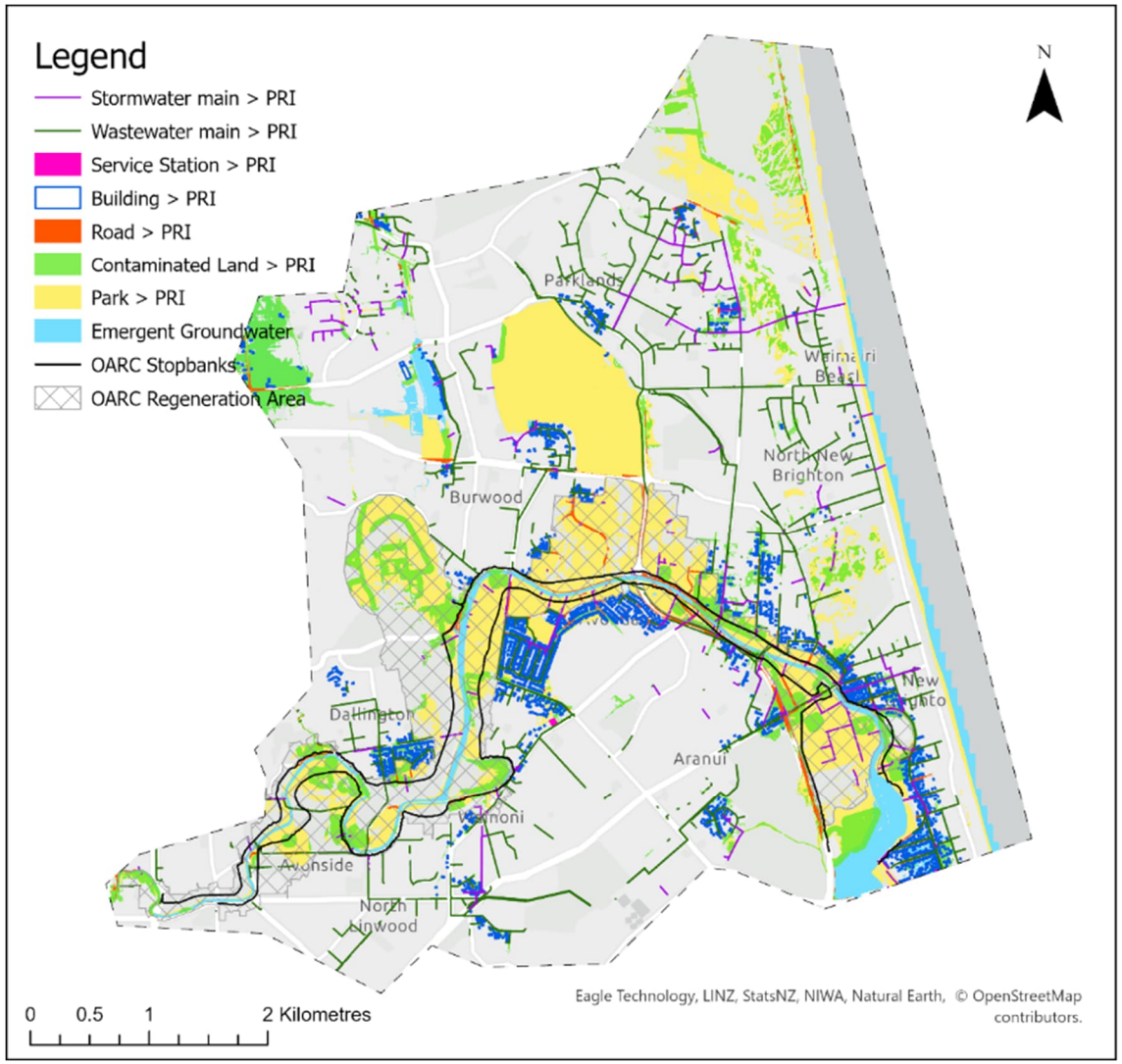
- VLM under scenario 2 increases exceedance of groundwater PRI's, primarily the buildings PRI in many suburbs compared to both the no VLM and S1 VLM scenario.
- The pattern and type of exceedances is broadly similar to the original no VLM but future earthquake scenario.
- The main increases in buildings exceeding the PRI are observed in South New Brighton, Parklands, Burwood, Dallington, North Linwood and Avonside



Groundwater – all PRI's

0.45m SLR (~2060) with S3 VLM + Earthquake

- Under this scenario greater exceedance of wastewater PRI's is observed, especially in the North New Brighton area which is outside of the flood management influence of the scheme.
- Building PRI exceedances are more prevalent, still focused in the same suburbs of South New Brighton, New Brighton, Parklands, Burwood, Dallington, North Linwood, Avonside and Aranui.
- Emergent groundwater is more extensive but generally within the OARC regeneration plan area.

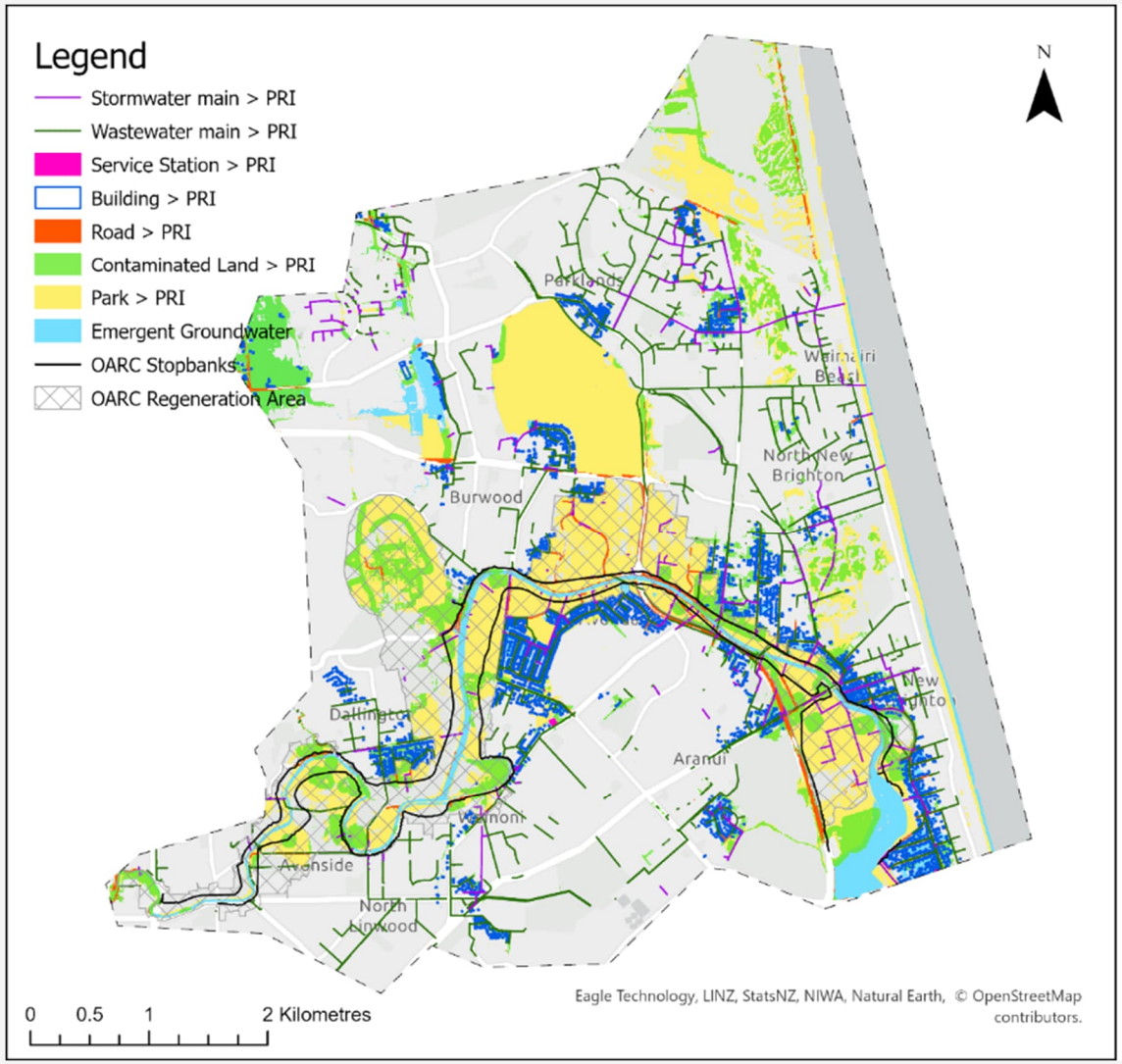


Groundwater - All PRIs

1.06 m SLR [2100]

Scenario: 9+ Scheme

- Increased lengths of wastewater main especially and some stormwater networks exceed PRIs, generally in the same suburbs but with a greater proportion of the networks impacted. To the north-east and east of the project area a large proportion of the networks exceed PRIs.
- Building PRIs more widely exceeded between New Brighton Road and Keyes Road in New Brighton, in Parklands, Burwood by Travis Wetland, around Owles Terrace and into South New Brighton, Avondale, Wainoni, Aranui and Dallington
- Many contaminated land sites exceed PRIs, these are a mix of Council parks and school grounds.
- Roads bordering the OARC Regeneration area exceed PRIs - SH74 in Aranui is impacted and again near Clare Park in Burwood.
- The first service station exceedance is observed along Wainoni Road.
- Emergent groundwater is starting to be seen outside of the OARC regeneration area in Avondale and New Brighton.

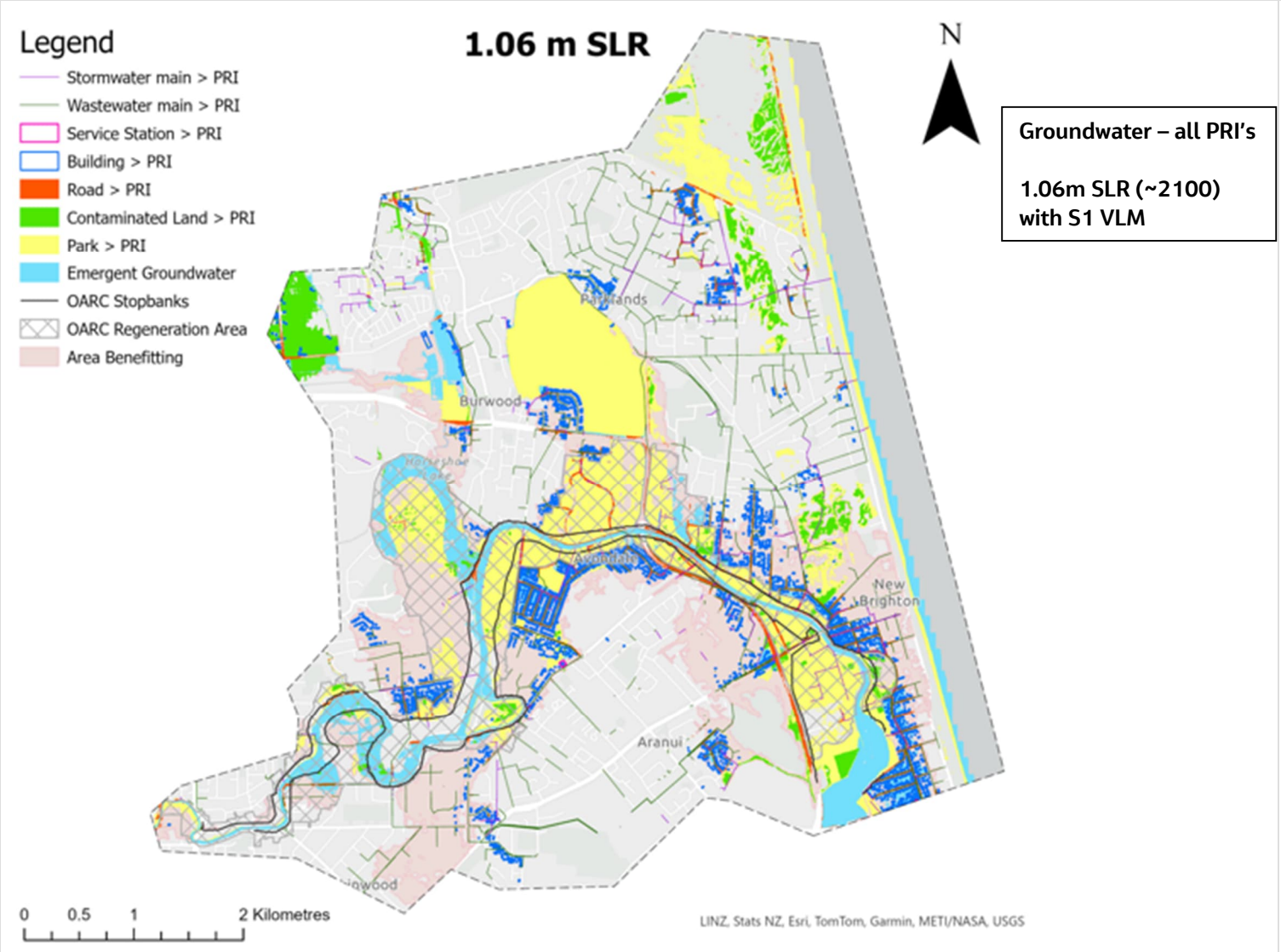


Groundwater - All PRIs

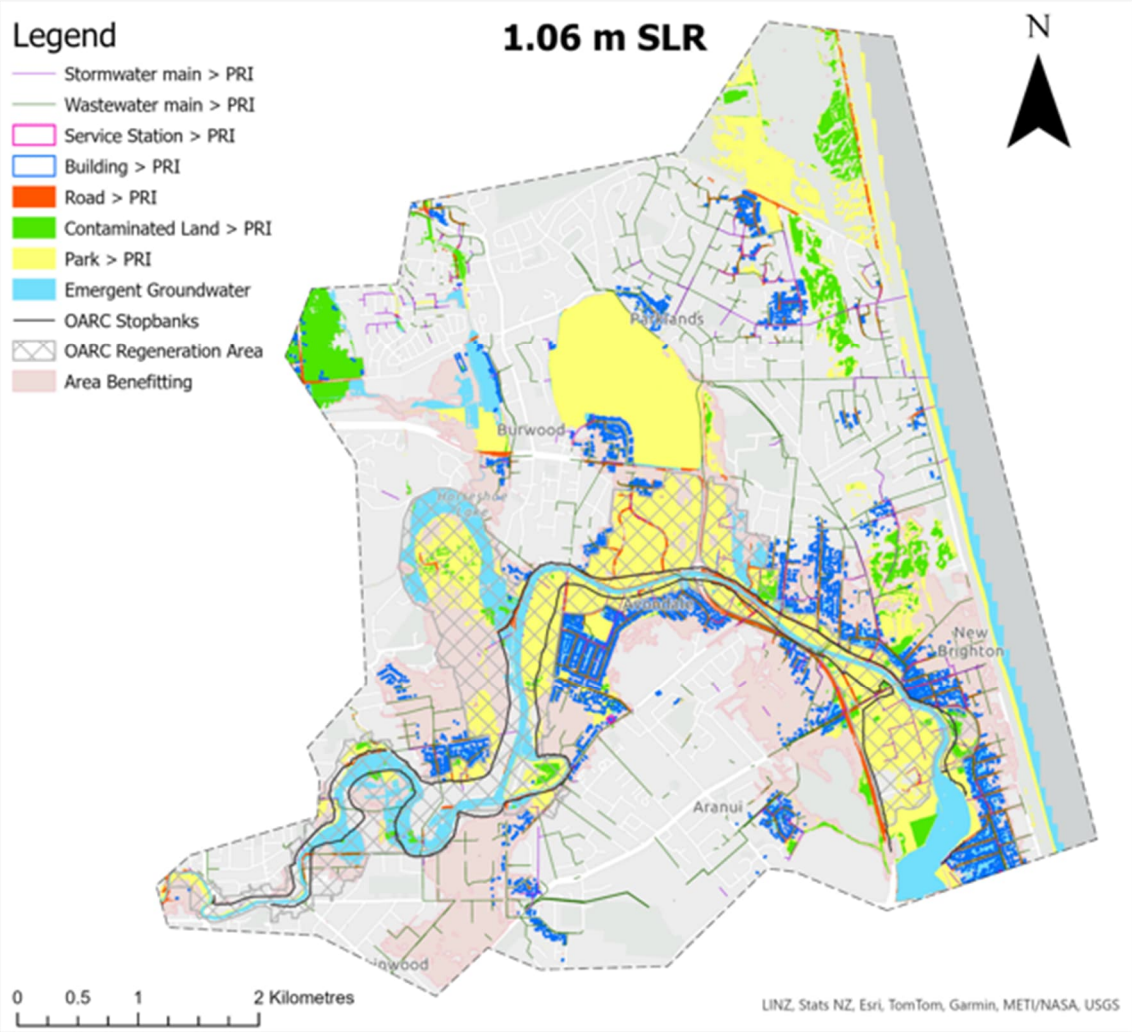
1.06 m SLR [2100] with earthquake settlement

Scenario: 10+ Scheme

- The addition of earthquake settlement in 2100 to 1.06m SLR only slightly increases the exceedance of PRIs for most asset types or landuses.
- An area that does appear to change more is the increase occurrences of exceedance of building PRIs in North New Brighton Between New Brighton Road and Keyes Road.
- An increase in occurrence of building PRIs is also evident in Burwood by Travis Wetland.

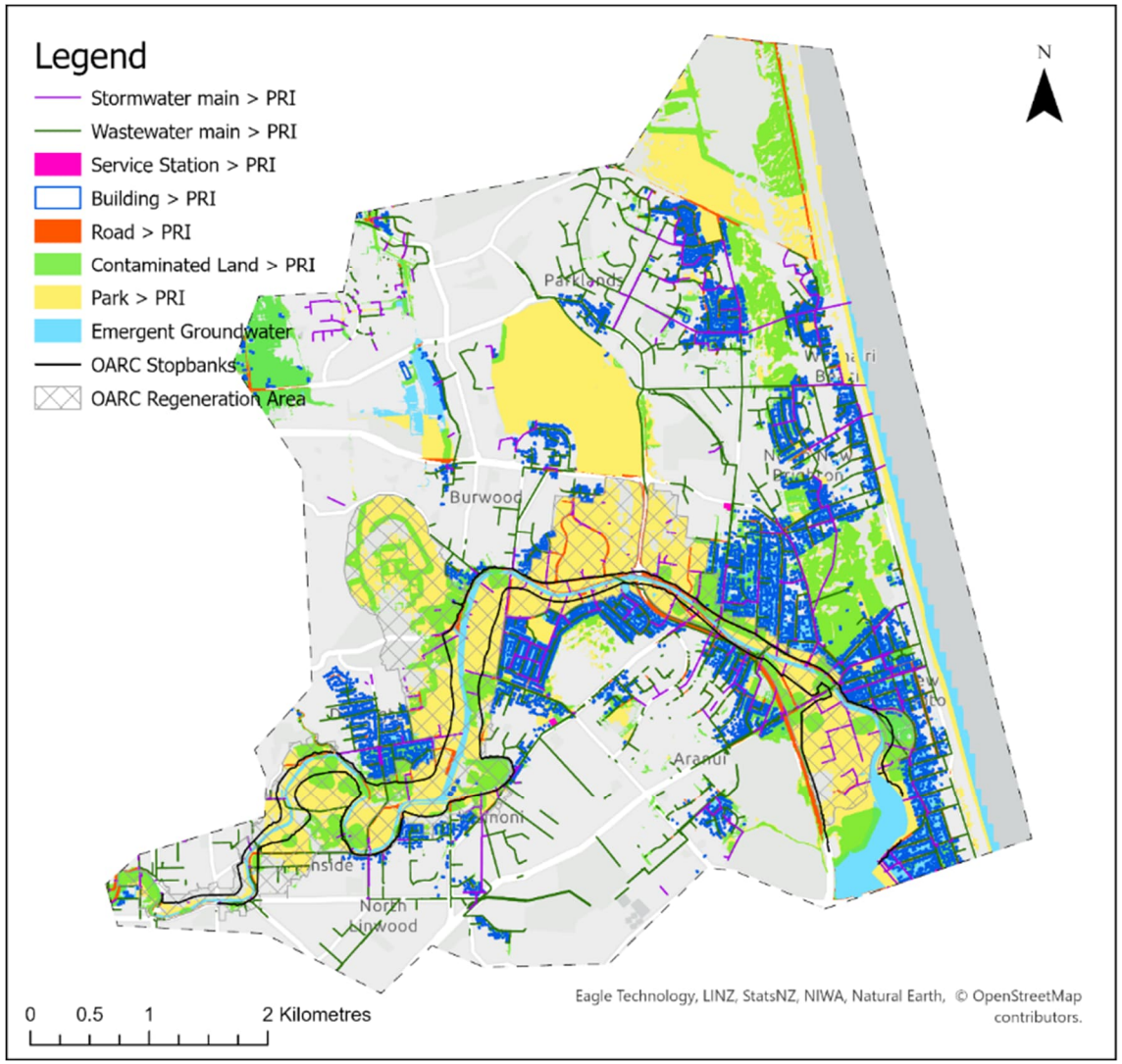


- VLM under a S1 scenario makes a small change to PRI exceedances only.
- The main change observed is on building PRI's with a scattering of new exceedances across the area.



Groundwater – all PRI's

1.06m SLR (~2100) with S2 VLM

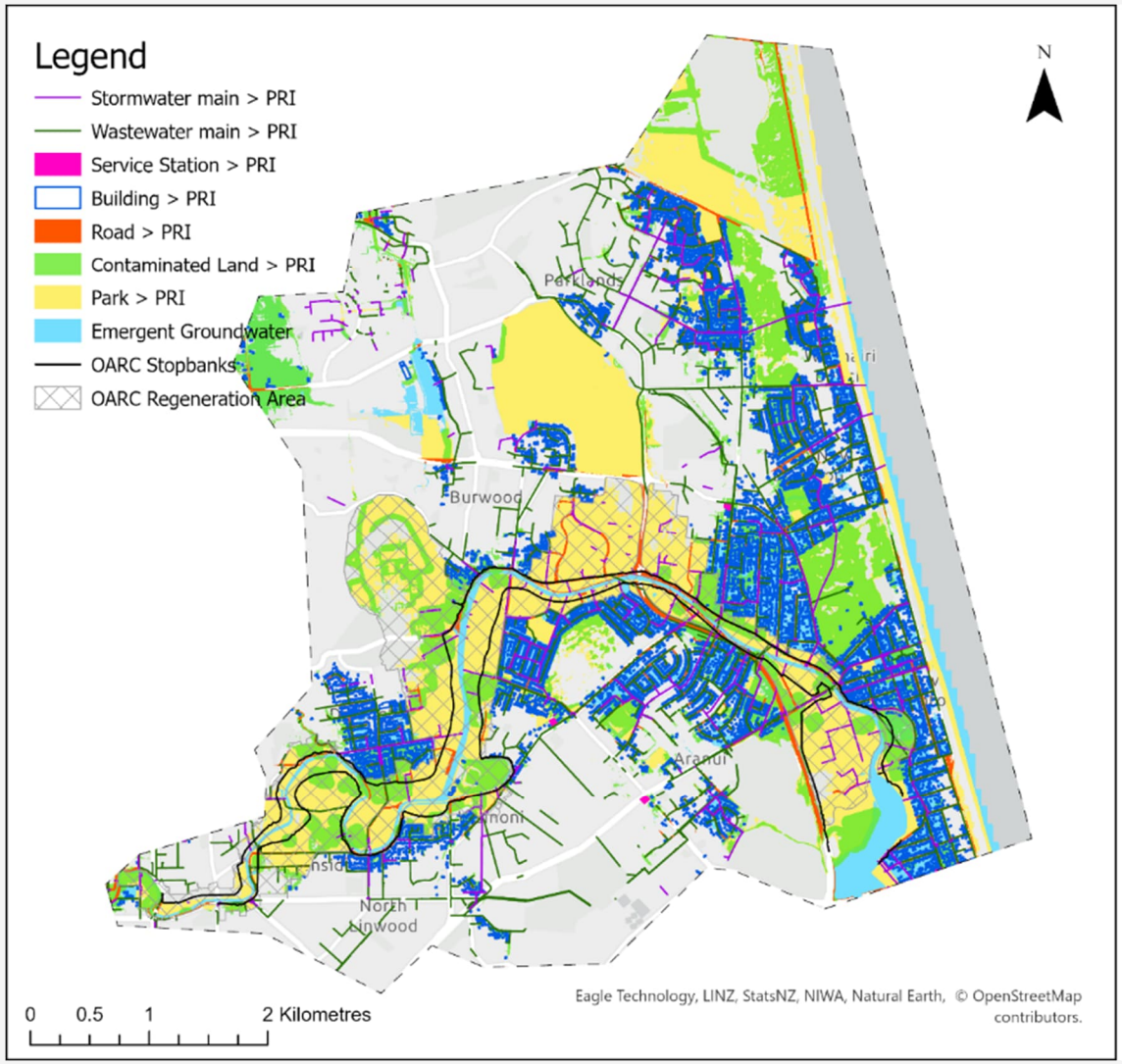


Groundwater - All PRIs

1.88 m SLR [2150]

Scenario: 12+ Scheme

- By 2150 with 1.88 m SLR the pattern of exceedances changes significantly.
- Emergent groundwater is observed through many areas closer to the OARC Flood defences in South New Brighton, North New Brighton, Dallington and Avondale. It is also predicted in areas in Parklands and Waimairi.
- Many more exceedances of building PRIs are also observed within these areas.
- Much longer lengths of SH74 exceed the PRIs in Aranui area but still few other roads outside the OARC regeneration area.
- Many contaminated land sites through New Brighton, North New Brighton and Waimairi exceed the PRIs.



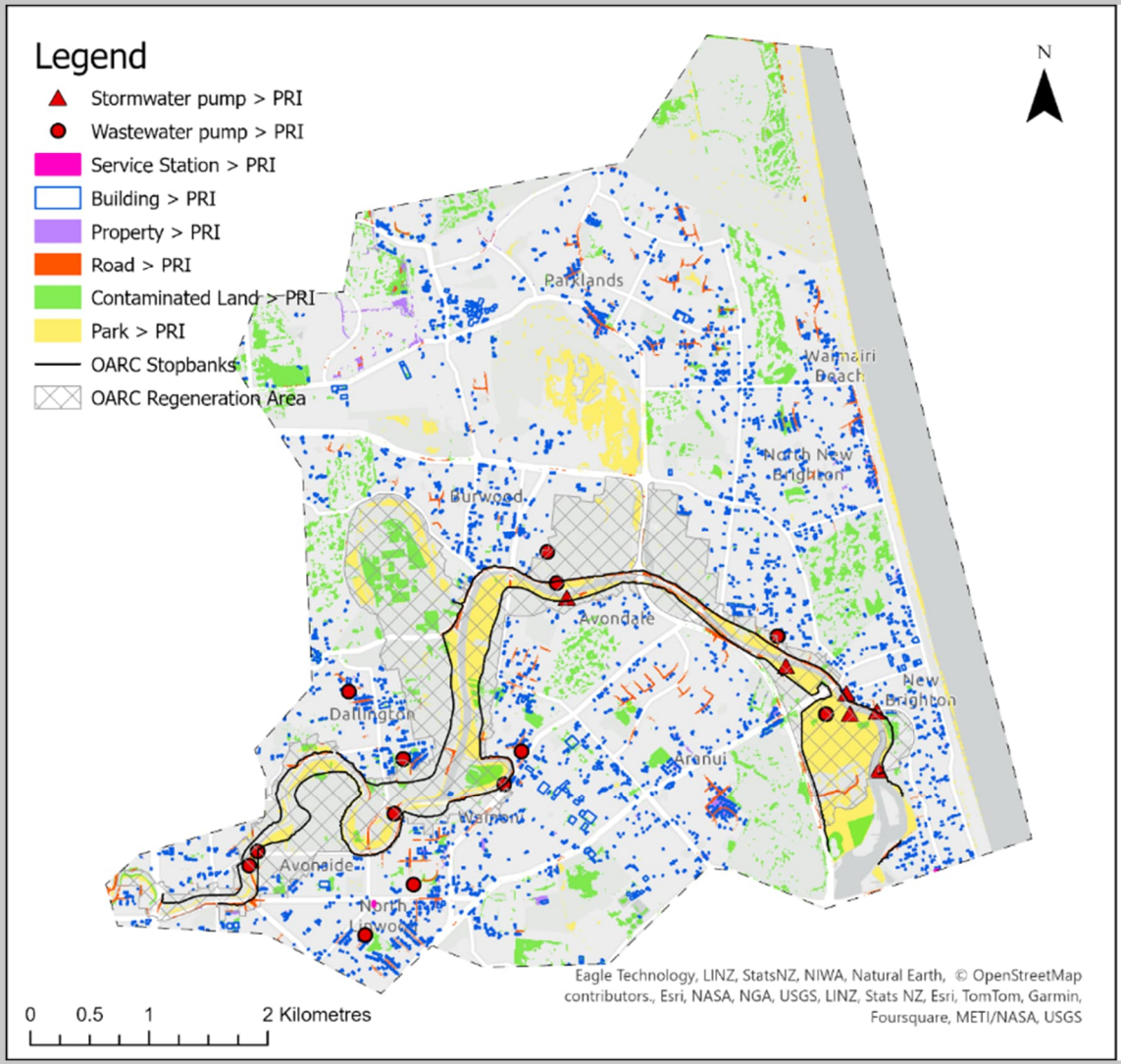
Groundwater - All PRIs

2.4 m SLR [> 2150]

Scenario: 13+ Scheme

- With 2.4 m SLR there is an increase in exceedances of building PRIs within most suburbs previously affected. Exceedances are especially seen in the coastal suburbs of South New Brighton, North New Brighton, Waimairi and Parklands as well as Dallington, Avonside and Aranui. A noticeable increase can be seen further from the Avon River in Aranui.
- Exceedance of pipe infrastructure PRIs also generally expand out wards from areas previously exceeding PRIs. Large areas of wastewater mains exceed PRIs and increasing amounts of stormwater mains across many suburbs.
- Emergent groundwater is much more prevalent across these same suburbs.
- SH74 is still the main roading asset identified as being impacted but there are a number of others through the area.

Appendix L. Flood hazard PRI mapping

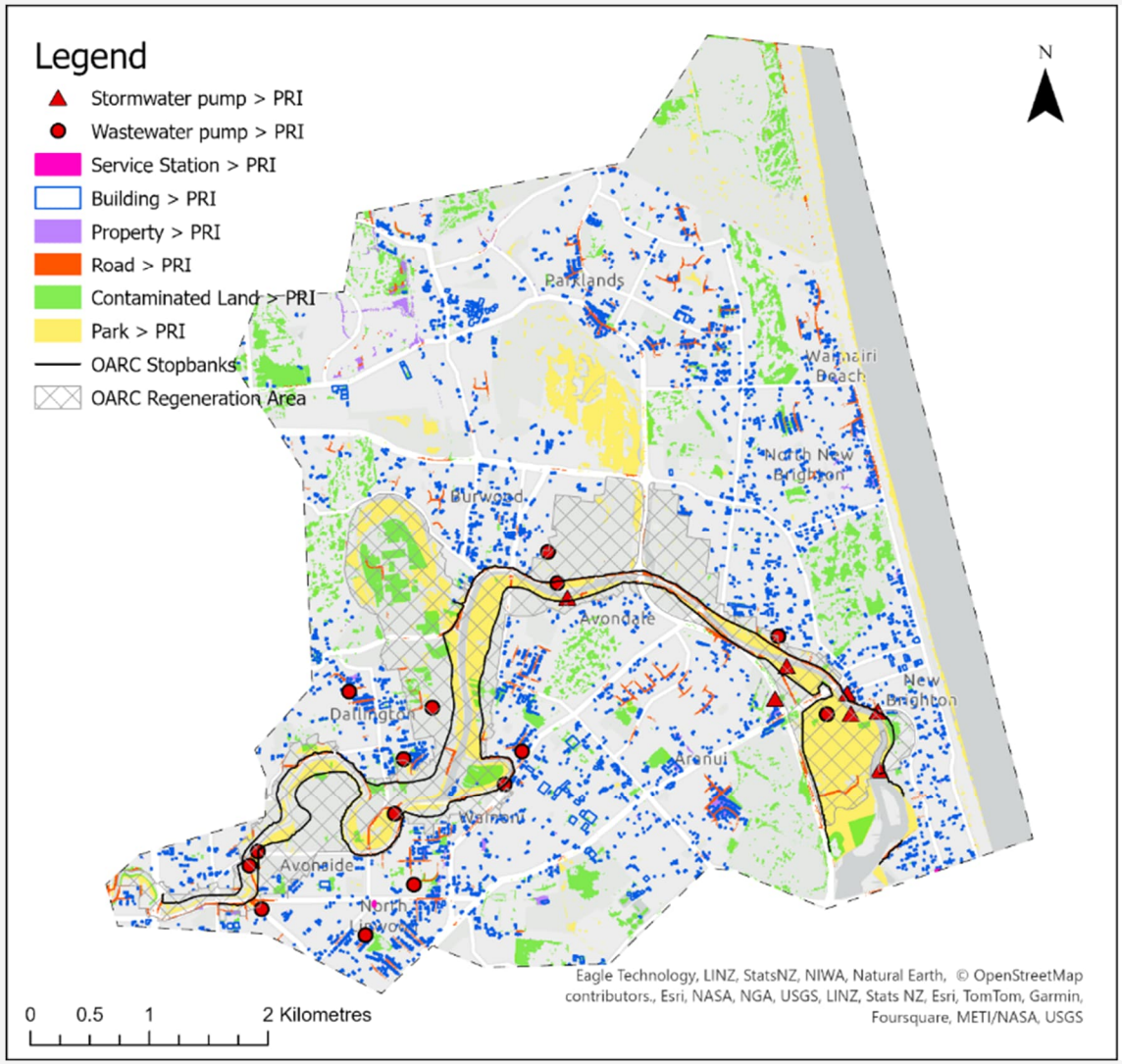


Surface Water - All PRIs

0.19 m SLR [2030]

Scenario: 4+ Scheme

- Exceedance of individual PRIs in scattered patches across most of the study. Few multiple overlapping exceedances.
- Pockets of flooding greater than road PRI in suburbs around the OARC Scheme - Aranui, the west of Avondale, Wainoni, North Linwood, Dallington and Burwood and in Parklands, Waimairi Beach and North New Brighton away from the OARC Scheme.
- Wastewater pump stations exceeding PRI and a few stormwater pump stations, all in proximity to the river.
- Fairly even spread of buildings exceeding PRI across all suburbs rather than dense clusters, reflecting widespread areas of shallow flooding where available data indicates floor levels close to ground level.
- A few isolated patches of property PRI exceedance (people's safety) reflecting deeper flooding in Aranui and North New Brighton.
- Parks PRI exceedances generally within the OARC Regeneration area, especially within the proposed OARC flood defences. This is expected as this area is intended to flood. Travis Wetland and Clare Park exceed PRIs.
- Contaminated land PRIs are exceeded in patches across much of the area reflecting ponding on identified HAIL sites.

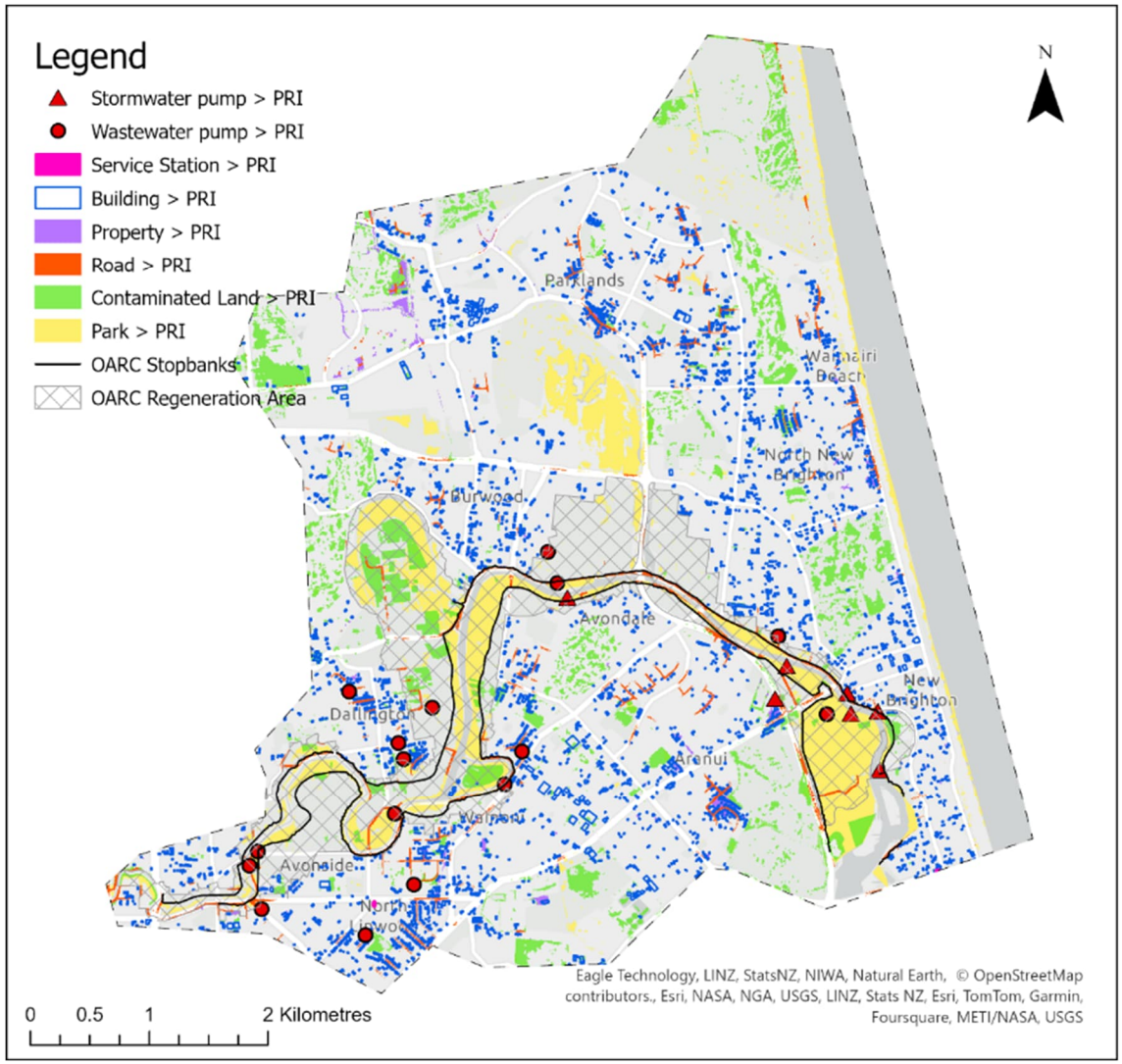


Surface Water - All PRIs

0.45 m SLR [2060]

Scenario: 6+ Scheme

- For 0.45 m SLR a generally similar overall pattern to 0.19 m SLR exists but exceedances of PRIs are more widespread.
- Some clustering of PRI exceedances for more than one asset types, such as roads and buildings in Avondale, North Linwood, Dallington, Parklands and New Brighton.
- Exceedance of the safety related (buildings) PRI and roads PRIs in Aranui and North New Brighton.
- More buildings exceed PRIs, still distributed widely across all suburbs. Clusters in the east of Wainoni, Central New Brighton and Burwood Hospital in Parklands.

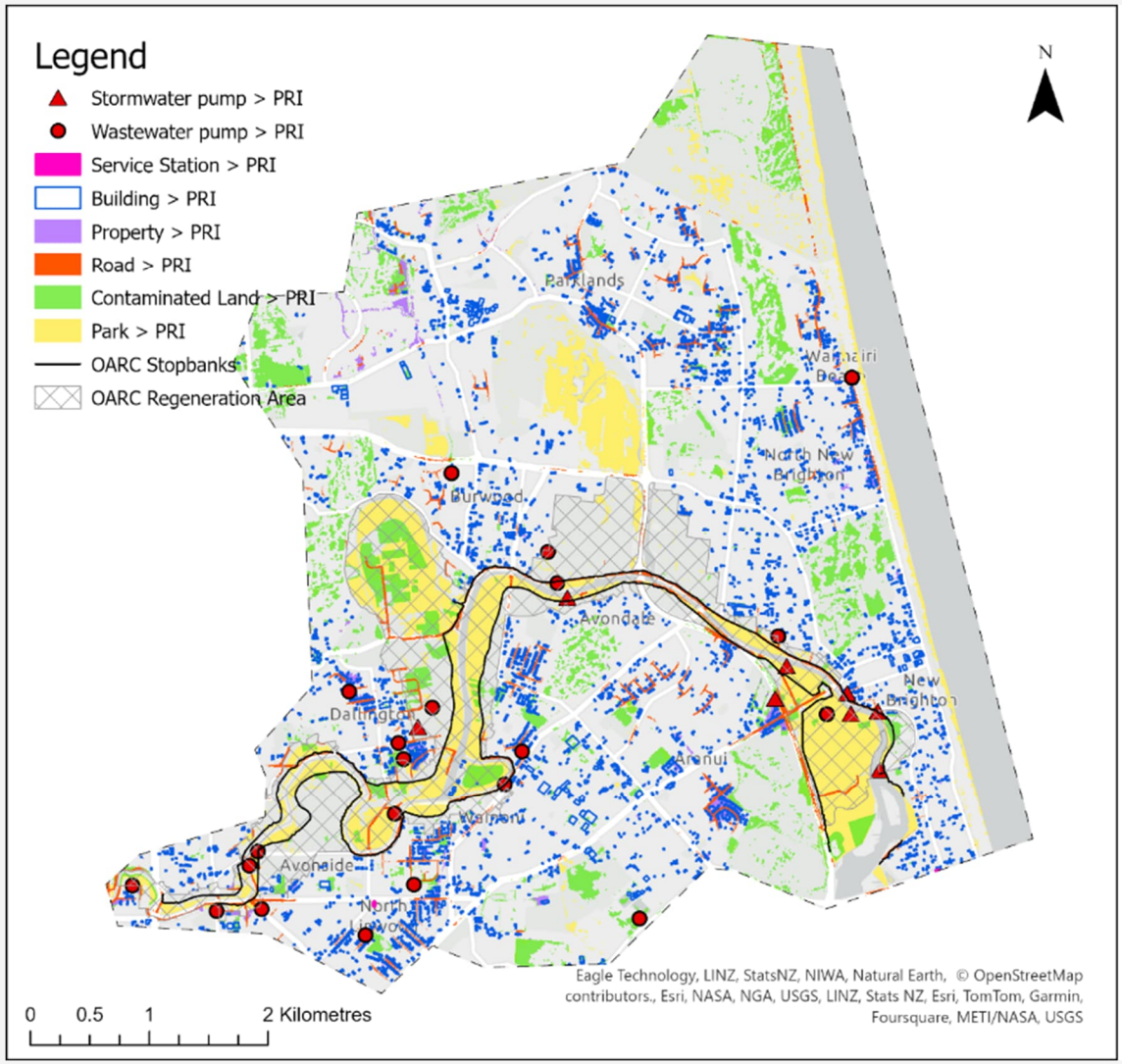


Surface Water - All PRIs

0.45 m SLR [2060] with earthquake settlement

Scenario: 8+ Scheme

- Inclusion of earthquake settlement on the 0.45 SLR (2060) scenario does not significantly alter the pattern of exceedances.
- Exceedances of PRIs for roads are still mainly in Aranui, Avondale, Wainoni, North Linwood and Dallington around the Avon River and North New Brighton, Waimairi Beach and Parklands to the north.

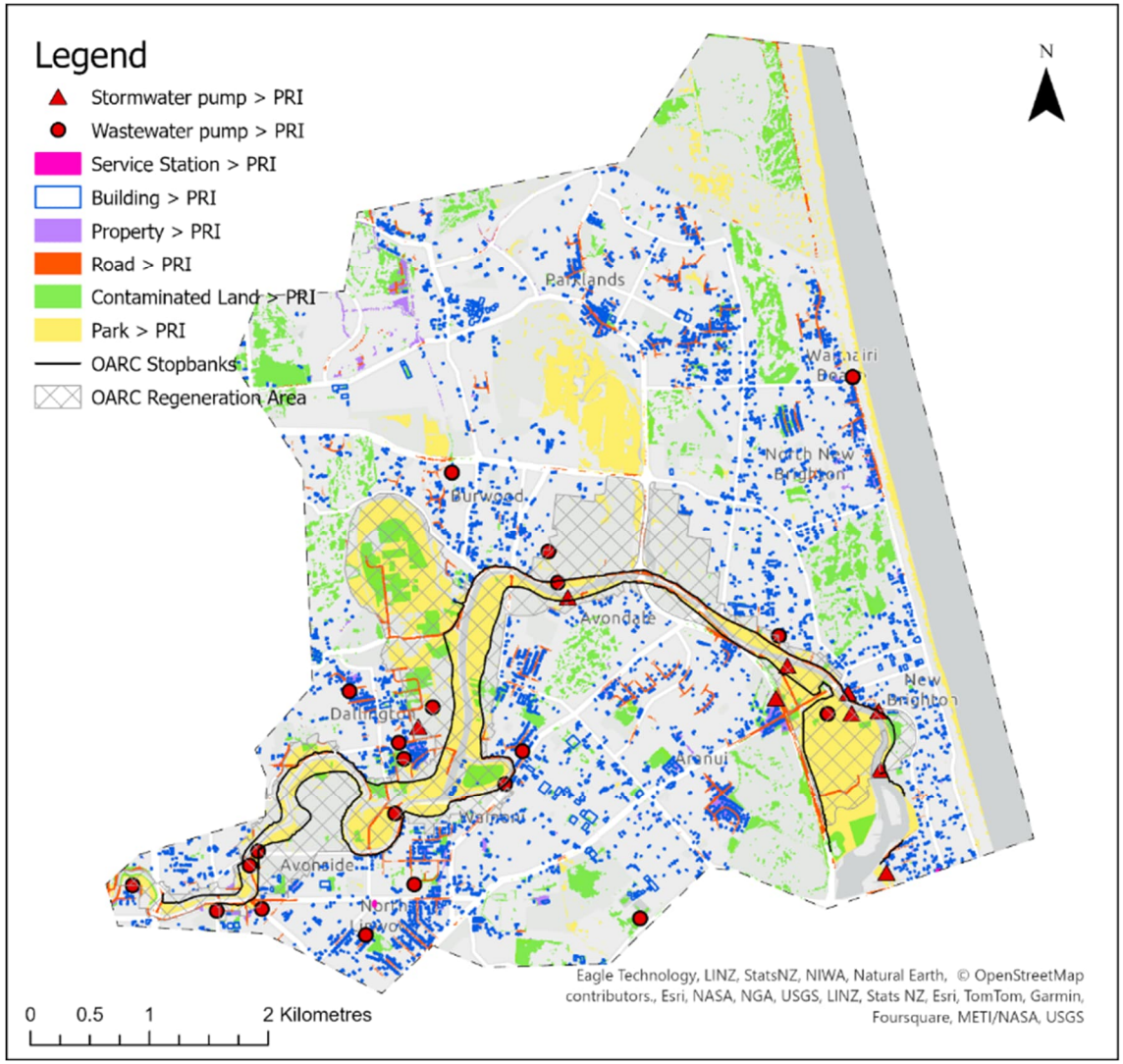


Surface Water - All PRIs

1.06 m SLR [2100]

Scenario: 9+ Scheme

- For 1.06 m SLR areas of PRI exceedances expand.
- Additional wastewater pump stations located away from the river exceed PRIs.
- Increasing numbers of building PRI exceedances but these are still spread widely across the project area rather than in dense clusters.
- New areas of property (peoples safety) flooding exceeding PRIs are identified. These include in Aranui by Pages Road, in North Linwood and Wainoni and in Dallington.
- Some longer lengths of road are exceeding PRIs including SH74 in Aranui. Clusters of roading exceedances continue in North Linwood, Wainoni, Avondale, Aranui, Dallington, Burwood, Parklands, Waimairi Beach and North New Brighton.



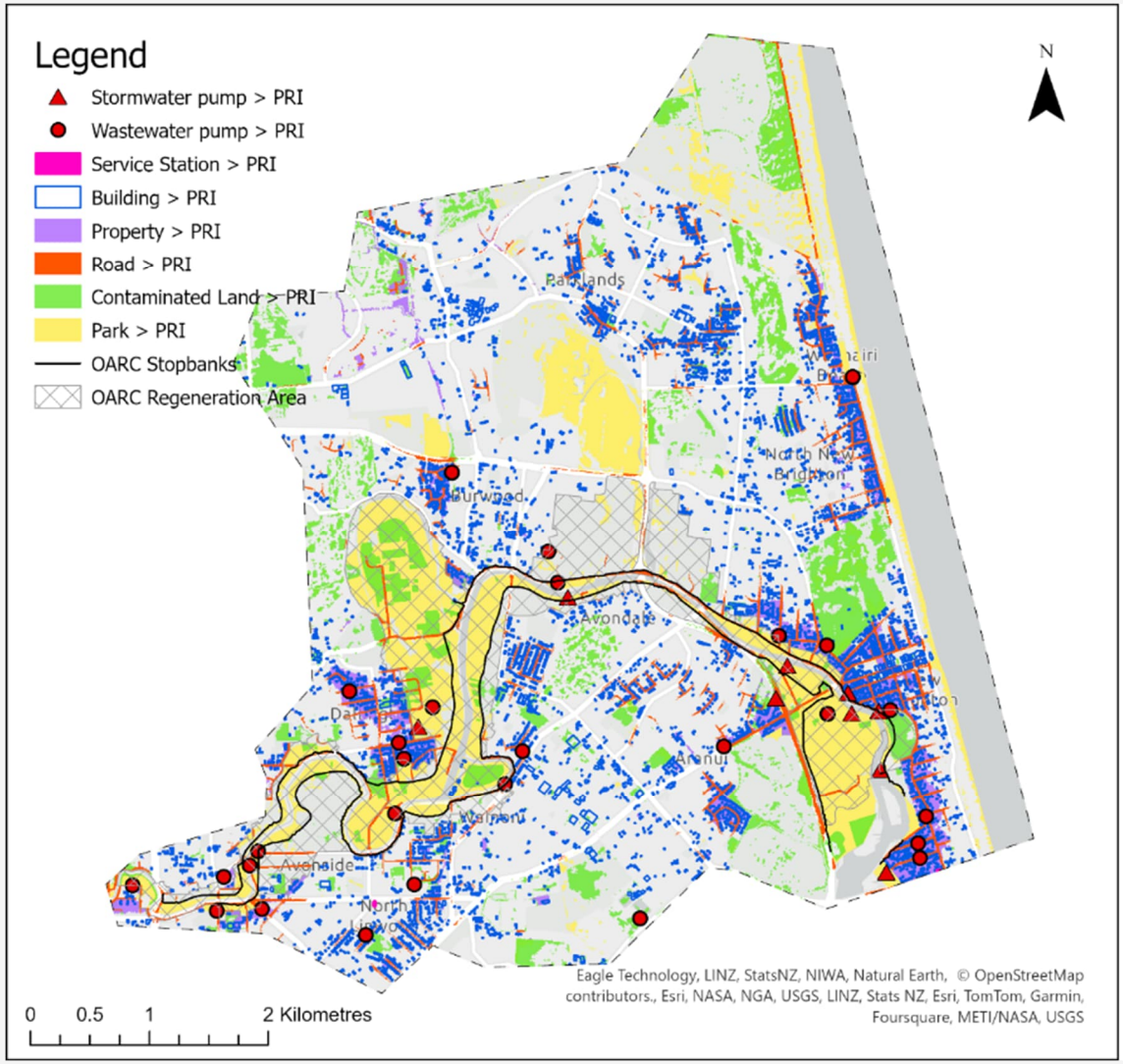
Surface Water - All PRIs

1.06 m SLR [2100] with earthquake settlement

Scenario: 10+ Scheme

The addition of earthquake settlement to the 1.06m SLR scenario does not make large scale changes to the pattern of PRI exceedances.

Distribution of buildings exceeding PRIs changes somewhat – some buildings come in and others go out – due to redistribution of flood water with uneven settlement of ground.

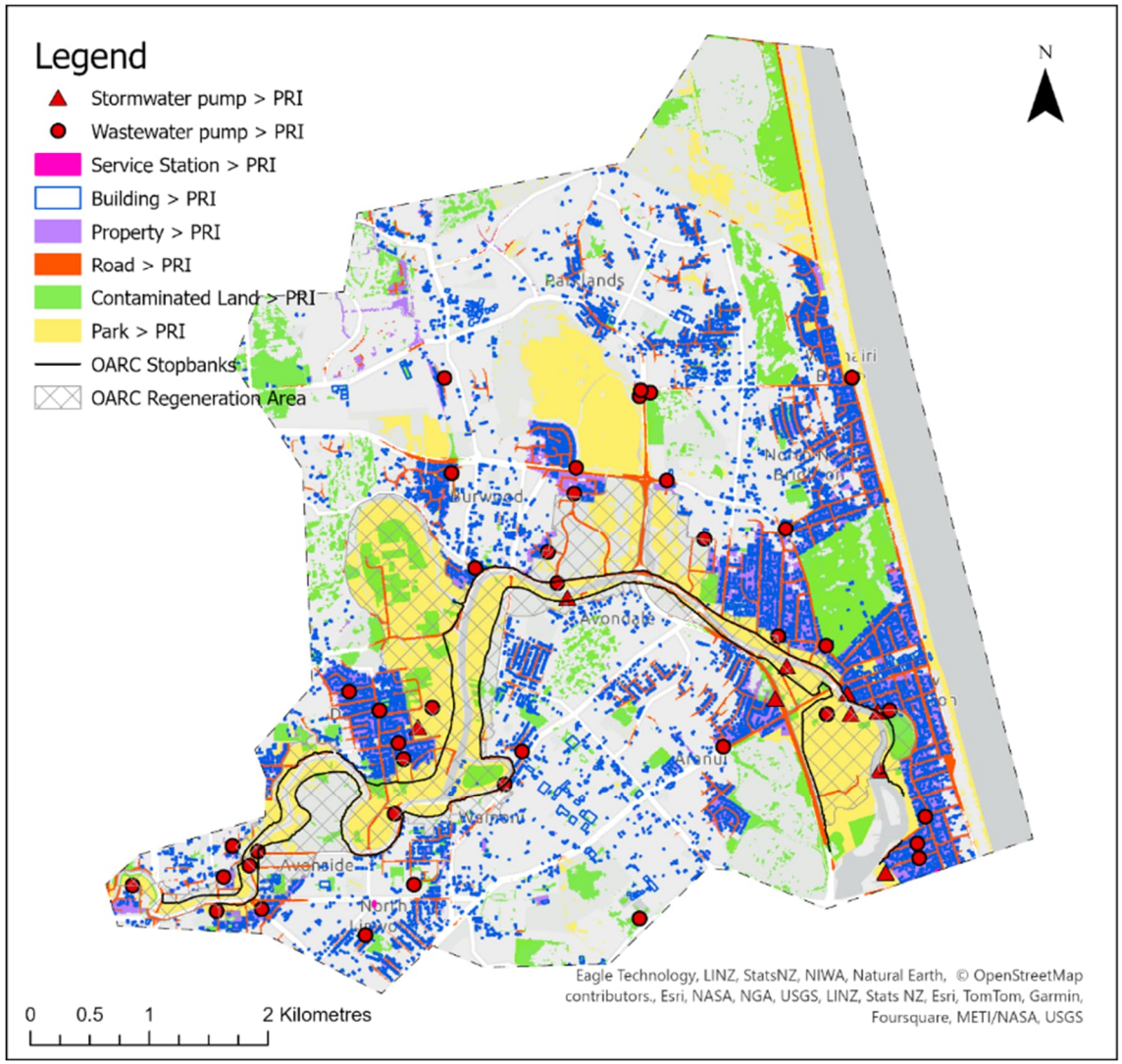


Surface Water - All PRIs

1.88 m SLR [2150]

Scenario: 12+ Scheme

- With 1.88 m SLR there is a large increase in exceedance of the property (peoples safety) PRI. A large expanse of areas in South New Brighton and New Brighton to the east of the proposed OARC flood defences is evident due to direct inundation from the sea into the area protected by the OARC Scheme. Other notable changed areas are Dallington, Burwood, North New Brighton and Waimairi Beach.
- Large increase in exceedance of road PRIs are also evident in the same suburbs as the property exceedances.
- Buildings exceeding PRIs continue to be scattered across the whole area with many being in the same suburbs as the road and property PRI exceedances and more clustering in the coastal areas.
- Overlapping of multiple PRI exceedances in South New Brighton, New Brighton, Aranui, Dallington, Burwood, North New Brighton and Waimairi Beach.
- Increased areas of contaminated land PRI exceedances are evident across the whole area.



Surface Water - All PRIs

2.4 m SLR [> 2150]

Scenario: 13+ Scheme

- With 2.4 m SLR there is another significant expansion of the areas exceeding PRIs from the 1.88 m scenario. There are many suburbs with considerable amounts of multiple PRI exceedances in any one location.
- Notable suburbs exceeding PRIs for roads, buildings, and property (peoples safety) in proximity to the Avon River and proposed OARC Scheme are Dallington, Burwood, New Brighton, South New Brighton and Aranui.
- A number of additional pump stations exceed PRIs in the areas to the north of the Avon River.
- Many more buildings now exceed PRIs, these are frequently in the suburbs which also exceed road and property PRIs.