Avon-Heathcote Tidal Barrier Pre-Feasibility Study

Contract Number: 14/15 – 185

Prepared for: Christchurch City Council

Date: July 2015

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Background

Tides have a significant effect on available capacity within Christchurch's rivers to carry flood flows. A tidal barrier works by artificially holding back the advancing tide, which permits the rivers to drain more freely into the estuary. A barrier can also be used to hold back exceptionally high tides, such as spring tides or storm surges, to protect low lying land adjacent to the estuary and river mouths.

The concept of a barrier in the Avon-Heathcote Estuary is not new, with available reports dating back over 50 years. At this stage Council is seeking to understand whether a tidal barrier is worthy of further consideration as a possible flood mitigation measure for Christchurch. A tidal barrier is being considered as part of a wider river and tidal flood management strategy which may include a mix of engineering and policy responses.

The purpose of this pre-feasibility study is to identify, as early as possible within the investigation, whether there are any factors significant enough to deem the barrier option to be clearly unfeasible or grossly unfavourable, when compared to the other possible flood mitigation measures. Where a tidal barrier is not deemed infeasible this report is to put forth a scope of work for subsequent investigations to allow the consent and construction of a barrier.

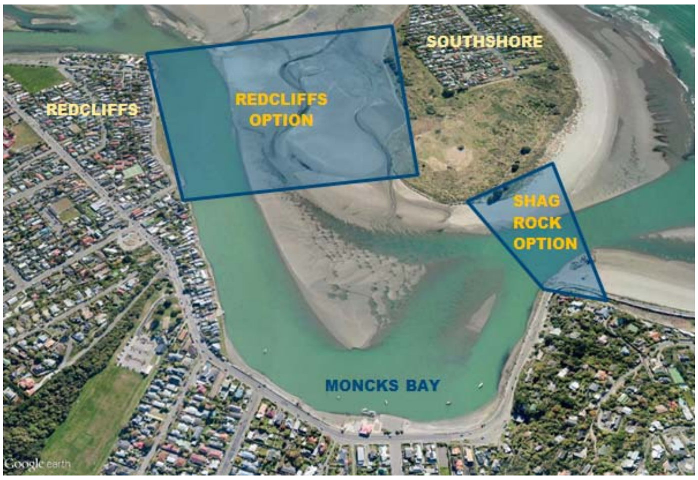
Barrier Requirements

There are a number of factors to consider when establishing the requirements for a tidal barrier, within the estuary. These include:

- **Tidal, storm surge and river discharge range**: These were established to set operating conditions considering available estuary and river storage volumes.
- **Sea level rise**: To be consistent with other studies undertaken within Christchurch, the potential effects of a 1 m sea level rise was considered. Opportunities were also considered to expand the structure for sea level rise in excess of 1 m.
- **Navigation requirements**: Consideration was given to current recreational use of the estuary.
- **Geotechnical considerations**: There are a range of ground conditions to account for. At the estuary mouth there is rock on one side and sands on the other, while within the estuary there are liquefiable sediments.
- **Spit and mouth morphology**: The Brighton Spit is formed from sand, chiefly sourced from the Waimakariri River. The spit tip is particularly dynamic, with past recorded changes in both size and shape. Just inside the estuary mouth the channel is far more stable, but the bed is constantly changing, so any structure will need to accommodate a flow of bedload sediment.
- **Ecological constraints**: The value of the estuary cannot be over stated. It is biologically diverse and the majority of the inhabitants can be vulnerable to changes in either salinity or tidal regimes.
- **Social and consenting constraints**: There are a number of relevant planning documents that address issues related to the values, hazards and amenity associated with the estuary. Barrier options are also likely to evoke significant public interest.

Barrier Pre-Feasibility Concept

Options considered for the location of the barrier included one across the mouth of the estuary, adjacent to Shag Rock, and one that crossed from Redcliffs to Southshore. The Redcliffs option was selected, for the purpose of this assessment, because the spit is more stable in this location and the barrier would be less exposed to coastal conditions.



In this location, around 95% of flow passes through a deeper channel adjacent to the Redcliffs side. A barrier in this location would therefore comprise of a gated structure within the channel portion and an embankment for the remainder of the distance across to Southshore.

A range of gate options were considered. Of the three types that are likely to be feasible, a vertical lifting gate was selected for the purpose of further assessment, within this pre-feasibility stage. As the name suggests, this type of barrier works by having gates that can be vertically lowered to close the channel. Construction of this structure should be within the capabilities of the existing construction industry within New Zealand.

The gate structure's main component parts would include:

- A concrete sill founded in the channel floor;
- Three bays approximately 50 m wide, each with a 6 m high, gate lifted clear of the water when the barrier is open;
- One gate could potentially be lifted 2 m clear to allow passage of kayaks and other small craft;
- Four 9 m high piers holding the gates, one at each side and two at 50 m intervals across the channel;
- A walkway attached to the piers to allow maintenance access and potentially a public pedestrian/cycle link.

A range of embankment options were also considered. A dune option was selected for the purpose of further assessment. It would be approximately 430 m long and up to 200 m wide. In time as vegetation establishes and material migrates naturally the dune will resemble an extension of the existing spit. The crest height would be a minimum of 3.4 m high, with some higher undulations to promote a natural look. The walkway from the gate structure could be extended across the dune to complete the link between Southshore and Redcliffs.

The abutment at the Redcliffs side would be an augmentation of the existing flood defences at Redcliffs and connect the gate structure at a 2.9 m contour level.

The estimated construction cost of the pre-feasibility concept (including barrier gates a dune embankment and flood defences for a 1km stretch along Redcliff) is approximately NZ$310M.

Operation and maintenance cost estimates are 1-5% of the capital cost per annum for the gate structure ($1.5M to $7.0M per annum) and 1% of the capital cost per annum for the embankment ($0.25M per annum).

Barrier Operation

Considering the current flood risks, the barrier may only need to be operated around twice per year. This would involve closing the barrier near low tide, in anticipation of a storm event, and opening it again on the ebb tide to permit the estuary to drain.

In the future, climate change is predicted to increase the frequency of flood flows within the rivers and increase sea levels. In response to these changes the frequency of the barrier operation is likely to increase. For example, the number of times that tides are expected to exceed a level of 1.56 m will increase from a current occurrence of around once per year up to 705 per year, following an assumed 1 m of sea level rise.

The barrier will have a local effect on morphology but, given that the structure presents little obstruction to flow or sediment when it is open, modelling predicts these effects will be small. Infrequent closures are also unlikely to have significant effect. However, frequent barrier operation, as potentially required under a climate change scenario, could trigger a change in the morphology of the spit tip or Sumner Bar. This potentially could impact on Sumner or Scarborough beaches, or on properties vulnerable to coastal erosion near the spit tip.

The ecological impact of infrequent barrier operation is low, as most estuarine organisms and communities can tolerate exposure to freshwater providing near natural low tides are allowed to occur. In a future climate change scenario, more frequent operation of the barrier could be tolerated, provided that it continued to mimic normal tidal patterns. The ecosystem could not cope if the operation of the barrier resulted in holding the estuary in any form of artificial state, for a prolonged period.

If Council proceeds with the barrier option, the further investigations required to support any consent application may effectively establish an upper limit on the frequency and duration of barrier operation, to minimise changes in morphology and to protect the estuary's ecological values. Therefore, while a barrier could postpone and reduce the need to implement other flood control measures, in response to future climate change, it is unlikely to entirely eliminate the need for other measures.

Barrier Assessment

The pre-feasibility barrier concept is buildable and resilient to anticipated environmental factors. While the temporary works during construction have the potential to cause a significant disturbance to the position of the main tidal channel, these effects could be managed.

The effectiveness of the barrier for flood mitigation was assessed by simulating estuary water level reductions and consequent river flooding reductions for a 100yr fluvial/tidal flood. These model results have been analysed to assess the effect of a tidal barrier on the required extent of other flood mitigation measures under present day and 1 m sea level rise scenarios.

The cost comparison shows that for the present day climate scenario the cost of a tidal barrier far outweighs the expected cost reduction for other defence measures. However in the 1 m sea level rise scenario the cost for flood defence with the barrier is comparable with the cost of flood defence without a barrier. This high level analysis was able to conclude only that a tidal barrier may form a cost effective part of a future flood defence strategy. Further work would be required to determine how far into the future investment in a tidal barrier would be most appropriate.

Effects on landscape and visual amenity will be unavoidable and significant in magnitude. A barrier is likely to receive mixed reactions within the community with those adversely affected by the visual impact being different from the communities likely to benefit from the structure. Some of these effects could be mitigated, to a certain extent, through sensitive barrier design.

Cultural value impacts will arise as the estuary location is recognised as being of significant value to local iwi. Effects on archaeological values are likely, as there is a high concentration of archaeological sites within the general area.

There will also be an effect on recreational boating within the estuary, some of which could be mitigated to a certain extent through sensitive barrier design. There is an opportunity for positive recreation effects, particularly improved access for walking and cycling, through enabling access over the barrier – but in turn, this has the potential to generate social impacts through connecting Redcliffs with Southshore.

Conclusions

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, it 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. What remains unclear from this study is whether a tidal barrier is a favourable option when considered as part the larger mix of options.

As such, future feasibility stages would need to consider the benefits, impacts and costs of a barrier in comparison/conjunction with the other available flood management options. As barrier impacts increase with operating frequency, consideration will also need to be given to operating procedures and the associated benefits and impacts. This element of a broader flood management strategy would benefit from community and stakeholder engagement, to gain feedback on the flood management options available.

1. Introduction

In recent years Christchurch City Council (Council) has commissioned a number of reports into river and tidal flood protection needs for the city. These reports consistently conclude that there is a high level of flood risk faced by the residents of Christchurch, and that this level of risk is going to increase substantially as climate change effects sea level and the intensity of storm events.

In order to plan for mitigation of present and future flood risk Council is seeking to understand the full range of options available. A tidal barrier in the Avon-Heathcote Estuary is one mitigation measure that was identified for potential inclusion in a holistic flood protection strategy, which is likely to include a mix of planning and infrastructure responses.

At this stage Council is seeking to understand whether a tidal barrier is worthy of further consideration as a flood mitigation measure for Christchurch. This pre-feasibility study is aimed at determining whether Council would be justified in conducting a full feasibility assessment of the tidal barrier option.

1.1 Scope

The scope of work put forward by Council and used as the basis for this pre-feasibility study is focussed on answering a number of questions:

A. What form would a barrier take?

B. Where would a barrier be best located?

C. Will a barrier work?

D. What are the benefits of a barrier?

E. What are the potential costs for construction and whole of life for a barrier?

F. When will a barrier be required and how long will it last in the face of sea level rise (durability and flood risk)?

G. What impacts will a barrier have?

H. What are the risks associated with construction and operation of barrier?

I. What other investigations are required to consent and construct a barrier?

1.2 Approach

In order to answer questions A and B, which relate to the form and location of the barrier, it was first necessary to generate a pre-feasibility concept for the barrier. Sections 2 to 7 of this report describe how this task was completed, including background investigations, determination of requirements, assessment of locations and comparison of barrier types.

Section 8 then provides a description of the chosen pre-feasibility concept. This section provides the principal information to be taken into account in the subsequent pre-feasibility assessment. Through this process the question of potential costs (Question E) are addressed.

Questions C, D, F, G and H are all covered in the pre-feasibility assessment, within Sections 9, 10 and 11 of this report. This assessment was broken into three sections:

1. Effectiveness – i.e. will the barrier work to reduce flood risk?
2. Resilience – i.e. will the barrier survive the local conditions and remain effective?
3. Impacts – i.e. will the impacts of building the barrier be acceptable?

Section 12 addresses Question I, discussing the future phases of work required to implement a tidal barrier.

Section 11 of this report effectively summarises our answers to all the questions outlined within the scope of this project.

1.3 Limitations

This Report was prepared by GHD for Christchurch City Council and may only be used and relied on by Christchurch City Council for the purpose agreed between GHD and Christchurch City Council as set out in Section 1.1 of this Report.

GHD otherwise disclaims responsibility to any person other than Christchurch City Council arising in connection with this Report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this Report were limited to those specifically detailed in the Report and are subject to the scope limitations set out in the Report.

The opinions, conclusions and any recommendations in this Report are based on assumptions made by GHD described in this Report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared the preliminary barrier cost estimate set out in Section 8.3 and 8.4 of this Report and comparative stopbank, stormwater infrastructure and house raising cost estimates in Section 9 of this Report ("Cost Estimates") using the information described in the same sections, which include assumptions related to foreign exchange rates and construction cost indices. The Cost Estimates have been prepared for the purpose of comparison with other potential mitigation options and must not be used for any other purpose.

1.4 Datums

Frequent reference is made throughout this report to the vertical level of a variety of items, such as sea levels, flood levels, the height of the conceptual barrier, and the existing height of stopbanks.

Throughout NZ there are numerous vertical datums used (a vertical datum is a coordinate system for defining and comparing heights), including at least four which are commonly used in Christchurch.

For the sake of consistency all vertical levels in this report are in the Lyttelton Vertical Datum 1937 (abbreviated as LVD). The current mean sea level is 0.13 m above the zero point on this datum, reflecting sea level changes since the datum was set at mean sea level in 1937. A conversion table between LVD and other common datums is provided below (Table 1).

Table 1 Datum comparison

Datum	Level (m)
Lyttelton Vertical Datum (LVD)	0
Mean Sea Level 2015	0.13
New Zealand Vertical Datum 2009 (NZVD2009)	-0.47
Christchurch Drainage Datum (CDD)	9.043
Lyttelton Port Chart Datum	1.25

2. Background

2.1 General principle

A barrier is an artificial structure across a river or estuary mouth. Generally such structures include a gated opening which can be open and closed according to a set of operating rules. The intent of such structures is typically to reduce the frequency and severity of river and/or tidal flooding. An example of a minor barrier structure in Christchurch can be found at the mouth of the Styx River in Brooklands, where tide gates prevent the ingress of high tides.

The intent of a barrier structure in the Avon-Heathcote Estuary would be twofold. Primarily, it could be closed in advance of predicted high sea level conditions, such as spring tides and storm surge, in order to protect low lying land adjacent to the estuary and river mouths. In addition, it could be closed in anticipation of flood conditions in the Avon and Heathcote Rivers to maintain lower river outfall levels and reduce the severity of river flooding. Other possible uses could be to reduce impact of a tsunami, or to prevent pollutants from entering the estuary in the case of a spillage at sea. The general barrier operating procedure in the case of river flooding would be as follows:

- Barrier gates would be closed at low tide preceding the predicted storm,
- Water level at the sea side of the barrier would rise with the tide and storm surge,
- Water level behind the barrier (in the estuary and on the rivers) would slowly rise due to river inflow,
- When level at sea drops below the level in the estuary, the barrier gates would be opened to release water stored in the estuary, and closed again at low tide,
- This would be repeated for 2-3 tidal cycles, until the storm has ended.

Figure 1 below demonstrates the reduction in estuary water levels theoretically achievable under certain tidal and river flood conditions.

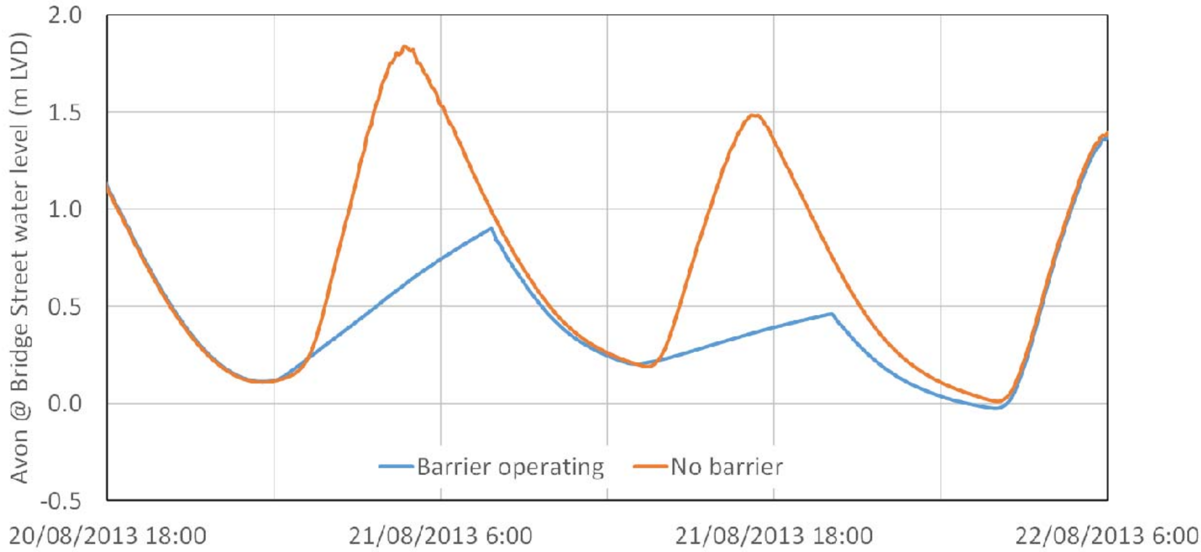


Figure 1 - Indicative reduction in water level at Bridge Street

Figure 2 demonstrates how a reduced estuary level could result in reduced river flood levels.

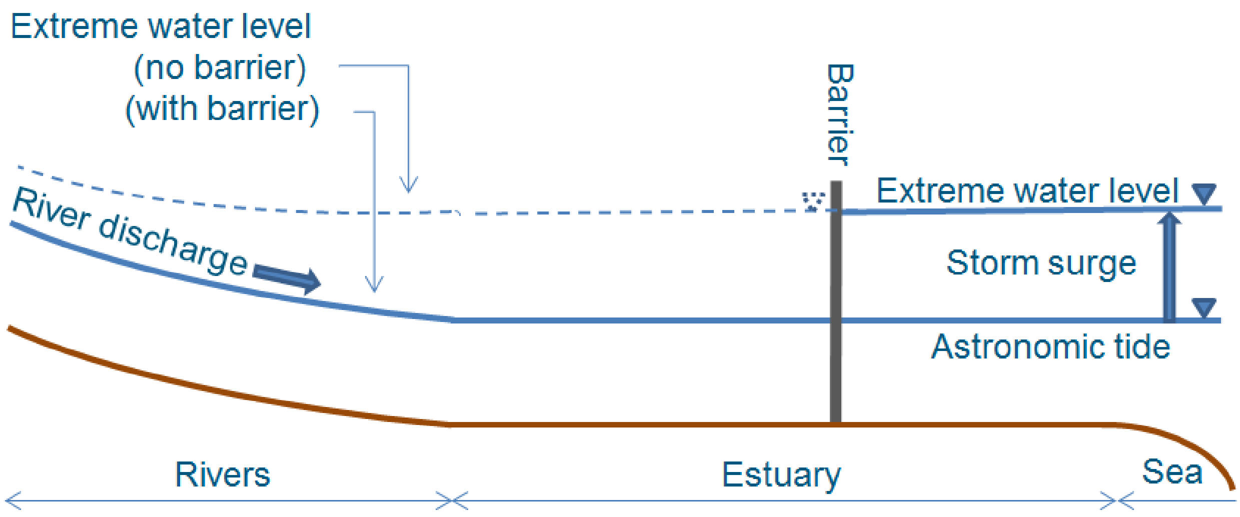


Figure 2 - River flood level reduction concept

2.2 Previous Studies

The concept of a barrier in the Avon-Heathcote Estuary is not new, with available reports dating back over 50 years. This section summarises the finding of these previous studies, focussing on the information relevant to consideration of the pre-feasibility of constructing a tidal barrier for conditions which are likely to prevail now and into the future.

2.2.1 Christchurch Drainage Board (1963)

The first available report dates from April 1963 and was authored by E.F. Scott, Chief Engineer (Planning) for the Christchurch Drainage Board. It is titled *Economic Report on the Estuary of the Avon and Heathcote Rivers and its Effects on the Land Drainage Problem of Christchurch* (Scott, 1963). This report refers to an earlier report prepared in 1959 by French engineers which recommended “a series of hand operated gates in a concrete structure in Moncks Bay.” Further saying:

> *The purpose of the gates would be twofold:*
>
> *(a) During periods of high spring tides they would be closed when estuary had reached the normal high tide level, so that the extra height of a very high spring tide outside the barrage would be excluded from the estuary and from the rivers.*
>
> *(b) During periods of heavy flood, the gates would be closed at low tide when the estuary would be empty, and by thus excluding the tide would provide a storage basin at a low level for the floodwaters. The outlets of the rivers and drains being thus kept low, a better gradient and higher discharge rate should be obtained, this helping to alleviate flooding upstream.*

The report continues by saying that the usual tidal movements are necessary for estuary function and would not be impeded under ordinary circumstances. Hence the barrier would only be used in the circumstances described above. Though the section describing the barrier concept does conclude with the statement that “[m]any drainage problems would be solved were the estuary always at low tide level.”

Having introduced the barrier concept, the report continues at length to compare this concept with a no-barrier scenario whereby a combination of estuary and river stopbanks, piped/channelised drainage augmentation and local pump stations are used to minimise flooding. The comparison is primarily conducted in terms of financial and flood risk objectives.

The concept of high volume, low lift pump stations at the Avon and Heathcote River mouths is also briefly discussed. It is concluded that whilst such an option is technically feasible it is unfavourable from a cost perspective. There is also favourable discussion regarding the potential benefits of a “cut” across the Woolston Loop and the “Dudley Creek Diversion”, plus unfavourable discussion on schemes to divert the headwaters of the Avon and Heathcote Rivers via various schemes towards adjacent catchments.

In order to “round out the picture” the report also raises the potential for a road bridge across the barrier, reclamation of land of land along the inside of the New Bright Spit as “a safety measure against piping” and plans for the Estuary to become “The Aquatic Playground of Canterbury.”

The report concludes that the barrier option is economically favourable when compared to other flood mitigation options and recommends that the Board proceed with model investigations, site studies and preliminary design. The final sentence states that “it seems to be a necessity to have the barrage at some future date for the adequate drainage of metropolitan Christchurch.”

Although the report presents a detailed economic comparison of the various options, this analysis is not useful for a modern cost comparison exercise. This is because many of the key parameters have changed, including the extent of development in flood prone areas and the stopbanks and drainage infrastructure associated with this development.

2.2.2 HR Wallingford (1970)

The second available report was dated from July 1970 and prepared by the Hydraulic Research Station (Great Britain). It is titled *Model Studies of Flood Alleviation* (HR Wallingford, 1970). Following the recommendations given to the Christchurch Drainage Board in 1963 (see 2.2.1 for detail), the Hydraulics Research Station (HRS) was engaged to investigate modelling methods that could be used to determine the effects of constructing a barrier across the entrance channel. Ultimately, the HRS suggested two laboratory models: they were termed ‘Christchurch I Model’ and ‘Christchurch II model’.

This report is composed of two parts. Part One firstly summaries the problems the Christchurch Drainage Board faced and listed potential solutions. The description of the Christchurch Model I, the model verification procedures, model test scenarios, modelling results and recommendations were then detailed.

Christchurch I Model was constructed in a watertight tank, representing the tidal reaches of the Avon and Heathcote Rivers, the whole estuary, New Brighton Spit, approximately 2.5 km of coastal line south of the estuary entrance and a strip of the offshore. The model was built based on the field survey data of the region. Initially, the model with fixed bed materials was used to study the effects of several flood mitigation measures on water levels. It is concluded that a movable barrier at the entrance to the estuary combined with deepening and straightening the Avon and Heathcote rivers and low-water channels is the most effective way to mitigate both tidal and freshwater flooding in Christchurch. For a picture of the HR Wallingford physical model refer to Figure 3 on the next page.

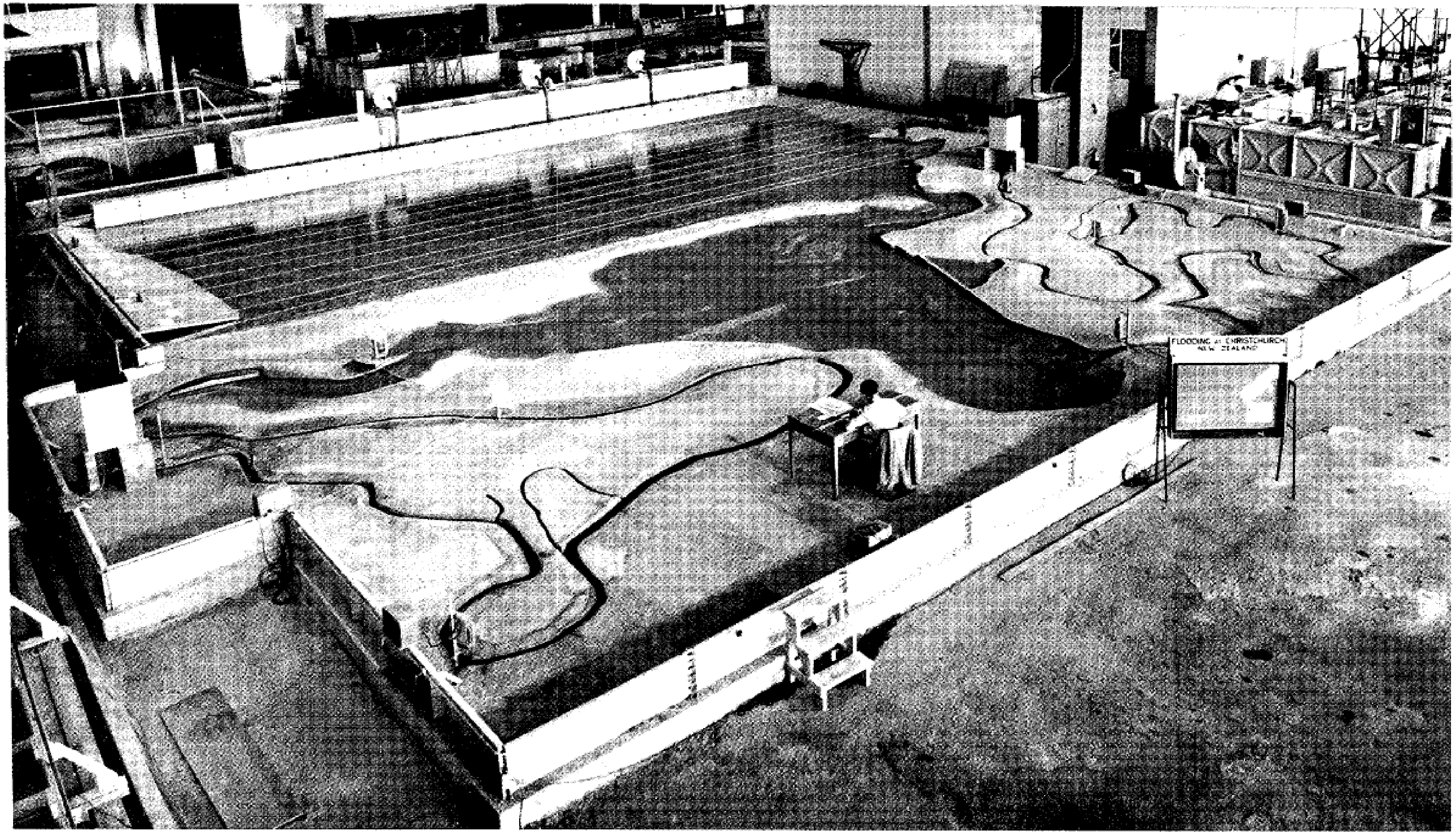


Figure 3 - Photograph of the HR Wallingford Christchurch I physical estuary model

Once the need to construct a barrier was established, the report then investigated the effects of barrier closure and barrier structure on the surrounding environment and infrastructure (note: the report suggested fish belly flap gates for the barrier, to avoid high flow velocities and associated scour near the bed and to provide navigable passage). These form the discussion of Part Two of the report. The description, verification, tests and results of the models applied were again explained in detail. To simulate the sediment movement to determine entrance channel stability, Christchurch I Model with movable bed materials was applied. The results of the model tests show that:

1. The closure of the barrier results in loss of entrance channel depth
2. The duration of the barrier that can be kept closed without causing blockage at the entrance depends on the magnitude and direction of the waves. The worst scenario arises when the wave is higher than 1.5 m and coming from the north or north-east direction. As the result, the entrance can be completely blocked at low water in a few days.
3. The blocked entrance can be restored to former values by keeping the barrier open. However, the channel course may deviate after a prolonged closure. Deviation to the south could starve Sumner beach of sand, while deviation to the north could erode New Brighton spit.

Finally, Christchurch II model was constructed to test local scour and deposition in the vicinity of the piers and abutments. Potential problems of scour near the opening of the designed barrier was identified from Christchurch I model current-velocity measurements. Accordingly, a scaled model of the barrier was built in a flume of 3.6 m length to investigate the issues. It was concluded that:

1. The presence of the barrier structure tested has little effect on the channel depth to seaward.
2. The barrier as tested in the model is likely to cause large scour holes opposite the gate openings on the landward side of the structure. A modification to the design is necessary to prevent the formation of the holes.

In summary, this report details a series of laboratory modelling studies conducted by the Hydraulic Research Station following the recommendation given to the Christchurch Drainage Board in 1963. The aim was to determine the best flood mitigation measure for Christchurch. In particular, the effectiveness and effects of constructing a barrier at the estuary entrance were examined. This report concludes that:

- Constructing a barrier with movable gates at the estuary entrance is necessary to protect Christchurch from flood damage.
- Closing a barrier for a long period of time could lead to complete blockage of the estuary entrance channel below low water.
- Designing an appropriate barrier is important to prevent the formation of large scour holes opposite the gate openings on the landward side of the structure.

2.2.3 Royds Sutherland and McLeay/Powell Fenwick and Partners (1973)

The third available report dates from December 1973 and was authored by a consortium of two firms of consulting engineers (Royds Sutherland and McLeay/Powell Fenwick and Partners). They were engaged by the Christchurch City Council Drainage Board to investigate the suggested flood control measures in conjunction with the HRS. The report is titled Report on Christchurch Drainage Investigation – with special reference to the Avon and Heathcote Rivers and Estuary. It is the result of an investigation which was commenced in 1964 after the Economic Report was published. The aim was to determine the best measure or a combination of the measures to alleviate the effects of both tidal and stormwater flooding within the Avon and Heathcote River catchment areas.

The report briefly describes the suggested measures and then focuses on the most feasible schemes: a waterway improvement scheme combined with an estuary barrage scheme or flood pumping scheme and a stopbanking scheme. The waterway improvement scheme involves enlarging the waterways of the existing rivers where the hydraulic profiles show it to be desirable to reduce high water levels caused by floods. The study shows that the waterway improvement scheme alone cannot achieve the specific lowered flood levels at various places in the rivers set in E.F. Scott's Economic Report. To meet the flood level criteria, the waterway improvement scheme would have to be combined with the additional estuary barrage scheme or the flood pumping scheme.

The estuary barrage scheme involves constructing a barrage across the estuary near its mouth at Moncks Bay with fitted gates. The gate would be closed at near low tide level on a rising tide so that the Estuary forms a ponding basin in a storm event. It would also be close at any time when a tide higher than ordinary spring tides is expected to prevent tidal flooding. The report summarises the HRS's 1970 report (see Section 2.2.2) on the hydraulic models for the estuary barrage scheme, and it considers the main conclusions and recommendations in the HRS's report are definite and valuable. However, it also states that after a close study by engineers of the Board and the Consortium, several discrepancies in the multitude of figures which would affect water levels and some apparent omissions in testing certain combinations of works which were thought desirable were found. Furthermore, by this time the Board's engineers had completed a flood probabilities study, and it was decided to concentrate only on 50 year and 10 year floods rather than a large number of flood flows to simplify the whole study. Therefore, an additional study was conducted by the HRS in 1972. In the report, a more detailed design of the barrage scheme was described including the site selection, gates selection, passage of boats, construction matters and cost estimate.

The flood pumping scheme involves a barrier with flood gates and pumps at the river mouths. The flood gates would be used to keep the tides out of the rivers when desirable. During the periods of high flood the pumps would be operated to keep the river water levels down to below critical levels. The estuary barrage and main pumping schemes are compared in the report. The main pumping scheme is considered to be preferable as being more effective in lowering flood levels and considerably less expensive than the estuary barrage scheme.

The stopbanking and local flood pumping scheme involves constructing stopbanks in the lower reach of the Avon and Heathcote Rivers and installing flood pumps to dispose of local stormwater by pumping as required over the banks. In his Economic Report of 1963 (see Section 2.2.1) E.F. Scott has already evaluated this scheme, and he did not recommend it. As this investigation revealed that the costs of the estuary barrage or main pumping scheme with their adjuncts in river waterway improvement schemes were very high, the stopbanking scheme was re-examined again. The investigation was conducted by the Board's staff. The report details the proposed locations for the stopbanks, types of stopbanks, pump stations, construction matters and the costs. It also compares the costs, advantage and disadvantage of the barrage, main pumping scheme and stopbanking schemes.

In summary, this report details the proposed design and estimates the costs for four flood alleviation schemes. The study concludes that:

- the main pumping scheme combined with the waterway improvement scheme are the only option that achieves the accepted criteria for reduced flood levels for the Avon and Heathcote rivers
- the main pumping scheme costs significantly less than the estuary barrage scheme
- the stopbanking and local flood pumping scheme is the cheapest option (at least by a factor of three when compared to the main pumping and estuary barrage schemes)
- the stopbanking and local flood pumping scheme is recommended based on economic grounds

Following this study, the Christchurch Drainage Board published a report concerned with the stopbanking work along the lower reaches of the Avon River in November 1981. It is titled Lower Avon River Stopbanking. The report re-states the conclusions drawn in the previous study. It acknowledges that the stopbanking scheme might not provide as much flood protection as other schemes can do. However, the stopbanking scheme is proposed based on the economic grounds. The scheme was also supported by its potential amenity value (provision of riverside footpaths). The report was focused on the proposed detail design for the lower Avon River including stopbank locations, shapes, heights, cross section designs and estimated costs. The study banks were separated into 28 sections. Each section has an identifiable character, and its particular problems and solutions were discussed accordingly. Finally, the report recommends the steps to be taken by Christchurch City Council to construct the proposed stopbanking work.

2.2.4 Harris Consulting (2003)

The fourth available report was dated from 2003 and prepared by Harris Consulting in conjunction with Christchurch City Council. It is titled *Climate Change Case Study: Assessment of the impacts of sea level rise on floodplain management planning for the Avon River* (Christchurch City Council and Harris Consulting, 2003). This report is essentially a case study on the impact of climate change and resulting sea level rise on risk management planning for the Avon catchment and associated coastal areas. As increase in flooding risk at the lower Avon is one of the primary concerns, one of the report's focuses is on possible flood mitigation options in the area. A tidal barrier was identified as one of the structural measures.

This report states that the Avon-Heathcote Estuary is likely to be the location to install a tidal barrier, as it is expected to have enough capacity to store flood run-off during barrier closure (note: An alternative location at the mouth of the Avon River, which had also been previously proposed, was not considered to have enough capacity). It was believed that the feasibility of the tidal barrier would require a significant investigation before a robust argument can be presented to prove its practicality, and two likely limitations of constructing a tidal barrier in Christchurch were identified in the report: negative environmental effects and cost.

The report suggests that environmental impacts of tidal barriers have halted the progress of this technology internationally with only a few commercial plants operating in the world. To build a tidal barrier in Christchurch, a rigorous environmental impact assessment will be needed, and resource consents required under the Resource Management Act may be difficult to obtain.

In terms of the cost, the report estimates a constructing cost of $25 million, which is approximately a factor six times greater than the estimated net benefit ($3.9 million) provided by a barrier. However, it states that the construction may become economic if it is delayed by fifty years. This report also notes that generating electricity from the barrier may offset the cost. However, the local tidal range is not considered large enough for power generation to be cost effective. The cost of tidal power generation is expected to be six to ten times the cost of generation of hydro-power or natural gas.

In summary, this report does not recommend constructing a tidal barrier as an immediate action against sea level rise. Environmental and technical issues around constructing and operating the barrier are the major constraints.

2.2.5 GHD (2013)

The fourth available report was dated from August 2013 and prepared by GHD. It is titled *Investigation into the River and Tidal Flood Protection needs in Christchurch Estuary and Sumner Stage 1* (GHD, 2013). This report examines the impacts of the Christchurch earthquakes on the reaches that are influenced by tides, and evaluates a range of flood mitigation measures based on flooding scenarios from tide events resulting from sea level rise. An estuary barrier is considered as one of the feasible flood mitigation measures that have effect over multiple reaches. However, the report briefly comments that the construction of the barrier will require international expertise, as well as a detailed assessment of environmental and ecological effects. It also says that electricity generation is not likely to offset the cost due to low tidal range, and is a less flexible option when considering sea level rise from a change in climate. The report provides rough estimates of the cost to implement a full river and tidal flood protection scheme and the cost to construct a tidal barrier in the estuary in conjunction with other fluvial protection measures. The assessment carried out does not include a cost benefit assessment based on life cycle cost and gained risk reductions.

3. Barrier Requirements

This section discusses initial requirements for a barrier in the Avon-Heathcote Estuary based on known parameters and constraints.

3.1 Tidal and storm surge range

Note that levels in this section and throughout this report are in Lyttelton 1937 Vertical Datum (LVD). For more information refer to Section 1.4.

Standard tide levels are provided in the Christchurch City Council Waterways, Wetlands and Drainage Guide (Christchurch City Council, 2011). They are summarised in Table 2 below.

Table 2 Standard tide levels (from Christchurch City Council, 2011)

Tide state	Level (m LVD)	Location
Mean Low Water (MLW)	-0.74	Scarborough
Mean Sea Level (MSL)	0.13	Scarborough
Mean High Water (MHW)	1.01	Scarborough
Highest recorded tide	1.91	Pages Road

Storm tide levels have been taken from Downstream Hydraulic Boundary Conditions for Avon and Heathcote Rivers (Goring, 2010). They are summarised in Table 3 below.

Table 3 Storm tide levels (m LVD, from Goring, 2010)

Return Period	Bridge St	Ferrymead
1	1.609	1.558
5	1.737	1.675
20	1.826	1.768
50	1.867	1.818
100	1.893	1.851
200	1.915	1.881
∞	2.036	2.167

The levels presented in the tables above do not take into account wave heights. MetOcean (2012) calculated a maximum significant wave height in the estuary of 0.46 m for a 100 year recurrence interval. This is the longest interval presented in the report. Given the distribution of the wave-height versus recurrence interval, a 200 year wave height is not expected to be more than a few centimetres higher.

3.2 Sea Level Rise

In 2014 Christchurch City Council commissioned a report by Tonkin and Taylor on the *Effects of Sea Level Rise for Christchurch City Council* (Tonkin and Taylor, 2013). This report draws upon earlier guidance provided by the Ministry for the Environment in the report titled C*oastal hazards and climate change: A guidance manual for local government in New Zealand* (MfE, 2008). This provided sea-level rise estimates for New Zealand and guidelines to local government for managing the risk. The Tonkin and Taylor report was based on analysing the impacts of one sea level rise scenario; being 1 m sea level rise by the year 2115. It was recommended that a sea level rise adaptation strategy should base assessment of the risk to existing property and strategic long term assets (major infrastructure) on the 1 m sea level rise projection.

Based on this, barrier requirements were assessed against a modelled sea level rise of up to 1 m. Government guidance on expected sea level rise is currently being reviewed based on 2014 International Panel on Climate Change assessment report.

3.3 Navigation requirements

There are a range of recreational users of the estuary that need to be taken into account when considering barrier type. There are three main locations where users of the estuary originate from; the Christchurch Yacht Club in Moncks Bay, the Mt Pleasant Yacht Club further upstream in Mt Pleasant and a beach access near the end of Linwood Ave. There is also a lesser used public boat ramp opposite Redcliffs Park. The different types of vessel tend to use different parts of the estuary in different ways. There is no known commercial boating carried out in the estuary.

A group of key recreational users of the estuary are P-class dinghies, optimists and similar one or small two person single hull sail boats. These typically sail in the main body of the estuary during high tide and predominantly launch from Mt Pleasant or Moncks Bay. They are known to sometimes sail out the estuary mouth if conditions are ideal, but are not generally capable of navigating breaking waves and are not suited to the open ocean.

Wind surfers, kite surfers and paddleboards launch predominantly from the Linwood Ave beach access. They mainly use the estuary in open water during high tide, and while feasible, navigating the constricted estuary mouth area is not typically popular for these craft.

Kayaks will generally leave from the Christchurch Yacht Club, paddle around that area, and out through the mouth to surf in the waves on the coast. It is important to note that portable craft like kayaks, windsurfers and kite surfers could readily cross over a bank/barrier as long as suitable landing and launch points (eg. artificial beaches) are included on each side of the embankment to enable this.

Trailer sailers are another type of single hull vessel routinely seen in the estuary. They typically carry 4-8 people and usually have sleeping quarters. These prefer deeper water and are not commonly sailed in the estuary, although some of the smaller ones do so occasionally. Some are anchored in Moncks Bay near the Christchurch Yacht Club, but this is principally as a storage location and they are usually trailered to other locations for use. They are capable of sailing out through the estuary mouth to the open ocean and more distant destinations such as Akaroa Harbour, but this would be a rare activity.

Beach craft - typical one or two person catamarans - don't require deep water and are also suited to sailing from beach areas. They would typically launch from boat ramps (eg: Moncks Bay or Redcliffs), and would be capable of navigating throughout the estuary during high tide, as well as the estuary mouth, coastal waves and open ocean and adjacent beaches. There are however not many of these within Christchurch and their users typically prefer larger water bodies such as Lyttelton and Akaroa Harbours.

In summary, the most likely passage of recreational users to the ocean is from Moncks Bay/the Christchurch Yacht Club. Other craft that launch from locations upstream of the potential barrier locations and which regularly traverse from the estuary to the ocean will be able to pass through the barrier except when it is required to be closed during a significant storm/tidal event. In present day, this is likely to be 2 or 3 times in a year.

3.4 Geotechnical considerations

During the last glaciation which began to end about 20,000 years ago, sea level was some 120 m lower than present, with much global water in the form of on-land ice sheets. At that time the gravel Canterbury plains extended well beyond the present coast-line. As warming began, the sea rose to reach its present level about 7,000 years ago, and at that stage the local coastline formed well inland, near the western side of Hagley Park. Progadation by sediments supplied by the Waimakariri River since then have pushed the coastline eastwards to its present position at New Brighton and the sand spit and estuary mouth near Shag Rock, and in the process covering the gravel plain (the Riccarton Gravel) with estuarine and river sediments.

Figure 4 shows a cross-section at the estuary from the Geology of the Christchurch Urban Area, based on drill hole data. This cross-section is a little to the west of the Barrier Site, but will be very similar to it, with marine sands overlying Lyttelton Volcanics

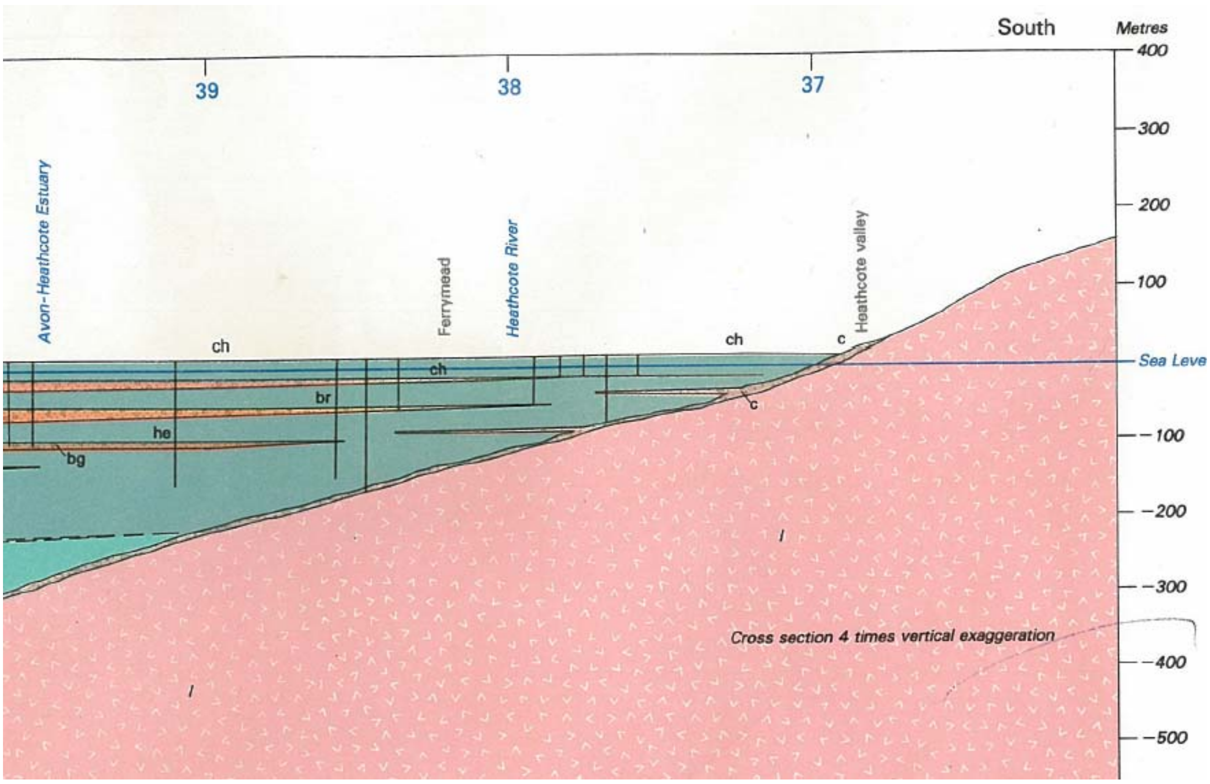


Figure 4 - Estuary cross-section from Geology of the Christchurch Urban Area

Within the present estuary the upper sediments are mainly loose, silty fine sand, a rock flour sediment composed of angular rock fragments that has settled out in a low energy, ponding environment during Waimakariri River floods. These sediments are prone to liquefaction.

In contrast, at Shag Rock and the sand spit, there is a high energy wave environment and the presence of coarser sand that originates from the Waimakariri river. This sand has had the finer grains washed out and the sand grains have been rounded as they have migrated along the beach by wave action and long-shore drift. This sand is dense and is not prone to liquefaction.

3.5 Spit and mouth morphology

3.5.1 Background

The Avon Heathcote Estuary is enclosed in the east by the Brighton Spit, a sand spit formed by littoral transport of sand from the north. Brighton spit started to form well after sea level stabilised 6000 years ago and grew southwards in several stages interrupted by periods of erosion and breaching until it finally enclosed the estuary in the last 1000 years (Bryan et al 2008). The main source of sediment to the spit is the Waimakariri River which discharges 20 km to the north of estuary mouth. The foreshore of the spit is backed by dunes ranging in height from 5 to 9 m.

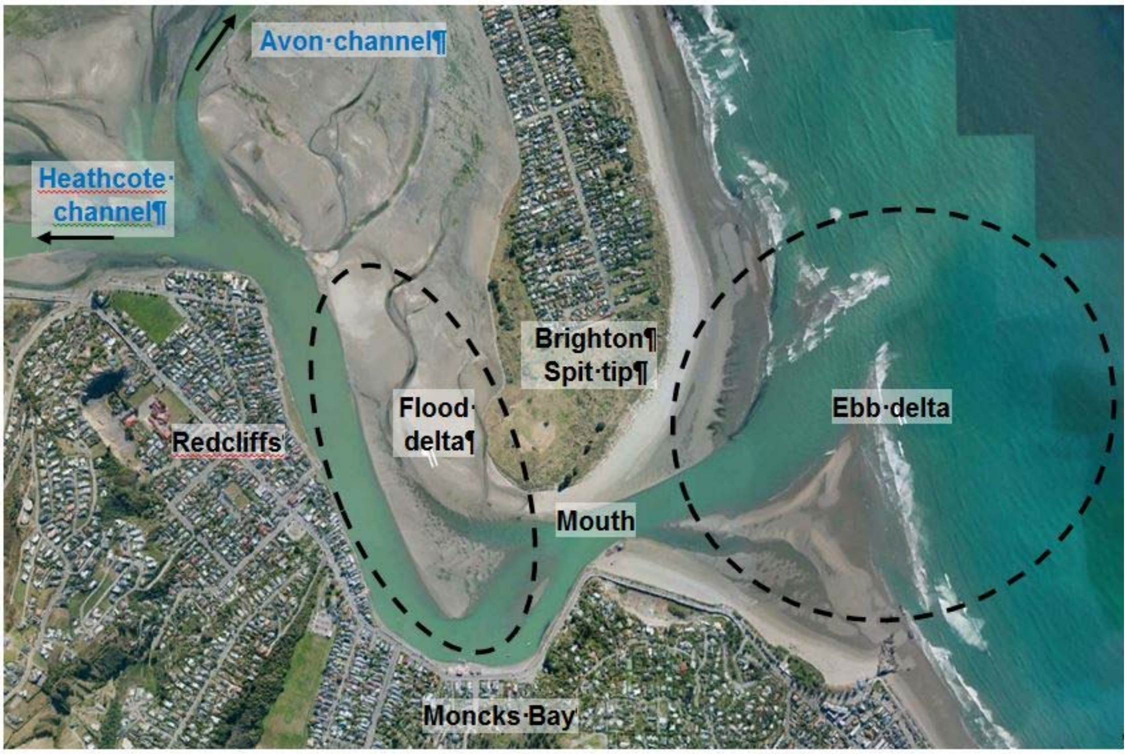


Figure 3- Aerial photo of the estuary mouth showing the location of features named in the text

Shoreline profile monitoring has been undertaken regularly since 1977 at sites along the Pegasus Bay shoreline, including on Brighton Spit (Gabites 2005). Initial analysis of the records for Brighton Spit shows a gradual net accretion of the Brighton Spit shoreline overlaid by 2-5 year cycles of storm erosion and recovery (Bryan et al 2008). The variability in shoreline position associated with the cycles of storm erosion and recovery is large and increases from north to south along the spit. At profile C0300 (southern spit) the mean sea level contour has moved backwards and forwards over a 125 m range as a result of these short term cycles, with changes in position of up to 75 m in a single year.

The spit tip is particularly dynamic. Findlay and Kirk (1988) describe historic variations in the spit tip shape and size from 1847 to 1973, during this period the outlet channel changed orientation and went through phases of erosion and accretion. (see Figure 5). The most northerly position of the spit was recorded following an extensive period of erosion in 1940-49 when the shoreline of the spit tip eroded to a position approximately 350 m north of its current position. Following this period of erosion a series of groynes and fences were constructed over the following years to encourage accretion.

Figure 5 - 1847-2005 tip shorelines (from Findlay and Kirk 1988 and Bryan et al 2008)

Pearce (1950) noted a large influx of marine/beach sand into the lower estuary in 1946-48, which added considerably to the flood delta at Redcliffs. It migrated up the inlet as a tongue, lapping over older sand bodies and mudflat, extending as far as Moncks Bay. This was accompanied by a northward retreat and recurving of the spit tip, so it is likely that the sand came from erosion of the spit tip by storm waves, and its penetration into the inlet was assisted by greater wave exposure while the inlet was wider.

The mouth of the estuary is positioned between the sands of Brighton Spit to the north and an outcrop of hard volcanic rock to the south. This bedrock outcrop prevents southward migration of the mouth, maintaining its current position. As a result of this bedrock control the position of the mouth adjacent to Shag Rock has remained stable since European settlement. Although the mouth position has been stable the mouth width, the orientation of the ebb tidal jet, and the associated shape of the ebb-tidal delta and Sumner Bar have all changed over time. The largest change influencing the mouth orientation and ebb-tidal delta occurred suddenly in 1938 when the ebb-tidal channel outside the mouth moved from a southerly orientation, flowing along Sumner Beach and past Cave Rock, to an easterly orientation (Findlay and Kirk 1988). Changes to the ebb tidal delta size and position and ebb channel orientation influence the build-up and erosion of sand on both Sumner and Scarborough Beaches, both of which are vulnerable to erosion and are important for recreation and shoreline protection. Scarborough Beach is currently in a depleted state.

Inside the estuary mouth the main channel currently follows the southern shore of the estuary around Moncks Bay and north past Redcliffs before splitting towards the Avon and Heathcote Rivers. Prior to around 1940 the main channel went more directly from Redcliffs towards the estuary mouth without following the shore around Moncks Bay (Findlay and Kirk 1988). However, since the main channel evolved into this position it has been relatively stable. Hydraulic modelling shows that on the ebb tide the current flows strongly around the southern shore of the estuary (Measures 2013). As this shoreline is protected from erosion by a sea wall preventing erosion the strong ebb current tends to maintain the size and position of this main channel. A smaller proportion of the flood tide flow goes through this main channel, with a significant portion flowing more directly over the sandbanks within Moncks Bay. This area of the estuary is much less stable with secondary flood tide channels forming and migrating. Peak depth-averaged velocities during normal tidal conditions are approximately 2-3 m/s (see Figure 6).

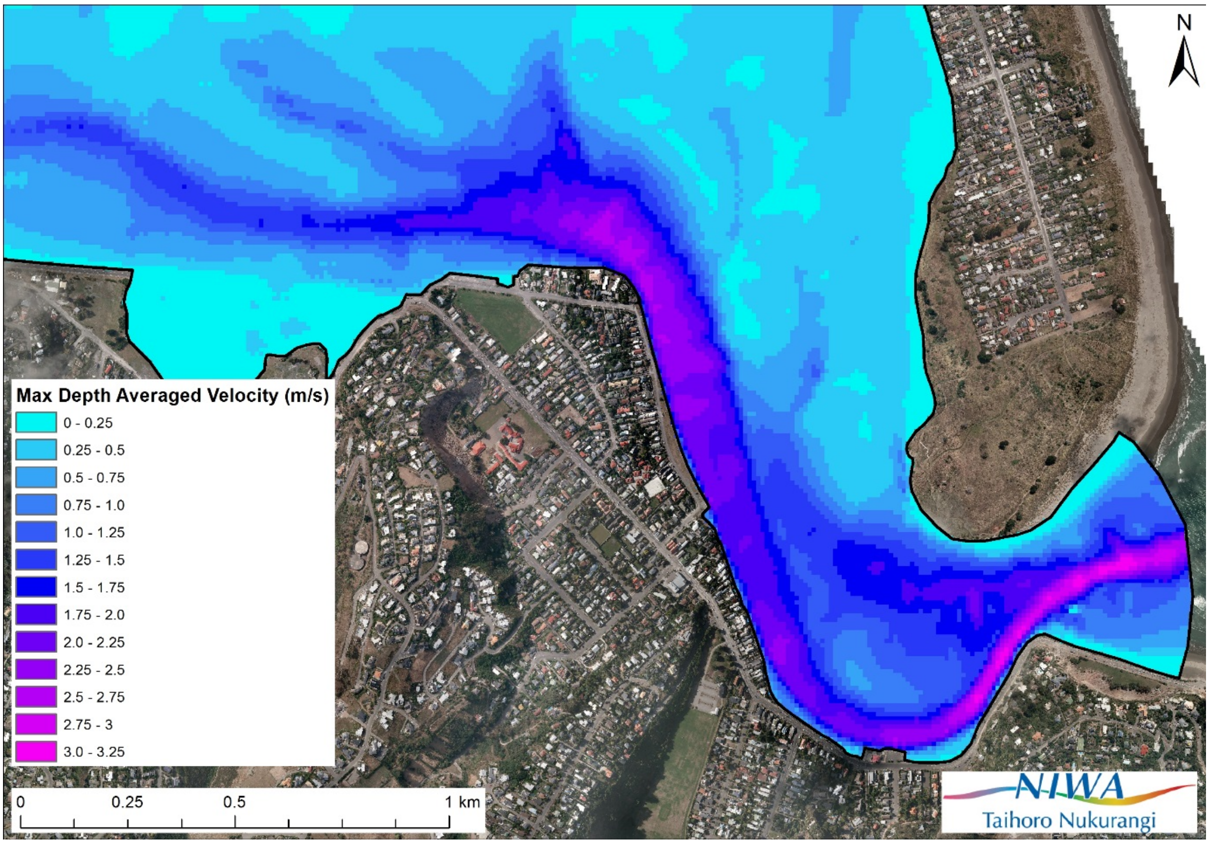


Figure 6 - Maximum depth-averaged velocity magnitude under normal tidal conditions (modelled data over flood and ebb tides)

As a result of the Christchurch Earthquake Sequence the bed of the estuary tilted, experiencing uplift in the south and subsidence in the north as shown in Figure 7 (Measures et al 2011, Hughes et al 2015). These changes reduced the tidal prism of the estuary by 15%, with the largest reductions occurring in the southern and western parts of the estuary (Measures 2013). The estuary bed is still responding to these changes as the width and bed level of the various channels in the estuary adjust to a new equilibrium.

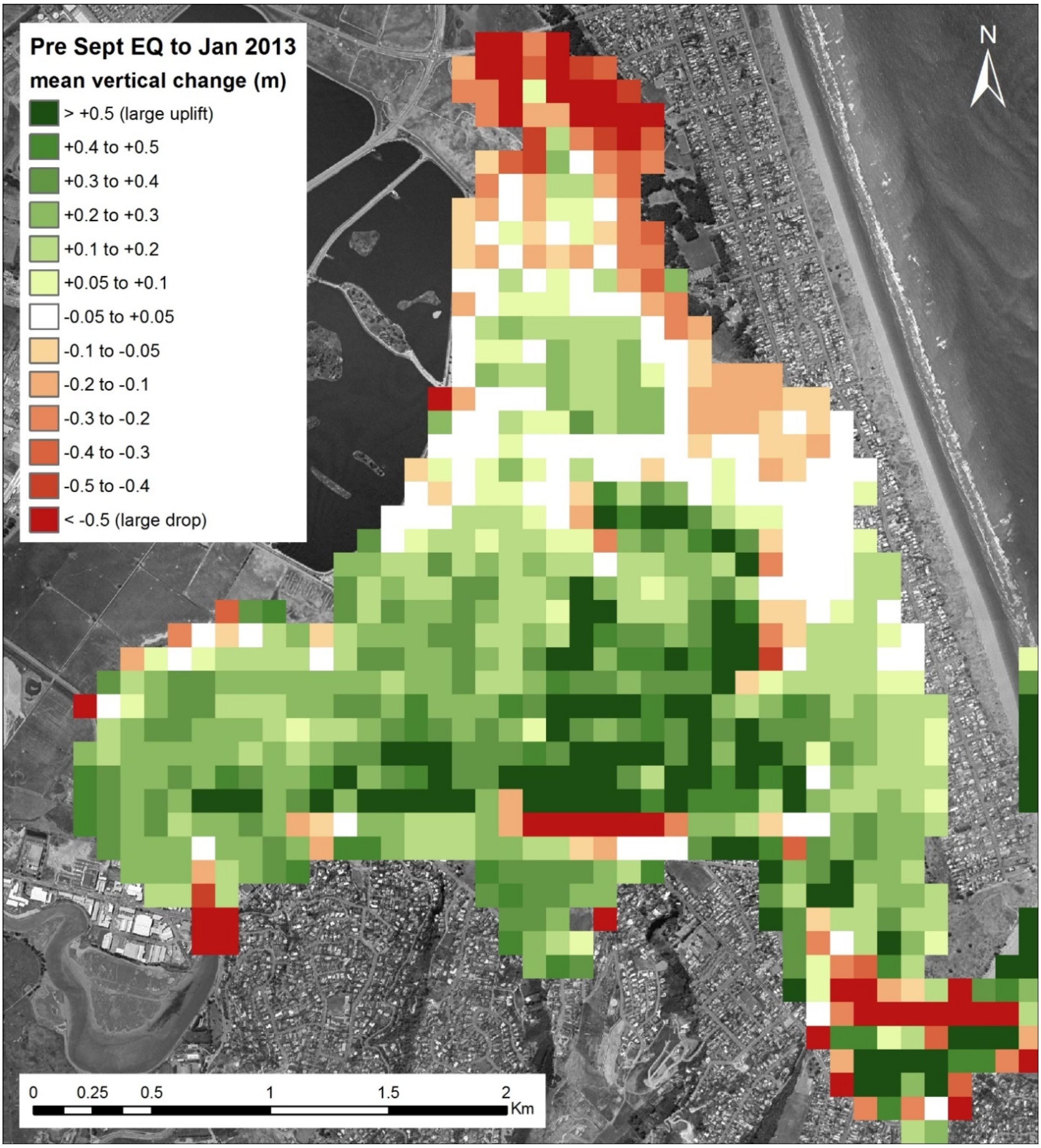


Figure 7 - Estuary bed level changes as a result of the Canterbury Earthquake Sequence

(Note that narrow bands of 'subsidence' in the estuary mouth area and near McCormacks Bay are related to morphological change between surveys rather than direct earthquake effects.)

Recent NIWA surveys of the mouth show that the mouth cross-section shape and area varied significantly since the earthquake (Figure 8). While some of the change is undoubtable the result of earthquake effects on the tidal prism and bed levels, some of it is likely due to natural variability in tidal inlet morphodynamics driven by the combined influence of waves and the tide. Unfortunately there is only infrequent survey data available for the mouth prior to 1998 (the only known surveys are 1854, 1904, and 1962, Findlay and Kirk 1988). From this limited data it is impossible to quantify the degree of short-medium term natural variability in outlet channel cross-section.

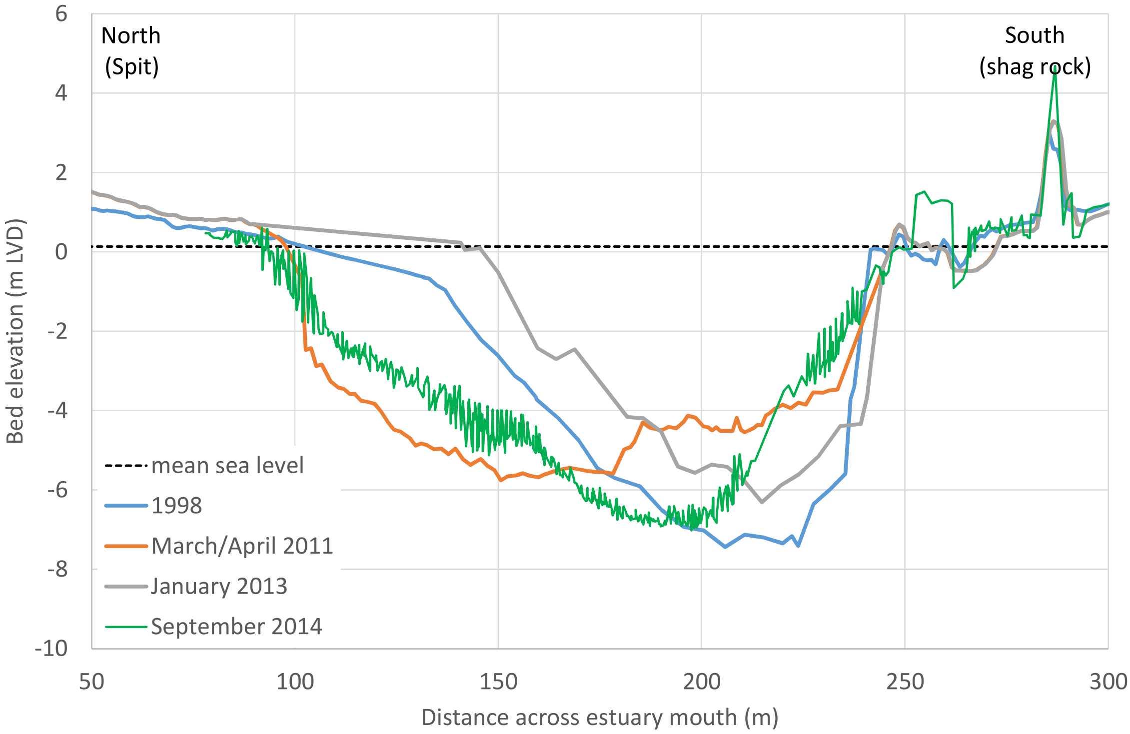


Figure 8 - Estuary mouth cross-sections

Accelerating sea level rise as a result of anthropogenic global warming will have an effect on the Brighton Spit and Avon Heathcote Estuary morphology in the future. Hicks (1993) calculated sedimentation in the estuary from river sources was occurring at an average rate of 1 mm/yr, significantly less than the expected rates of sea level rise. Consequently it is expected that the tidal prism of the estuary will increase as the high tide level of the estuary increases. The increasing tidal prism of the estuary will increase flow rates through the estuary mouth and tidal channels, enlarging the channels, the mouth and the tidal deltas. Based on the expected increase in tidal prism it is estimated that the estuary mouth will increase in width by 20-30 m with a 0.5 m sea level rise and 40-50 m with a 1.0 m rise (Tonkin and Taylor 2013).

On the Brighton Spit sea level rise is expected to result in shoreline retreat. Tonkin and Taylor (2013) estimate the sea level rise of 0.5 to 1.5 m would result in shoreline retreat along the spit of 30-90 m. They highlight that there is significant uncertainty in this figure as it is dependent not only on the amount of sea level rise but also any changes in sediment supply from the Waimakariri River and also any effects on wave height or direction as a result of climate change. If anything the retreat will be larger closer to the inlet as the increased equilibrium sand stocks on the ebb and flood tidal deltas (required by the increased tidal prism) will be sourced from the adjacent beaches.

3.5.2 Design considerations

The dynamic nature of the spit tip, the importance of tidal flows for maintaining the mouth of the estuary and the sediment flow and change inside and outside the estuary present a number of design considerations:

- The current size of the estuary mouth is maintained by the tidal flow of water through it. Any reductions to the tidal flows as a result of a barrier have the potential to reduce the size of the estuary mouth and ebb-tidal delta, due largely to the action of the waves washing sand bars shoreward. Extended closure of the barrier over many tides, only allowing discharge equivalent to freshwater inflows, could result in closure of the estuary mouth, particularly if the barrier was closed during high wave conditions (highly likely). Any significant changes in the tidal flow rates, mouth orientation or position have the potential to effect the ebb delta with knock on effects on Sumner and Scarborough beaches. The operating philosophy of the barrier should be to keep it open as much as possible in order to minimise the impact on Ocean-side morphology.
- Depending on the location of the barrier and the extent to which it is keyed into Brighton Spit and the use of ground treatment to mitigate liquefaction and weak soils under and along the barrage wings, there is a risk that the structure could be bypassed by movement of the spit tip. The closer to the mouth the barrier is positioned the greater this risk, as the spit is most dynamic near the mouth. The barrier should be positioned in a location where the main tidal channel is stable.
- In the estuary mouth and main tidal channels, large volumes of sand are transported by tidal flows as bedload. The barrier structure will need to be able to accommodate this flow of bedload sediment. The structure's design would also need to tolerate the presence of sand over its sill, without hindering its operation. Since the main sand exchanges tend to occur between the ebb and flood tidal deltas, the amount of bedload to be managed will diminish the further up the inlet the barrier is built.
- The bed of the estuary is highly mobile and there is likely to be some local scour around any hard structure. The barrier design should take local scour effects into consideration.
- Sea level rise will increase the size of the estuary tidal prism increasing flow rates into and out of the estuary on each tide. The capacity of the gates needs to be large enough to convey these higher flows.

3.6 Known environmental constraints

3.6.1 Context

The Avon-Heathcote Estuary is identified as one of the city's sites of outstanding biodiversity value within Christchurch and Banks Peninsula areas. It, along with the adjacent unbuilt environments, is important for water birds, with nationally and internationally significant concentrations of wetland and coastal birds in the area at times. The high proportion and importance of the wetland and coastal bird species makes the Christchurch City area the "wetland bird capital of New Zealand".

The Council, other organisations and the community share responsibility for the estuary under the City Plan and its Biodiversity Strategy (CCC 2008). To this end, Council and Environment Canterbury have signed a memorandum of understanding with the Avon-Heathcote Estuary/Ihutai Trust to:

- "pursue … the preservation of its [the estuary's] natural and historic resources to maintain their intrinsic values, and to seek the protection of these resources, including restoration and enhancement, for their appreciation and recreational enjoyment by present and future generations", and to
- "achieve healthy working ecosystems for the Estuary and its catchments".

Under its strategic vision concept plans, the city considers that "[continued] protection of the [estuary's] nationally important wildlife values of the oxidation ponds, salt marsh and estuarine mudflats is a high priority … to protect and restore breeding populations of coastal birds and provide high tide feeding and roosting habitat". It works in partnership with Avon Heathcote Estuary Ihutai Trust, Environment Canterbury, Department of Conservation, Ngāi Tahu, and the Christchurch Estuary Association to achieve this objective.

Ngai Tahu noted that "Te Ihutai [Avon-Heathcote Estuary] and the surrounding coastal environment is an area of immense cultural value adjacent to a highly urbanised area", with the estuary's ecosystem health identified as a priority concern for the iwi. Its Mahaanui Iwi Management Plan seeks "restoration of the cultural health of the Ihutai catchment, … [and that] Mahinga kai values and associations with the Ihutai catchment are re-established, … [t]he restoration and enhancement of indigenous biodiversity is an essential part of the image and brand of Ōtautahi, and an improved balance between exotic and indigenous plant species is achieved" (Jolly & NPRWG 2013).

Environment Canterbury's long-term plan and its biodiversity plan identify estuarine ecosystems as priority habitats for sustaining and protecting sites with high natural values, notably biodiversity values. The Avon-Heathcote Estuary is consistently listed as one of a small number of significant estuaries within the region.

Recent diversion of Christchurch city's wastewater from the estuary to a 3 km long ocean outfall at a very substantial cost, plus continued support for the joint (Christchurch City Council, Environment Canterbury, Avon-Heathcote Estuary/Ihutai Trust) "The Healthy Estuary and Rivers of the City" monitoring programme, indicate the importance placed on the estuary's biodiversity and ecosystem health by the community and stakeholder groups (Batchelor et al. 2009).

3.6.2 Ecological constraints

The estuary's key biodiversity values are its avifauna, with abundant and diverse bird life, fishes, invertebrates, salt marsh communities around the estuary's margins (especially at junctions with the rivers). Proximity of a large and visible, functioning ecosystem within a city is also of importance. Mahinga kai species in the estuary are valued more for their symbolic value, especially as cultural indicators of ecosystem function, than as food (continuing contamination apparently compromises its cultural acceptability at present).

Table 4 describes the significant species and their ecological requirements for sustained life.

Table 4 Key biodiversity components of the Avon-Heathcote Estuary's ecosystem, their ecological functioning and requirements

Biological unit	Significant species	Ecological function	Ecological requirements
Salt marsh habitats	Various plants: Juncus, Carex, Bulboschoenus.	Primary producers, nutrient removal, source of detritus, food & shelter for some invertebrates.	Light for photosynthesis, tidal cycles, variously brackish water, dissolved nutrients, fine sediments
Sea grass	Zostera spp.	Sediment binder, habitat former, primary producer, detritus source.	Specific light, salinity & immersion-emersion requirements.
Microphyto-benthos	Euglena spp., diatoms, etc.	Primary producers (base of trophic system), nutrient removal	Light for photosynthesis, tidal cycles, dissolved nutrients, variously brackish water, fine sediments
Macroalgae	Ulva sp., Enteromorpha sp., Gracilaria sp.	Primary producers, nutrient removal, source of detritus, food & shelter for some invertebrates.	Light for photosynthesis, variously brackish water, dissolved nutrients
Meiobenthos	Foraminifera, protozoans, nematodes, small worms & crustaceans.	Grazers, scavengers; transfer energy to higher tropic levels, especially juvenile flatfish.	Tidal cycles, variously brackish water, fine sediments, microphytobenthos, biofilms, fine organic detritus
Benthos	Snails, bivalves, worms, crustaceans (including crabs, shrimp, etc.)	Grazers, scavengers, predators. Primary food for to higher tropic levels (including juvenile flatfish, wading and diving birds).	Tidal cycles, (feeding, recruitment to channel and flats from sea, etc.), variously brackish water, diverse physical (sedimentary, water depths, etc.) environments, macro & microalgae, biofilms, organic detritus
Shellfish	Cockles, mudflat snails, mud snails, whelks, pipi, wedge shells.	Suspension feeders, deposit feeders, scavengers, predators. Bivalve molluscs are a key food for several bird species.	Tidal cycles (feeding, recruitment from sea, etc.), variously brackish water, diverse physical (water depths, substrata, etc.) environments, fine sediments, microalgae, biofilms, organic detritus.
Fish	Juvenile flatfish, other juvenile fish, whitebait, adult flatfish, yellow-eyed mullet.	Grazers, herbivores, omnivores, predators. Significant food source for wading & diving birds & other fishes.	Tidal linkages to sea for migration, etc., variously brackish water, macro & microalgae, biofilms, organic detritus, benthos.

Biological unit	Significant species	Ecological function	Ecological requirements
Birds	Godwits, stilts, oyster catchers, herons, ducks, spoon-bills, shags, gulls, terns, dotterels, Canada geese, kingfishers.	Herbivores, omnivores, predators that export nutrients from the ecosystem via faeces & migration.	Tidal cycles, variously brackish water, macroalgae, organic detritus, benthos, shellfish, fish (including juveniles).
Whole ecosystem	Stable, rich biodiversity.	Ecosystem services delivery that is resilient to environmental change.	Natural tidally variable estuarine environment with heterogeneous physical habitat spaces.

Most estuary biota (marsh plants, algae, invertebrates, fishes) are variously vulnerable to the following environmental factors:

- Salinity regimes. A predictably varying salinity regime is the most significant characteristic of estuaries, and most estuarine ecosystems are tightly driven by this (i.e., most salt marsh plants restricted in salinity tolerances over medium term, many estuarine invertebrates and fishes have physiological adaptations and/or behaviour to avoid).
- Tidal water level changes. Tidal exchanges of a large proportion of the estuary’s water is a fundamental to all natural estuarine ecosystems. Tidal rise and fall drives ecosystem functioning in that inundation allows some species to grow and feed and/or be protected from predators or other harmful agents, whereas low tides allow other species to do some or all of these. Notably, many bird species are tightly constrained in their energy budgets (i.e., face starvation if food is unpredictably inaccessible) and their population sizes are frequently food-limited.
- Drying. Most invertebrates are vulnerable to drying. But some (e.g., cockles) are resistant, whilst others (e.g., some crabs) have physiological and/or behavioural adaptations.
- Over-heating. Most organisms are vulnerable to over-hearting. But some are very tolerant (e.g., sea lettuce), whilst others have behavioural adaptations (e.g., some polychaete worms, crabs).
- Freezing or cold-associated mortality. Most organisms have a degree of vulnerability to cold.
- Sunlight (UV) exposure. Most organism have morphological, physiological and/or behavioural adaptations to cope with UV exposure. But these may be compromised by artificial tidal regimes.

Considering these vulnerabilities, the barrier design should seek to minimise its effect on the natural tidal regime, both through design and operation. Specifically, barrier operation must pay attention to:

1. Allowing tidal flow. Under all conditions, the tidal regime must continue (i.e., the estuary water levels must fall as low as practical at the time of each ambient low tide and rise as high as practical at the time of each ambient high tide). This is essential because many of the wading birds are completely reliant on food items exposed during low tides within the estuary and some invertebrates rely on fluctuating tides for their normal feeding activities.

2. Replicating natural (non-controlled) emersion durations of ecosystems. This will minimise exposing intertidal areas and organisms to non-natural sunlight levels, temperatures (high or low), desiccation or deoxygenation. Barrier operation should not effectively introduce a lag in the ambient tide cycle.
3. Allowing normal free exchange with the sea. To minimise ecosystem disruption, normal tidally driven water levels and salinity regimes must occur as frequently as practical. In effect this means minimising the frequency and duration with which the barrier might be closed.
4. Consider barrier use to minimise extreme events. A barrier provides some opportunity (within its engineering constraints) to manipulate tidal water levels and salinity regimes and, hence, the estuary's ecological values. The likely consequences of such manipulations require more thorough investigation and stakeholders should participate in determining the preferred ecosystem values and required tidal regime under sea level rise.

3.7 Known social and consenting constraints

A brief assessment has been carried out of the planning features of the area, and the constraints to both of the potential alignments. Relevant planning documents have been reviewed and a summary provided below of the some key features/constraints.

- The South Brighton Spit is identified on Environment Canterbury's Listed Land Use Register as it is listed as a former landfill site (No: ACT 0949, G3 Landfill site). Therefore, it may be contaminated.
- The *Canterbury Natural Resources Regional Plan* (NRRP) identifies the South Brighton spit as being within the groundwater protection and allocation zones, and is also identified as having a coastal confined gravel aquifer system, so it's important to avoid any impacts on groundwater quality.
- The entire study area of the estuary is identified as an area of Significant Natural Value under the *Canterbury Regional Coastal Environment Plan.*
- The *Operative Christchurch City Plan* identifies most of the land adjacent to the study area as a Flood Management Area. This is important to consider in terms of the barrier location and the offset of effects downstream.

  The land bordering the South Brighton spit, and the land bordering Sumner Beach is zoned Conservation 1a. This zone is focused on the protection of the integrity, functioning and resilience of the coastal margin. The land bordering the southern part of Sumner Beach has a special amenity area overlay (ref 35 and 18). Therefore, a seaward (Shag Rock) alignment is considered to be less suitable for the barrier siting in terms of these notations.
- The *Proposed Christchurch Replacement District Plan* which is only partly in effect identifies several Natural Hazard overlays which are relevant to the proposal. This includes the liquefaction assessment area which covers the whole study area, and the cliff hazard management area along Main Road. We understand that phase 2 of the District Plan review will include Outstanding Natural Feature Overlays and High Natural Character Areas (Avon/ Heathcote Estuary and Christchurch Coast, South Brighton Spit and Estuary Entrance), and Sites of Ecological Significance (Avon/Heathcote Estuary).

- The *Avon Heathcote Estuary Ihutai Estuary Edge Master Plan 2010* and the *Main Road Master Plan (Part of the Ferry Road / Main Road Master Plan) Phase Two – Ferrymead Bridge to Marriner Street* identify particular areas along the estuary that are preserved for amenity which should influence the potential location of the barrier in terms of amenity values. This is elaborated on further in section 9.3.3.
- The *New Zealand Coastal Policy Statement* is a high level document which provides direction around how to respond and adapt to coastal hazards. This document provides key policy guidance for consent applications under the RMA. Objectives and policies of particular relevance to the potential barrier proposal are objective 5, and policies 3, 25, 26, and 27. Objective 5 provides direction in the form of locating new development away from areas prone to risk and considering responses including managed retreat for existing development, and by protecting or restoring natural defences to coastal hazards. Policy 3 states that a precautionary approach to the use and management of coastal resources potentially vulnerable to the effects of climate change. Other relevant policies are about avoiding the risk of social, environment and economic harm from coastal hazards (Policy 25), and considering a wide range of options to reducing coastal hazard risk (Policy 27). Policy 27 anticipates that hard structures may be appropriate to protect existing development . While the policy seeks to reduce the need for hard protection structures and similar engineering interventions (Policy 27(2)(a)), their relevance in some situations is acknowledged. For example, 27(1)(c) *recognising that hard protection structures may be the only practical means to protect existing infrastructure of national or regional importance, to sustain the potential of built physical resources to meet the reasonably foreseeable needs of future generations*, Policy 27(1)(d) *recognising and considering the environmental and social costs of permitting hard protection structures to protect private property*; and Policy 27(3) *Where hard protection structures are considered to be necessary, ensure that the form and location of any structures are designed to minimise adverse effects on the coastal environment.*There are many archaeological sites within and in close proximity to the study area.

4. Location

To assess the feasibility of a tidal barrier it was necessary make some assumptions about location. This section describes how a location was chosen for the purpose of assessing the feasibility and potential benefits/impacts of a tidal barrier (refer to Section 1.2 for more information about this approach).

4.1 Study area

As described in Section 2.1, one objective of a tidal barrier would be to utilise an empty estuary for flood storage in order to mitigate upstream flood hazard. To achieve this objective it is desirable to maximise the estuary volume available for storage by placing the barrier as close as possible to the estuary mouth. On this basis the study area was limited to assessment of barrier locations close to the estuary mouth.

The shape of the estuary helped to further limit the study extent. West of the headland at Redcliffs the estuary widens substantially, which increases the required length of a barrier structure whilst decreasing the available flood storage volume. As both of these are undesirable outcomes the headland at Redcliffs was adopted as the western extent of the study area on the Port Hills side of the estuary.

The eastern extent of the study area was also constrained by topography. East of Shag Rock the estuary mouth widens rapidly and becomes more exposed to the open ocean. Furthermore, the high ground on the Port Hills side of the estuary recedes inland in the direction of Sumner. For these reasons Shag Rock was adopted as the eastern extent of the study area on the Port Hills side of the estuary.

The extent of the study area on the Southshore side of the estuary was determined based on potential barrier alignments from the Port Hills side of the estuary, as shown in Figure 9 below.

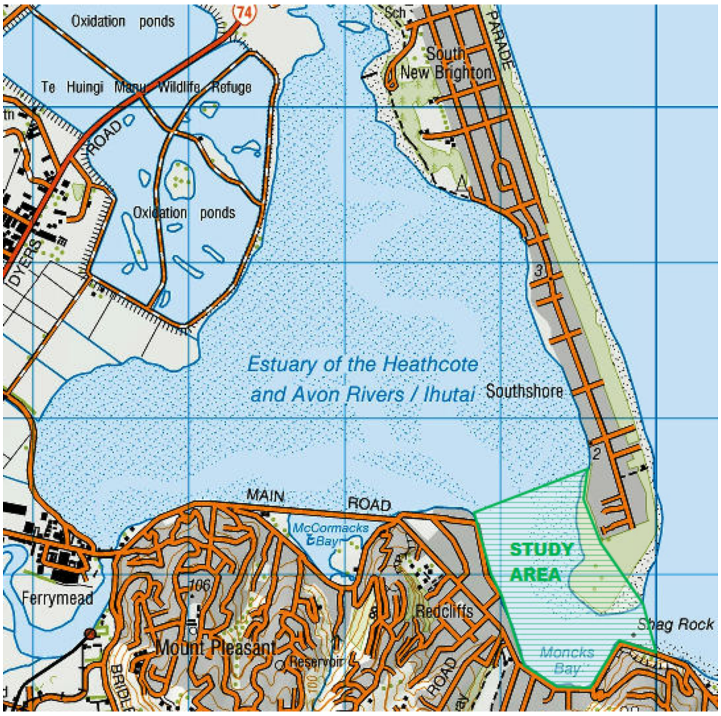


Figure 9 - Barrier study area

4.2 Location options

Within the study area described in the previous section, there were two potential location options identified. The “Redcliffs Option” would span from somewhere along Beachville Road in Redcliffs to inner side of the spit in Southshore. The “Shag Rock Option” would span from somewhere near Shag Rock on the south side of the estuary mouth to somewhere near the tip of the spit in Southshore. The location options considered are shown in Figure 10 below.

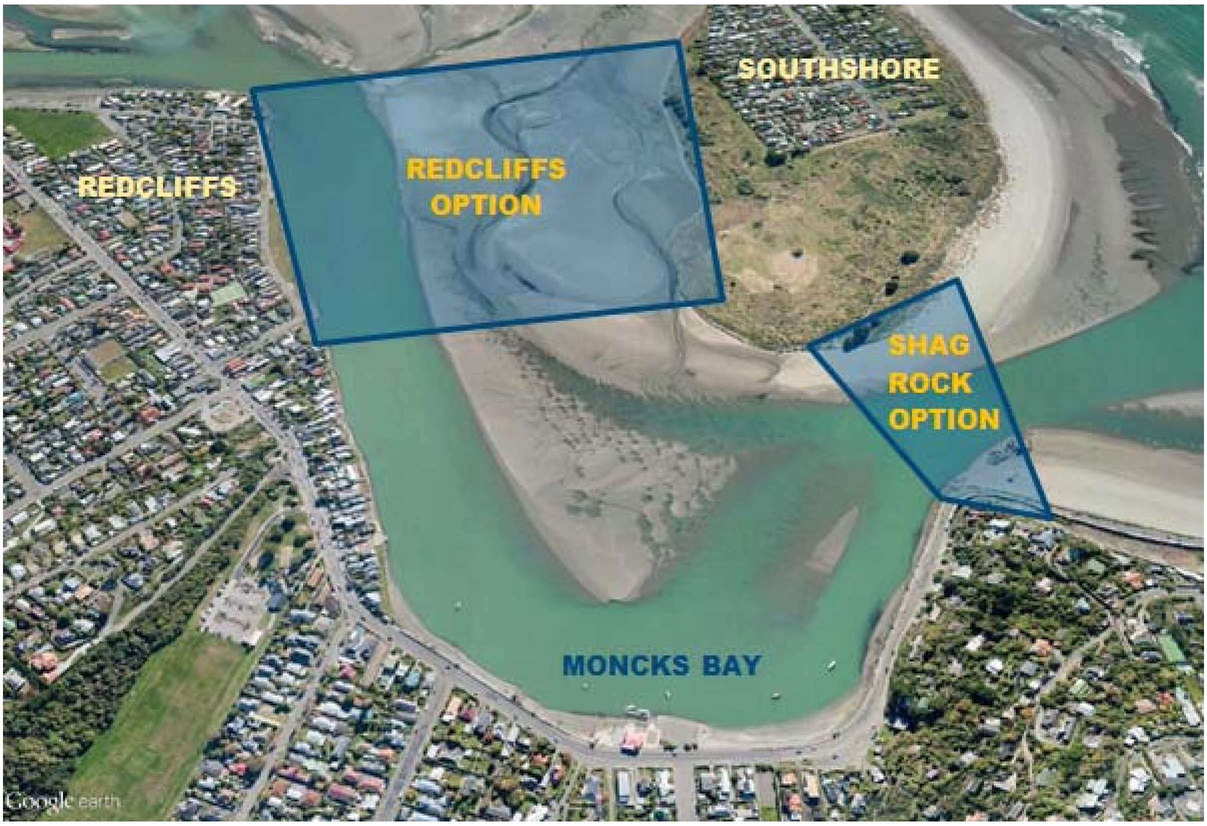


Figure 10 - Barrier location options

No option was considered through Moncks Bay because of the requirement to span a much longer length than either of the other two options, with no apparent benefit. The options are depicted as areas rather than alignments because for the purposes of this pre-feasibility study specific alignments were not determined.

The 1963 Christchurch Drainage Board report (Scott, 1963) proposed a barrier in the Redcliffs area.

4.3 Comparison of options

A comparison of the Redcliffs and Shag Rock location options with regard to key criteria is presented in Table 5 below. Within Table 5 the green colour represents a 'favourable' comparison, while the red colour represents an 'unfavourable' comparison. Any future project phases would need to revisit these options (and others) taking into account the results of further investigations.

Table 5 Comparison of location options

Criteria	Shag Rock	Redcliffs
Length	Shorter length – 250 m total, with 90 m shallow & 160 m deep	Longer length – 600 m total, with 430 m shallow & 170 m deep
Utilisation of estuary volume	Maximises use of estuary volume	11% reduction in estuary volume at 1.6 m LVD
Sand spit connection	Connected to a section of the spit known to actively migrate	Connected to a section of the spit stable throughout the last century
Connection to high ground at the south	High ground immediately adjacent to the shore	Connection required through houses or along waterfront to high ground
Geotechnical stability	Dense sands – more stable with no liquefaction potential and less foundation treatment required	Liquefiable sediments – less stable with liquefaction potential and foundtation treatment required
Channel stability	Channel margins known to be dynamic	Channel margins consistent
Exposure to open ocean	Relatively large exposure to ocean waves and coastal processes	Largely sheltered, peak ocean wave heights mitigated
Tsunami exposure	Exposed to tsunami with broad face toward likely direction of approach	Partially sheltered with narrow face toward likely direction of approach
Currents	Very strong tidal currents (2-3 m/s)	Less strong tidal currents (1-2 m/s)
Navigation	Obstructs passage of yachts between Moncks Bay and the ocean	Obstructs passage of tall vessels between Moncks Bay and the estuary
Pedestrian / vehicle passage	Potential "lifeline" link Sumner to Southshore, however connection is constrained at Shag Rock end	Limited potential as a "lifeline" connection, however much better space availability at Redcliffs end
Visual impact	Obstructs view to horizon from inside the estuary, but potentially less visible otherwise (and smaller)	Some sight lines from within estuary maintained, however more visually obtrusive otherwise (plus larger)
Potential to "soften" embankment	Exposure to ocean will require a solid / hard engineered embankment	More sheltered location allows for softer embankment options
Constructability / cost	Constraints at the Shag Rock end plus a highly dynamic estuarine environment would make construction complex / expensive	Additional space on land coupled with more benign estuarine conditions would make construction less complex / expensive

On the basis of this comparison it was decided that the Redcliffs option is preferable. This option was adopted for consideration through the pre-feasibility assessment process.

4.4 Configuration

At the Redcliffs location a barrier would consist of three components; gates, embankment and abutment extension. Figure 11 below shows two recent bed level cross-sections at Redcliffs (in orange and grey) with the gates and embankments overlaid. The crest level of the structure for present day conditions has been set at 2.4 m LVD, which is the 200 year annual exceedance probability (AEP) storm tide level of 1.9 m LVD plus a 0.5 m allowance for storm wave heights (the basis for these figures can be found in Section 3.1). The figure also shows the 1 m additional height added to the gates and embankment to allow for sea level rise. Each of the components is described in more detail in the following sub-sections.

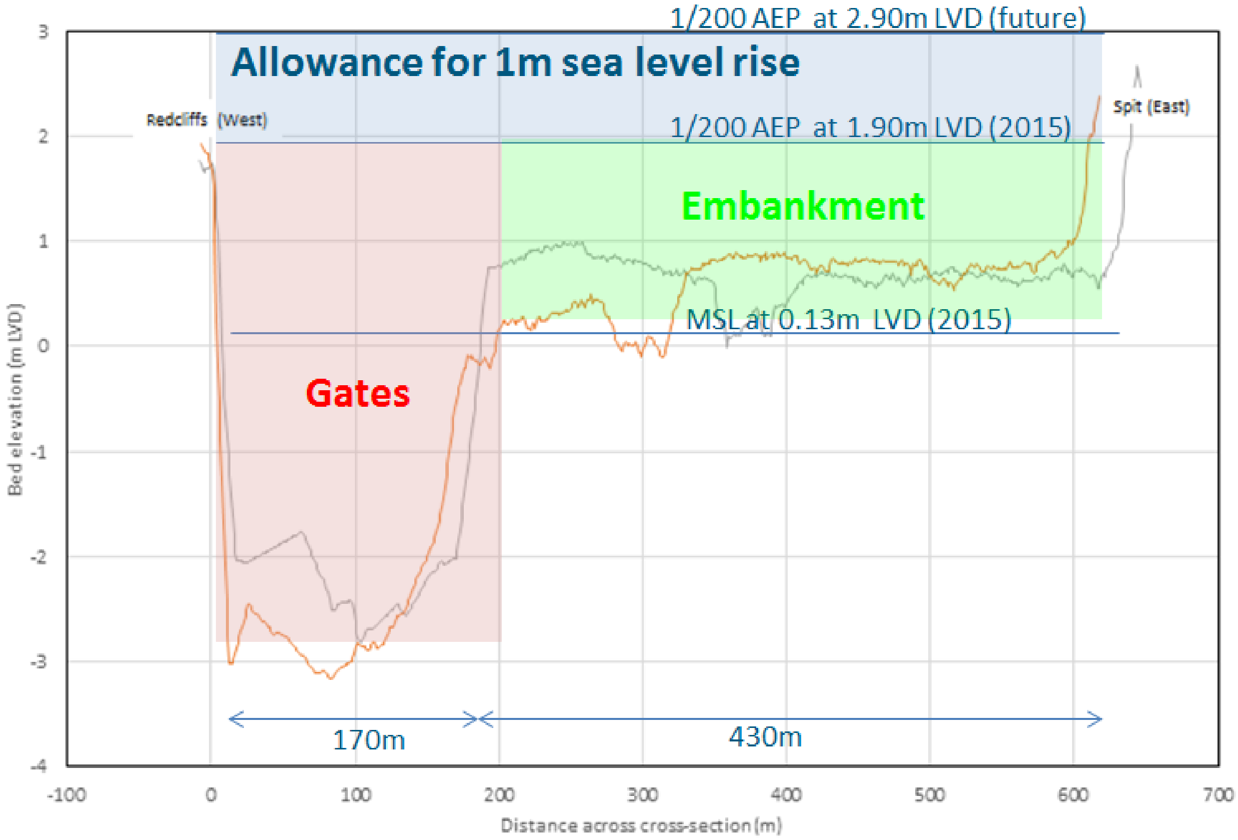


Figure 11 - Redcliffs cross-section showing barrier components

4.4.1 Gates

The gate component of the barrier is the portion that opens and closes to regulate water levels in the estuary. It is located in the deep part of cross-section as this is where approximately 95% of the flow passes on a daily basis. In order to regulate flow through the channel the gates will need to extend approximately 3 m below mean sea level to match the current channel invert. The gates will also need to extend approximately 3 m above mean sea level in order to effectively stop water inflow to the estuary in high tide with storm surge under a 1 m sea level rise scenario. The options analysis for gate configurations is presented in Section 5.

4.4.2 Embankment

The embankment is the component of the barrier that connects the gates to the spit at Southshore. Although there is potential to pass minor flows through the embankment, it would generally form a continuous obstruction across the estuary. Use of an embankment avoids the need to extend the expensive and complicated gate structure the entire distance across the estuary, when this additional distance only currently conveys 5% of the total flow. The embankment would be founded at the existing estuary base level, which is largely above present mean sea level across this portion of the section. The crest will need to be constructed to approximately 3 m above mean sea level, in order to effectively contain the high tide with storm surge under a 1 m sea level rise scenario. The options analysis for embankment configurations is presented in Section 6.

4.4.3 Redcliffs abutment extension

As the existing ground surface is relatively low at the Redcliffs end of the barrier it would be necessary to extend the abutment to a point where it connects with the 2.9 m LVD contour. Due to the hydraulic conditions which would prevail on the seaward side of the barrier it would also be necessary to heighten the existing sea defences along Beachville Road to a height of approximately 2.4 m LVD for present sea level conditions. Over time the defences would need to be raised to 3.4 m LVD to provide continued protection in a 1 m sea level rise scenario. Specific options for achieving these outcomes are beyond the scope of this study; however the general impact of such measures were considered as a part of the pre-feasibility impact assessment. Figure 12 below depicts the general arrangement of on-shore flood protection measures at Redcliffs that would be associated with the barrier.

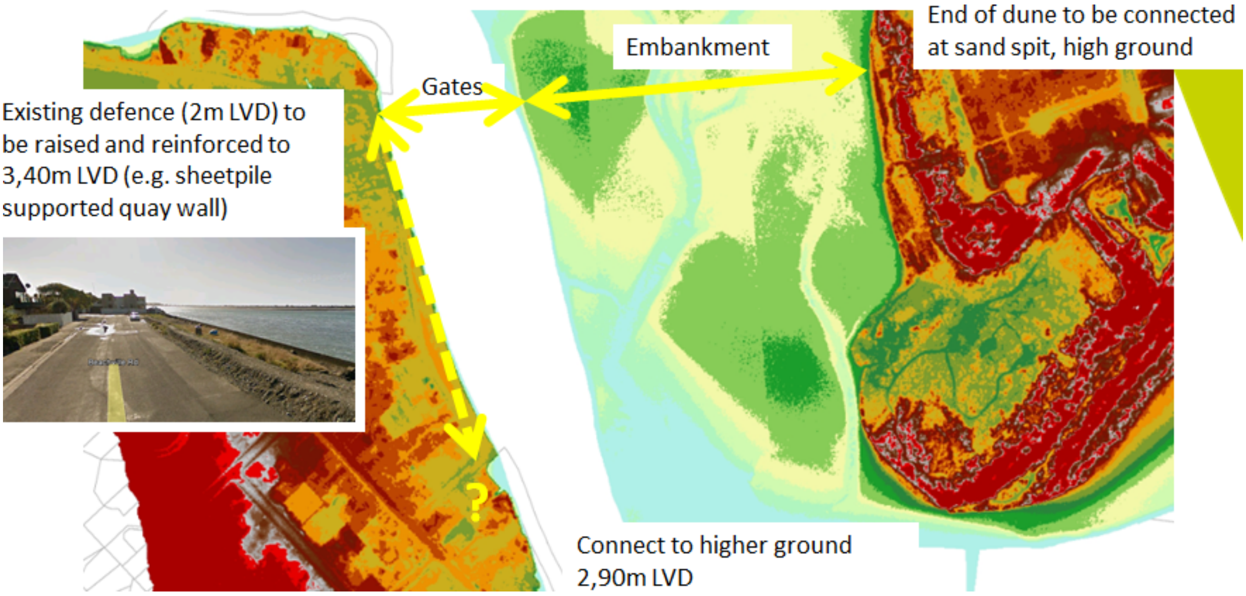


Figure 12 - On-shore flood protection measures at Redcliffs

Consideration was also given to the potential for failure of the barrier arrangement due to overtopping of the sand spit remote from the barrier location (for example in the vicinity of New Brighton). Tonkin and Taylor (2013, p.43) addressed the likelihood of this occurring, concluding that "[a] rise in mean sea level is not expected to have any effect on inundation risks from storm events due to the existing dune crest elevations being above predicted storm surge levels."

5. Configuration Options – Gates

This section provides a summary of technically feasible barrier types in use around the world, and outlines the decision process for selecting a gate type to be considered for this pre-feasibility assessment. Other barrier type options, such as river mouth pump stations may also be feasible, and should be considered in any future project phases.

5.1 Gate Options

5.1.1 Vertical lifting gate

Criteria	**Description**		
Physical Description	Lifted vertically from the sill to open. A tower with overhead cables, sheaves and bull wheels supports the gate during its operation to enable the lifting.		
Photo	  Example: Hartel Barrier – Rotterdam, the Netherlands		
Functionality	**Pros:** Can handle heavy loads, no problems with overtopping. Sedimentation of the sill is not a problem. Can be closed in a current. Can also be combined with a road to increase functionality (this would require additional structures), since navigation is already impacted upon. Requires relatively limited space.		
Proven Technology?	Proven technology.	**Maintenance**	As the gates are above the water, it is easy to maintain.
Closing time	Relatively short (minutes).	**Visual impact**	High – with visible gate and large towers up to 9 metres in height.
Limitation to navigation	Navigation limited when open as the structure is above the water. One gate could be raised slightly higher (say 2 m) to allow passage of paddleboards, kayaks, etc.		
Expandability	Possible to expand in the future. If sea level rise is accounted for in the design of the foundations and supporting structures, an increase in gate height could come later.		
Feasibility at Redcliffs	Feasible – proven technology which is relatively simple to maintain and provides the necessary functionality.		

5.1.2 Vertical rising gate

Criteria	Description
Physical Description	Gates lie beneath the sill in open position. They are lifted vertically to close the barrier. When in both open and closed positions, the gates are positioned largely under the water.
Photo	 Example: Saint Petersburg Flood Protection Barrier, Russia
Functionality	**Pros:** No problems with overtopping. Can be closed in current. Require relatively limited space. **Cons:** Could be possible issues with keeping sedimentation out of the recess. Difficult to construct and maintain because of its submerged structure. Can be combined with a road, although then negatively impacting on its ability for allowing passage of vessels.
Proven Technology?	Known maintenance and operation challenges with constructed examples.
Maintenance	Difficult to maintain as the gate is below the water in a recess.
Closing time	Closing time is relatively short (minutes).
Visual impact	Medium - visual intrusion restricted to structures on either side of the estuary as the gate lies below the water (has to be lifted above water for maintenance).
Limitation to navigation	No limitation to navigation when the gate is open.
Expandability	Difficult to expand it in the future.
Feasibility at Redcliffs	Not favourable – due to known difficulties with construction, maintenance and operation in high sediment environments.

5.1.3 Inflatable gate

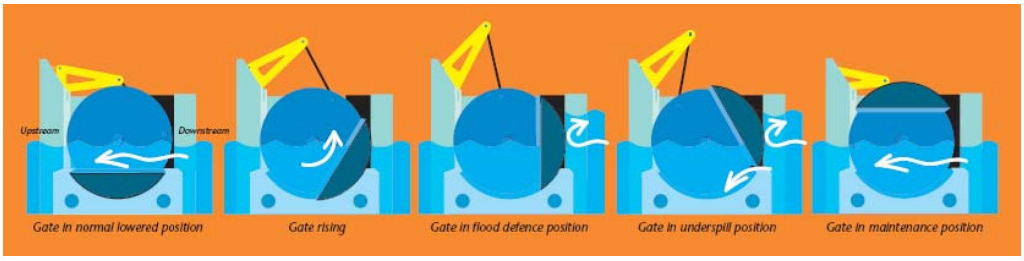
<table>
<tr><th>Criteria</th><th colspan="2">Description</th></tr>
<tr><td>Physical Description</td><td colspan="2">A sealed tube made out of a flexible material: synthetic fibre, rubber or laminated plastic stored below the water. Anchored to the sill and walls by means of anchor bolts and an air and watertight clamping system. The gate is inflated with air, water, or a combination of the two.</td></tr>
<tr><td>Photo</td><td colspan="2">
Example: Ramspol, the Netherlands</td></tr>
<tr><td>Functionality</td><td>Pros: No problems with overtopping. Requires relatively little space. Can handle heavy loads. Not subject to wind. No hinges.</td><td>Cons: Can be combined with a road although then negatively impacting on its ability for allowing passage of ships. Possible issues with sedimentation due to its closed position under water. Intermediate opening at low water during a storm not possible. High frequency use (say daily/weekly) not possible due to maintenance.</td></tr>
<tr><td>Proven Technology?</td><td colspan="2">Some operating examples. Technologically simple in comparison to other options.</td></tr>
<tr><td>Maintenance</td><td colspan="2">Difficult to maintain as the tube is stored below the water. Relatively short life span. Extensive inspection after each closure.</td></tr>
<tr><td>Closing time</td><td colspan="2">Relatively long closing time.</td></tr>
<tr><td>Visual impact</td><td colspan="2">Low - no visual intrusion as it is under the water most of the time.</td></tr>
<tr><td>Limitation to navigation</td><td colspan="2">No limitation to navigation when the gate is open. When closed, risk of ship collision causing damage.</td></tr>
<tr><td>Expandability</td><td colspan="2">Possible to expand in the future by installing a larger tube, but complex.</td></tr>
<tr><td>Feasibility at Redcliffs</td><td colspan="2">Feasible – technically inferior to some other options due to slow gate operation, but considered the most likely of the low visual impact options due to its superior ability to withstand sediment impacts relative to other subsurface options.</td></tr>
</table>

5.1.4 Segment gate

Criteria	Description
Description	Rotates around a horizontal axis which passes through the bearing centre. In recess the segment gate rests in a sill and in open position it is lifted.
Photo	  Examples: Woolston Barrage, Christchurch and Haringvlietdam, the Netherlands
Functionality	**Pros:** Less susceptible to sedimentation. Can be closed in current. Can be combined with a road. Requires relatively little space. Can handle heavy loads.
Proven Technology?	Proven technology.
Maintenance	Easy to maintain as the gate is held above the water.
Closing time	Relatively short closing time.
Visual impact	High - significant visual intrusion due to its height and width.
Limitation to navigation	Limitation to navigation when open.
Expandability	Possible to expand in the future. By taking into account sea level rise in the design of the foundations and supporting structures, this leaves the option to increase height of gates later.
Feasibility at Redcliffs	Not favourable, based upon visual impact.

5.1.5 Rotary segment gate

Criteria	Description
Description	Gate rotates around a horizontal axis, which passes through the bearing centre. In recess the gate lays in a sill, allowing navigation. It can be lifted up above the water for inspection.

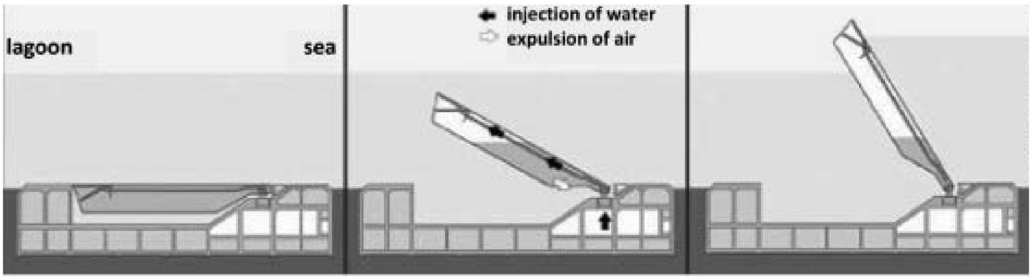
<table>
<tr><td>Photo</td><td colspan="2">


Example: Thames Barrier, England</td></tr>
<tr><td>Functionality</td><td>Pros: Less issues with sedimentation. Can handle heavy loads. Can be closed in a current. Can be combined with a road on the side.</td><td>Cons: Problems with overtopping. Requires a relatively large space. Complex to construct.</td></tr>
<tr><td>Proven Technology?</td><td colspan="2">Sufficiently proven, though not extensively adopted.</td></tr>
<tr><td>Maintenance</td><td colspan="2">Gate can be lifted above water making the gate easier to maintain.</td></tr>
<tr><td>Closing time</td><td colspan="2">Relatively short closing time.</td></tr>
<tr><td>Visual impact</td><td colspan="2">High – with large structures (both height and width) above the water.</td></tr>
<tr><td>Limitation to Navigation</td><td colspan="2">In recess the gate lays in a sill, allowing navigation.</td></tr>
<tr><td>Expandability</td><td colspan="2">Difficult to expand in the future.</td></tr>
<tr><td>Feasibility at Redcliffs</td><td colspan="2">Feasible, although works on the sill could be quite complicated.</td></tr>
</table>

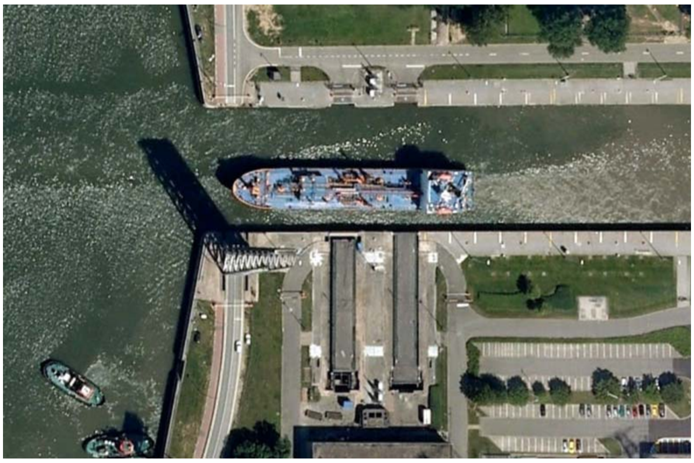
5.1.6 Sector gate

Criteria	Description
Description	A double gate, circular shape. Transfer forces through a steel frame to the hinges at each side of the opening. Operates by rotating around two vertical axes.
Photo	 Example: Rotterdam Barrier, the Netherlands
Functionality	**Pros:** Less problems with sedimentation as the gates rest on land in recess when open. Can handle heavy loads. No problems with overtopping. **Cons:** Cannot be closed in current. Two circular gates are not connected to each other, leakage of water through a large (2m) gap. Large structure requires a lot of space on land. Difficult and complex design to construct due to stability issues. Could be combined with a bridge although then negatively impacting on its ability for allowing passage of ships.
Proven Technology?	Proven in a small number of applications.
Maintenance	Easy to maintain as the gates rest in recess on land.
Closing time	It can be closed in about one hour, including travelling and sinking. Preparations take longer (filling of docking chambers).
Visual impact	High - very large structure on land, with 10 m high gates.
Limitation to Navigation	No limitation to navigation when open.
Expandability	Difficult to expand in the future.
Feasibility at Redcliffs	Not feasible – obtaining the necessary space on land for storage of the open gates is considered to be unfeasible.

5.1.7 Flap gate

Criteria	Description
Description	Flap gates are hinged along the upstream edge of the gate and attached to a sill foundation. They are stored submerged and flat to the bottom. To close the flow, the downstream edge is rotated upward.
Photo	 Example: Venice, Italy
Functionality	**Pros:** Require relatively limited space. **Cons:** Problems with sedimentation and maintenance as it is stored underwater. Cannot handle heavy wave loads. Problems with overtopping. Cannot be closed in a current. Cannot be combined with a road although then negatively impacting on its ability for allowing passage of ships. Complex to construct as it is new technology.
Proven Technology?	Venice is nearing completion, under water caissons have been placed recently. Still unproven.
Maintenance	As the gate is stored underwater, it is difficult to maintain.
Closing time	Relatively short.
Visual impact	Low - no visual intrusion as the structure is located underwater when open.
Limitation to Navigation	No limitation to navigation when open.
Expandability	Difficult to expand in the future.
Feasibility at Redcliffs	Not feasible – due to potentially large issues with sedimentation and the unproven nature of the technology.

5.1.8 Rolling gate

Criteria	Description
Description	Rolling gates are closure panels stored adjacent to the waterway. They are rolled into position in anticipation of a flood event.
Photo	 Example: Port of Antwerp, Belgium
Functionality	**Pros:** Can handle heavy loads. No problems with overtopping. Require relatively limited space. **Cons:** Problems with sedimentation. Cannot be closed in current. Can be combined with a road bridge although then negatively impacting on its ability for allowing passage of ships.
Proven Technology?	Proven technology.
Maintenance	Gate stored on land, easy to maintain.
Closing time	Relatively short.
Visual impact	High – with large gates on land.
Limitation to Navigation	No limitation to navigation when open.
Expandability	Expandable in height in future.
Feasibility at Redcliffs	Not feasible – the maximum length of a rolling gate is approximately 60 m.

5.1.9 Swing gate

Criteria	Description
Description	Caisson/boat stored on one side of a waterway, pivoting around a vertical axis to close.
Photo	 Example: Mississippi, New Orleans, USA
Functionality	**Pros:** No problems with sedimentation. No problems with overtopping. Require relatively limited space. Simple construction. **Cons:** Cannot be closed in current. Cannot be combined with a road on the top. Intermediate opening at low tide and closing again during storm difficult (can be achieved using additional gates on the caisson/boat). Visual intrusion due to its length and storage location, for most parts above still water level.
Proven Technology?	Technically simple concept, though unproven in this context.
Maintenance	Easy to maintain as gate stored along the water edge.
Closing time	Relatively long closing time.
Visual impact	Medium – gates visible at all times.
Limitation to Navigation	No limitation to navigation when open.
Expandability	Possible to expand in the future by taking into account sea level rise in the design of the foundations and supporting structures; leaving the option to increase height of gates for later.
Feasibility at Redcliffs	Not feasible – the manual closing procedure does not provide sufficient certainty of operation during storm conditions.

5.2 Comparison of shortlisted options

The three options considered feasible based on the criteria considered in the previous section were:

- Vertical lifting gate (Section 5.1.1);
- Inflatable gate (Section 5.1.3); and
- Rotary segment gate (Section 5.1.5).

Further comparison of these three options, with regard to key criteria, is presented in Table 6 below.

Table 6 Comparison of shortlisted gate options

Criteria	Vertical lifting gate	Inflatable gate	Rotary segment gate
Reliability	Simple, proven, quick to close – very reliable	Slow to inflate - less reliable	More complex, but still quick to close – reliable
Maintainability	Mostly above water – simple to maintain	Partly stored below water – but limited maintenance required	Can be raised above water level to perform maintenance
Expandability for further sea level rise or EQ land damage	Possible to expand	Possible to expand by replacing tube, complex	Possible to expand
Low tide outfall	Can be quickly opened to allow outfall when tide levels drop	Would require an additional structure to allow low tide outfall	Can be quickly opened to allow outfall when tide levels drop
Resistance to sedimentation	Closing process flushes sediment from sill – good resistance	Sedimentation may slow deployment – acceptable resistance	Sedimentation may cause operations and maintenance issues
Visual intrusion	Large structure, stored mostly above water – highly intrusive	Almost entirely stored subsurface – low intrusion	More scope to mitigate visual impact, but still quite intrusive
Navigation	Could be designed to pass kayaks, but will inhibit all larger craft	Will not inhibit passage of any type of craft	Could increase the level of hazard associated with passage of craft
Pedestrian / vehicle passage	Pedestrian / vehicle passage could potentially be included	Pedestrian / vehicle passage not possible	Pedestrian / vehicle passage could potentially be included
Construction cost	100%	70%	200%
Constructability	Some complexity with achieving bottom seal.	Some complexity because of the extent of work below bed level.	Some complexity due to greater levels of mechanisation.

Note: all options were considered to have comparable impacts on estuary morphology and ecology.

Upon consideration of their relative merits, the vertical lifting gates were selected as the most appropriate option to be considered by the pre-feasibility assessment process. For all criteria, except visual intrusion and navigation considerations, the vertical lifting gate is considered equal or superior to the inflatable and rotary segment gate options.

6. Configuration Options – Embankment

Gates are to be constructed to allow for:

- Tidal movements;
- Discharge of flood flows; and
- Sediment transport.

The remaining stretch of the barrier consists of an earthen embankment. An embankment reduces capital cost, visual impact, environmental footprint, and can be constructed to fit with local surroundings.

6.1 Embankment Options

The embankment would need to be approximately 430 m long joining the gate structure at the Redcliffs side of the estuary to the shore on the Southshore side. At the interface between the gates and the embankment there would need to be a transition between hard engineered gate structure and the softer and wider embankment.

The embankment would be founded on 5-6 m deep mud flats (sandy silts), which are prone to liquefaction during an earthquake. The sandy silts are underlain by dense sand layers.

This section describes the types of embankments potentially suitable for use at the Redcliffs site, and outlines the decision process for selecting an embankment type to be considered for this pre-feasibility assessment.

6.1.1 Traditional embankment

The traditional embankment option is what most members of the public would envisage when thinking of an embankment, as it would resemble the types of stopbanks seen along many New Zealand rivers. In the case of the barrier it would have a 3 m wide crest, with slopes rising 1 m in height for every 3 m of width (1 in 3) side and rock protection extending most of the way up the seaward side and part way up the estuary side. To achieve the required 3 m height above mean sea level it would need to be 21 m wide (also at mean sea level). Figure 13 below shows typical sections through traditional embankments.

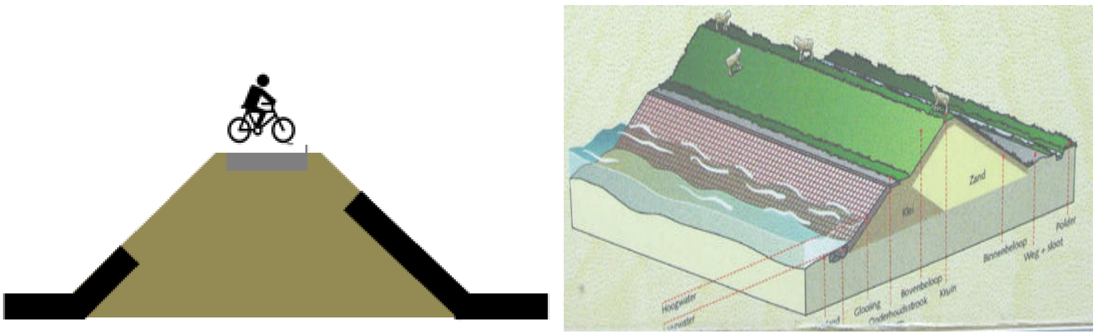


Figure 13 - Traditional embankment example cross sections

6.1.2 “Eco embankment’

The “Eco embankment” is effectively the traditional embankment with flatter slopes to allow for the introduction of some diversity. These shallower slopes could be protected in part using vegetation and other natural materials, limiting the need for rock protection. There would still be a hard crest as per the traditional embankment option, but the side slopes would be approximately 1 in 12, resulting a structure approximately 75 m wide (at mean sea level). Figure 14 below shows typical sections through the “Eco embankment” concept.

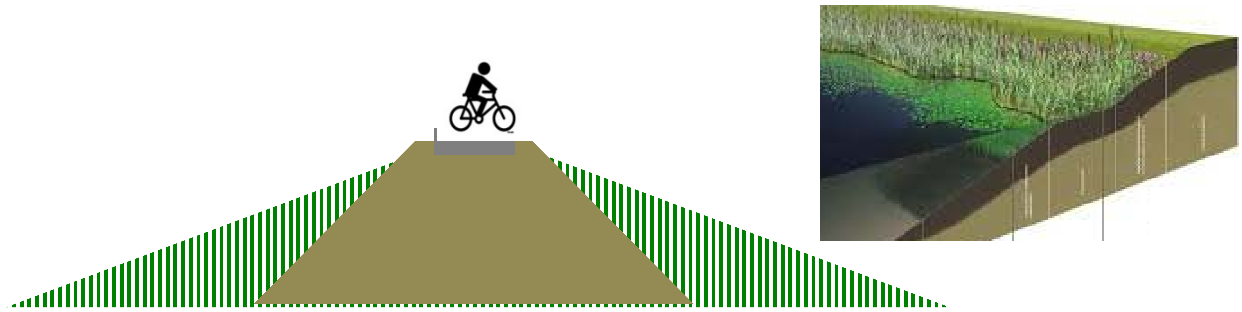


Figure 14 - "Eco embankment" example cross sections

6.1.3 Dune

The dune concept is intended to mimic a natural dune system. It would be constructed of imported material of a composition similar to the adjacent sand spit. Initially the dune would be constructed to be approximately 200 m wide. Over time the dune would be allowed to naturally develop its own form, with only minimal intervention to ensure that it remains connected to both the gates and Southshore. The intention is that eventually the dune would appear to be a natural extension of the spit. Figure 15 below and to the right shows an example dune cross section and artist’s impression.

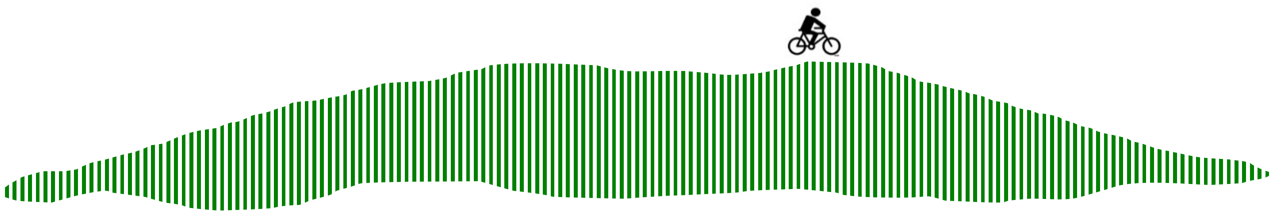


Figure 15 - Dune example cross section and artist's impression

6.2 Comparison of shortlisted options

A comparison of the three embankment options described in the sub-section above with regard to key criteria is presented in Table 7 below.

Table 7 Comparison of embankment options

Criteria	Traditional embankment	"Eco embankment"	Dune
Geotechnical requirements for EQ resistance	Requires densification of subsoils	Requires densification of subsoils	Can be constructed on natural material
Maintenance requirements	Maintenance as per typical embankment	Combination typical and ecologically sensitive maintenance	Minimal maintenance, needs to be ecologically sensitive
Area of disturbance	Minimal physical footprint	Intermediate physical footprint	Maximum physical footprint
Morphological / ecological integration	Nil	Some allowance for ecological integration	Good allowance for morphological and ecological integration
Aesthetic impact	Least aesthetic appeal	Reasonable visual integration	Good visual integration
Cost	Densification and revetment works increase cost	Requires densification and naturalisation works	Cost savings by avoiding densification[1]

[1] The cost effectiveness of this option will be dependent on the cost and availability of large quantities of suitable construction material. Construction works could be phased over a longer period in time, based on availabilities of materials. Alternatively it may be possible to win material from historical fill sites adjacent to other parts of the estuary.

For all criteria except area of disturbance, the dune option was considered to be equal or superior to the traditional embankment and "Eco embankment" options. In the case of the area of disturbance for the dune, it was considered that the impact of the additional footprint is outweighed by the morphological and ecological benefits. On this basis the dune option was selected for consideration through the pre-feasibility assessment process.

6.3 Layout options

Additional connections through the embankment could be considered to allow tidal flow to cross the embankment at several locations. Such connections (e.g. culverts) could be advantageous from the environmental point of view. However, these connections would have to be closed too when the barrier is closed. This would introduce additional mechanical elements in the barrier and reduce its reliability. Furthermore, structural measures would be necessary to prevent seepage along these structures.

These additional connections do not significantly impact on the overall barrier concept, so can be left to be considered as part of a later, more detailed, optimisation stage.

7. Operating Philosophy

This section discusses possible scenarios for how the barrier will be opened and closed to manage flood risk. This is to inform the assessment of the likely effectiveness and impacts (Section 9), which will be reliant on an understanding of the range of possible barrier operating scenarios.

Present day conditions would only require infrequent use of the barrier. While the operating philosophy could be agreed in principal today, practical implementation of the philosophy will need to evolve over time, based on environmental considerations, predicted climate change and sea level rise.

To take account of this change the following subsections discuss barrier operation in the present conditions and in an assumed future condition, which includes a 1 m rise in sea level. This rise in sea level was selected as it is consistent with Council's current assumed sea level rise for planning purposes. The timeframe for this change in sea level is not important to this analysis as gradual adaptation and/or changes in operating philosophy will be possible to match sea level rise at it occurs. Future project phases would need to consider sea level rise timing as it influences economic considerations.

7.1 Present conditions

Under present conditions the barrier would be closed to protect against three scenarios: tidal flooding (including storm surge), river flooding and tsunami.

7.1.1 Tidal flooding

To protect against tidal / storm surge flooding the barrier would be closed when abnormally high tides are expected, generally due to storm tides. The as built level of the temporary Avon River stopbanks is 2.16 m LVD (equivalent to 11.2 m CDD). Since construction, localised slumping and loss of material from the top of the temporary stopbanks, mean that the maximum contained water level is now 200 mm lower than the design height – 1.96 m.

Allowing for 400 mm freeboard it would be necessary to operate the barrier when the tide level is expected to exceed 1.56 m. As discussed in Section 3.1 the 1 year return period storm tide height is 1.61 m, hence under present conditions the barrier could be expected to close to protect from tidal flooding slightly more than once a year on average. It would only be required to close for a single high tide cycle, and could be closed at mid-tide rather than low tide as it is not necessary to maximise available estuary volume as with the river flood scenario.

7.1.2 River flooding

To protect against river flooding in the Avon and Heathcote Rivers the barrier would be closed when high river levels are expected, generally due to high rainfall in either or both catchments. The frequency of closure would be determined by a range of factors:

- The desired level of flood protection – i.e. will the barrier only protect against major flooding or will it be used to reduce the frequency of nuisance flooding?
- The level of conservatism applied to rainfall forecasts – rainfall forecasting is not as precise as tidal forecasting, hence some allowance for inaccuracy in rainfall forecasts will need to be allowed, occasionally resulting in barrier closures which turn out to be unnecessary.

- The level of conservatism applied to river flood level models – complex and imperfect hydrological and hydraulic models are used to predict flood levels as a result of rainfall. Some allowance may need to be made for model inaccuracies.
- The level of conservatism applied to storm surge forecasts – there is also some inaccuracy in the prediction of storm surge (mainly caused by the inherent inaccuracy in the prediction of weather systems), so some allowance for inaccuracy in storm surge forecasts will need to be allowed, occasionally resulting in barrier closures which turn out to be unnecessary.

In the event that the barrier concept is progressed, further analytical work will be required to determine trigger conditions for barrier closure to mitigate river flooding. Based on historic knowledge, flood events in the Avon River have historically occurred once a year, on average. With the additional conservatism associated with the barrier operation being based upon forecasted events, an assumed frequency of operation of twice per year is adopted for the purpose of this assessment.

7.1.3 Tsunami

The barrier could potentially be closed when a tsunami warning is issued. This would be extremely infrequent and effectiveness of this would require further analysis. For further information refer to Section 10.5.

7.2 Future 1 m sea level rise

The effectiveness and impacts of the barrier operation will vary, depending on how the operation of the barrier is modified to adapt to sea level rise. Alternatives are outlined in the following subsections.

7.2.1 Retaining present day trigger levels

Climate change is predicted to cause increased storm flows within the rivers, while sea level change reduces the ability of the rivers to drain. Therefore, if the present day tidal and flooding trigger levels remain unchanged in the future, then the frequency of barrier closure will increase as climate change and sea level change occurs.

Even with increased rates of barrier closure, its capacity to mitigate flood risks is finite and in the face of continuing sea level rise flood risks will eventually begin to increase. This is because the minimum water level achievable inside the barrier (and hence the volume available for flood storage) is limited by the low tide level, which will increase with sea level rise. Whilst there would be some reduction in effectiveness relative to present conditions, there would still be significant reduction in future flood risk compared to a future scenario without a barrier. Due to the approximately linear height-storage relationship of the estuary, this future benefit would be of a similar magnitude to the present day benefit.

A more simplistic analysis can be applied with respect to mitigation of tidal flooding. If the 1.56 m trigger level (refer to Section 7.1.1) were to be retained then the frequency and duration of barrier closures would increase. Figure 16 below shows the number of tide events per year which exceed 1.6 m for a range of sea level rise scenarios up to 1.0 m. It shows that by the time sea levels have increased by 1.0 m all 705 tides in a year would exceed the trigger level. Figure 17 shows the percentage of time that the sea level will exceed 1.6 m for a range of sea level rise scenarios up to 1.0 m. In the 1.0 m sea level rise scenario the sea will be above the trigger level and the barrier closed for about 30% of the time (average of 3.6 hours per closure).

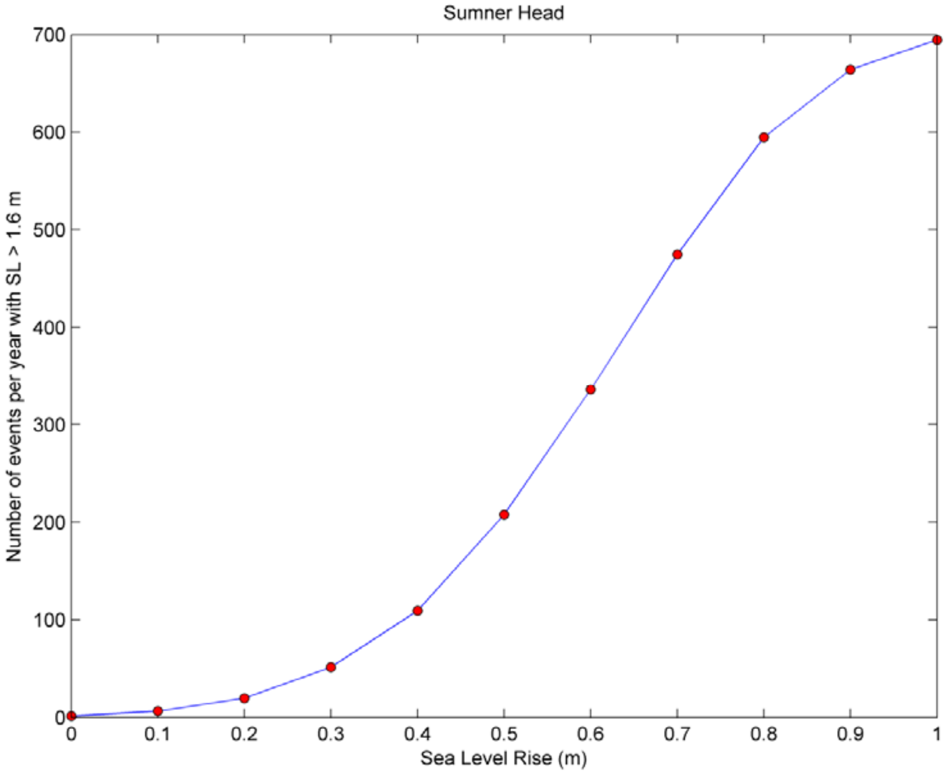


Figure 16 - Number of tidal events per year exceeding 1.6m LVD vs. sea level rise (m)

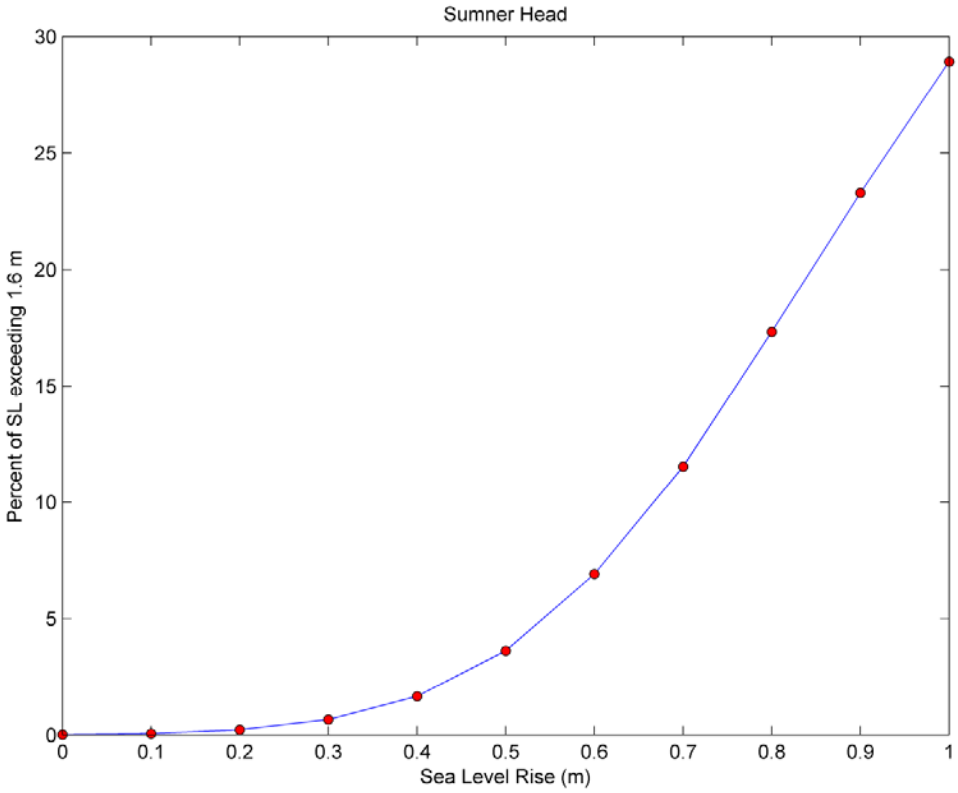


Figure 17 - Percentage of time that sea level will exceed 1.6m LVD vs. sea level rise (m)

7.2.2 Retain present day operating frequency

As an alternative to increasing barrier operating frequency to compensate for rising sea level, the barrier could be operated to retain (approximately) the present day operating frequency. In this scenario, as sea levels rise, flood risks would increase.

In order to mitigate future flood risks in this scenario other strategies would need to be adopted such as stopbank enhancements, pumping and retreat. These measures would be smaller and less expensive than would otherwise be required without a barrier.

7.2.3 Permanently closed barrier

A further alternative is to increase the frequency of barrier closure up until a point when it is then decided to permanently close the barrier to protect Christchurch from tidal inundation. In this scenario the estuary would become a freshwater system, with stormwater outfall to the ocean provided by flushing during low water, possibly combined with pumping across the barrier.

This option was discussed during this project's initial workshop process. It was agreed that the environmental impacts associated with permanently converting the estuary to a freshwater system would be unacceptable. As such the option of a closed barrier has not been explored further in this pre-feasibility assessment.

7.2.4 Combined approach

The most probable future operating philosophy will be a combination of the approaches described. With sea level rise the frequency of closure could be increased until an upper limit is reached, based on acceptable environmental effects.

Beyond this point some increase in flood risk could be tolerated, up until a point that this becomes unacceptable. Then other flood management measures, besides the barrier, will need to be implemented progressively to allow for further sea level rise and increased rainfall.

These other flood management measures could include retreat from flood prone areas and augmentation of other flood mitigations works (i.e. stopbanks, pumps). Such management measures would need to be planned and implemented well in advance to allow barrier operating criteria to meet the opposing goals of environmental and flood protection objectives.

The various present and future operating philosophies are summarised in Figure 18.

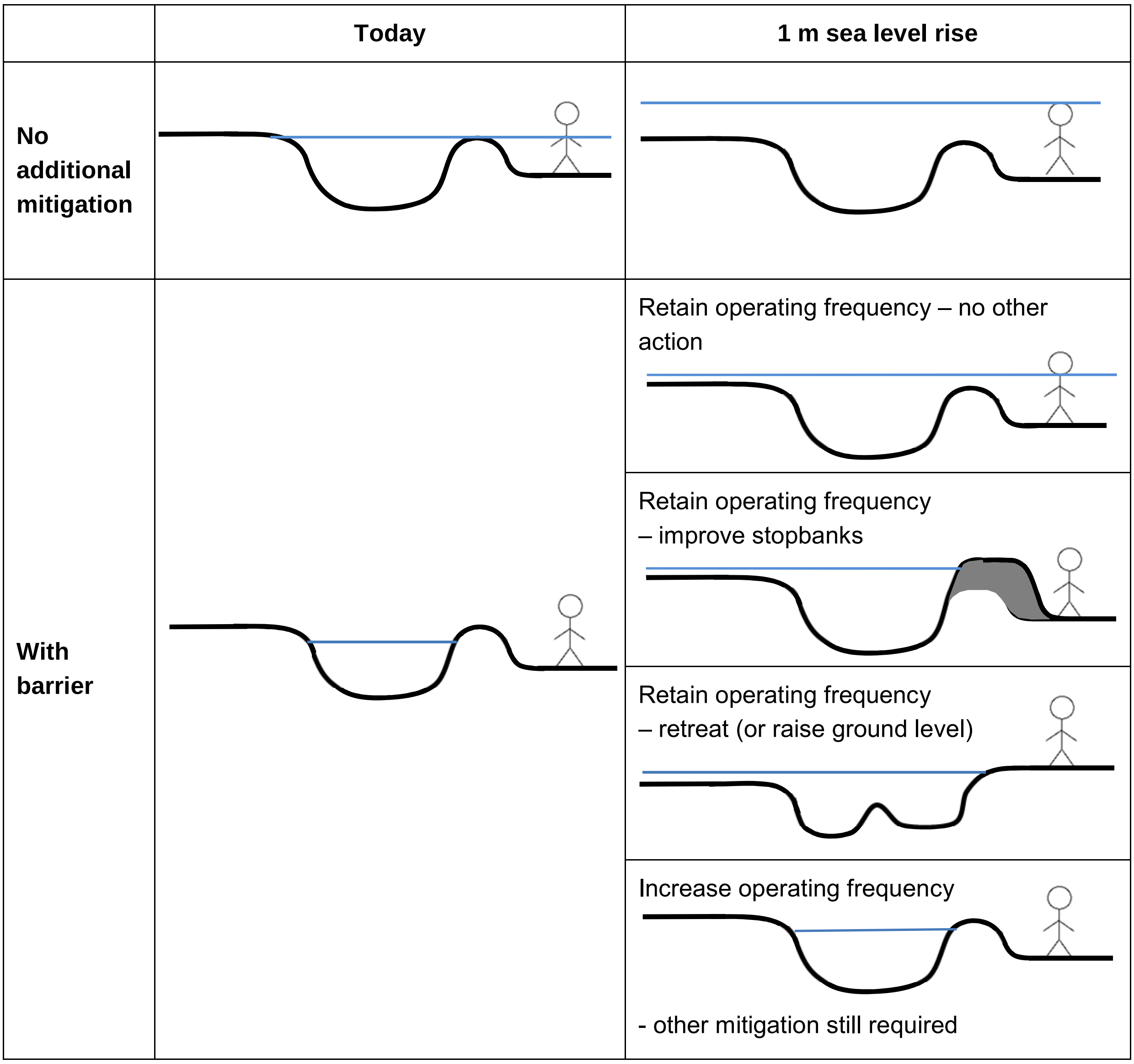


Figure 18 - Barrier operating philosophies

8. Pre-Feasibility Concept

A pre-feasibility concept was developed based on the information and assessments described in the previous sections of this report. The purpose of developing this concept was to allow assessment of the effectiveness, resilience and impacts of a tidal barrier in Christchurch. It represents a barrier that is considered most likely to be feasible based on the very limited investigations undertaken to date. With further work it may be found that this concept is not the most optimal barrier solution, however it is considered adequate for testing the pre-feasibility of the barrier concept, and if necessary informing the scope of further work.

8.1 Description

As described in Section 4.4 this barrier concept consists of gates, an embankment and abutments.

The vertical lift gate structure would be approximately 170 m wide spanning the main channel, anchored to the Redcliffs shoreline at one end and the newly constructed barrier embankment at the other. The gate structure's main component parts would include:

- A concrete sill founded in the channel floor at approximately -2.6 m LVD;
- Three bays approximately 50 m wide each;
- Each bay containing a 50 m wide gate, 6 m high, lifted clear of the water when the barrier is open;
- The crest of the gates when closed is 3.4 mLVD, allowing for the 200 year storm plus a 0.5 m allowance for storm wave heights and a 1 m allowance for sea level rise;
- One gate could potentially be lifted 2 m clear to allow passage of kayaks and other small craft;
- Four 9 m high piers holding the gates, one at each side and two at 50 m intervals across the channel; and
- A walkway attached to the piers (separate from the gate) to allow maintenance access and potentially a public pedestrian/cycle link.

The structure could potentially be constructed to allow for greater than 1 m sea level rise. This would have cost implications initially as improved foundations would be required, plus eventual cost implications when the pier and gate heights needed increasing.

The embankment would be a constructed dune linking one end of the gate structure to the spit at Southshore. It would be approximately 430 m long and up to 200 m wide. In time, as vegetation establishes and material migrates naturally, the dune will resemble and extension of the existing reserve. The crest height would be a minimum of 3.4 m LVD, with some higher undulations to promote a natural look. The walkway from the gate structure could be extended across the dune to complete the link between Southshore and Redcliffs.

The abutment would be an augmentation of the existing flood defences at Redcliffs to connect the gate structure with the 2.9 m contour. Options for achieving this include increasing the heights of the existing sea wall, coupled with localised raising of road levels.

Refer to Appendix A for visualisations of the proposed barrier structure.

8.2 Construction

The gate structure would be constructed within a temporary sheet-piled area. Dewatering (pumping) would be required to form a dry building site. The construction of the temporary dry area and permanent works within would be conducted using a phased approach to ensure open flow in and out of the estuary is maintained. Due to the reduced channel cross-section during construction, temporary bed and bank protection works would likely be required.

The dune would be constructed gradually as suitable quantities and appropriate material become available. The material could be placed on site using mechanical or hydraulic methods. Connection to the gates would be through a sheetpile structure to prevent erosion and seepage.

Construction timing would be largely driven by social and environmental requirements. Assuming 60% of the year is workable construction would be completed in 2 to 3 years.

8.3 Preliminary cost estimate (top-down)

A preliminary cost estimate has been prepared based on the following components:

- 170m gate structure (3 x 50m opening plus 20m for piers)
- 430m of embankment(construction of dunes)
- 1km floodwall reinforcements

The cost estimate has been based on an overview of cost of construction of tidal barriers around the world taken from the Journal of Coastal Research (Jonkman S.N. et al., 2013). Table 8 below summarises unit costs of various barrier structures.

Table 8 Barrier unit price costs (million euro per m (2009))

Structure	€M/m
Ramspol's (inflatable gate)	0.55
Eastern Scheldt Barrier (lifting gates)	1.82
Hartel barrier (lifting gates)	0.84
N.O. Seabrook barrier (lifting/sector gates)	0.88
Ems (sector gates)	1.02
Thames (Rotary segment gates)	2.73
Venice (flap gates)	1.46
Maeslant Barrier (floating sector gates)	1.82

The Hartel Barrier, which had a 143 million euro construction cost (at 2009 price level) is the most similar to the Avon-Heathcote pre-feasibility concept. It has a similar total width of spans, though the concept barrier is shorter and has a lower head difference. The Christchurch concept has more complex site conditions, more hydraulic dynamics and a phased construction approach.

The basis of quantities for the construction of the dune assume approximately 400,000 m^3 of material will be required. Beach/foreshore nourishment in the Netherlands typically costs between 3-7 euro per m^3 and elsewhere in Europe between 4-11 euro per m^3. On this basis the cost of construction for the dune component of the works is estimated to be 5 million euro.

Reinforcement of 1km of flood defences estimated at 5 million euro.

The total estimate for construction works is 153 million euro (2009), which after adjustments for construction price increases, international construction price indices and foreign exchange equates to 300 million New Zealand dollars (Statistics New Zealand, 2014; XE, 2015; ARCADIS, 2014).

8.4 Preliminary cost estimate (bottom-up)

Due to uncertainties about the comparability of European and New Zealand construction costs (used to determine the top-down estimate in the previous sub-section) a bottom-up cost estimate was also completed to improve confidence in the preliminary cost estimate. This estimate was generated using the following methodology:

- Detailed design drawings for similar structures and construction activities were reviewed, including:
    - Construction drawings for the Yongam Barrier in South Korea were used to inform potential characteristics of the gate structure;
    - Arrangement information for the Hartel Barrier in the Netherlands was also referenced as a gate structure example;
    - SCIRT design information for the Main Road Causeway Seawall Renewal was used to inform supplementary works such as the embankment extension;
    - SCIRT design information for the South Brighton Bridge was used to inform bridging, piling, coffer dam and abutment elements.
- A schedule of quantities was developed by considering the major components likely to be required if the pre-feasibility concept were to be constructed. Where the concept was sufficiently resolved or where relevant background information existed the quantities were broken into base units. Otherwise lump sums were assumed.
- Unit rates for the various schedule items were obtained from Christchurch/New Zealand sources, including:
    - SCIRT rates (including various projects working adjacent to the estuary);
    - Rates from Fulton Hogan developed during the Avon Stopbanks Refinement project;
    - Rawlinsons (2014).
- Unit rates were applied to the schedule of quantities to determine a base cost estimate for the embankment, gates and Redcliffs stopbanks;
- Additional allowances were added for preliminary and general works, construction contingency, design and consenting.

Design assumptions (in addition to the design description in Section 8.1) used in the construction estimate were:

- Four composite piers holding the gates founded at -4.0m LVD. The base of each pier is 46m long by 10m wide and 8m high with a top level at 4.0m VLD. The upper part of each pier (which lifts the gate clear of the water) is 18m long by 6m wide and 9m high;
- A 170m wide by 46m long and 1.5m thick concrete sill with a top level of -2.6 VLD founded on a 1.0m thick gravel foundation layer;
- Piled foundation 20m deep under the concrete sill at 2.0m spacing and piled foundation 20m deep under the piers at 1.0m spacing;
- Rock channel/scour protection for 46m on the sea side of the sill and for 40m on the estuary side of the sill;
- An 8.0m wide pedestrian/cycle/maintenance bridge spanning the piers; and
- Flood defence stopbanks 1000m long on the Redcliffs side of the estuary with associated drainage and road modifications

The estimated cost of the pre-feasibility concept (including barrier gates, a dune embankment and flood defences for a 1km stretch along Redcliff's) is NZ$310M. A breakdown of this cost estimate can be found in Table 9 below.

Table 9 Barrier construction cost estimate

Description	**Cost $M NZD**
Preliminary and general (20%)	43
Dune embankment	19
Gate structure	132
Redcliffs stopbank	11
Construction contingencies and miscellaneous (25%)	54
Construction sub-total*	**260**
Design (10%)	25
Consenting & Community Consultation (10%)	25
Total tidal barrier cost estimate (millions NZD)	**310**

* Further breakdown of this estimate can be found in Appendix B.

The construction cost estimate was peer reviewed by Beca, with a likely expected cost range at pre-concept stage of $300M to $350M. The barrier cost estimate has been revised to incorporate a number of the Beca peer review comments, in particular allowances for temporary works in the estuary, construction contingency, preliminary and general costs and allowance for design and consenting.

A number of uncertainties were identified during the cost estimation process. In consideration of these uncertainties the contingent amounts listed in the table above have been allowed. Key uncertainties include:

- Construction methodology through the estuary for the gate structure has assumed to be sheet piled works in sections. A larger diversion may be possible which would reduce the cost of construction for the gate structure, but potentially increase environmental impacts and/or costs to construct mitigation works.
- Supply and construction rates were adopted from projects generally of a smaller nature. Some efficiencies may be gained, and hence rates reduced, as a result of the scale of this project.
- Material source for the dune embankment is uncertain. It may be possible to source material from elsewhere in the estuary, for example from historical sediment disposal sites in the Bexley area. The suitability of this material and environmental impacts of removal and transport would need to be investigated in a future stage of work.
- Ground treatment options (and hence costs) will need to be confirmed once detailed on-site geotechnical investigations have been completed.

Annual operation and maintenance cost estimates are as follows:

- Gates at 1-5% of the capital construction cost ($1.5M to $7.0M per annum); and
- Embankment at 1% of the capital construction cost ($0.25M per annum).

8.5 Operations and maintenance considerations

The construction works for the barrier could be done through a Design, Construct and Maintenance (DCM) type of tender process. By doing so, flexibility would be given to the contractors that are best equipped and positioned to deliver high quality engineering and construction solutions. From a technical perspective, the construction of a barrier could be done in different ways. In a DCM contract the contractor decides on a preferred method within the given contractual boundaries on technical, environmental and for example stakeholder issues. Depending on the contractor's eagerness and other factors, such as cost, risks, working programs and available equipment, it is expected that the Council will receive competitive and technically challenging proposals to choose from.

As part of the Design, Construct and Maintenance contract the contractor is tasked to ensure for (for example) 10 years after completion of the construction works of the barrier, that the entire system will perform all its functionalities (as per scope of functional specifications) to the required standard.

A breakdown of all structural and contractual objects in the system provides the contractor with all contractual obligations that shall be met during the span of the contract. It can be left up to the contractor to decide on the methodology, schedule and priorities of the services to be provided in order to make sure that all system functionalities are met. These would include:

- From year one onwards (after completion of construction works) the contractor will carry out all in maintenance activities (structural, electrical and mechanical etc).
- Most likely the contractor will apply a risk based, probabilistic approach in which the most crucial (based on probability of failure and expected consequences) elements of the system are maintained at high level. The relevant items will be listed in the functional specifications of the contract documents.

- The maintenance contract will most likely highlight time restrictions in relation to working times during storm seasons.
- The contractor will have to show system performance of the barrier on an annual basis.

8.6 Control Systems

The decision to close and open the barrier should be based on an accurate prediction of storm magnitude and duration, and the expected rainfall runoff from the Heathcote and Avon rivers. This could be fully automated in a control system making real-time predictions using the meteorological predictions and water level measurements which are fed to a computer model. Typically, such systems provide predictions which are updated every 10 minutes.

The entire operation of the barrier can be automated. The decision to close and open the barrier gates can be taken either by the responsible manager upon a warning from the prediction system (human decision making), or by an automated system which excludes the human factor. A fully automated system has been implemented for the Rotterdam Barrier. Also an intermediate option is possible: the decision is made by the responsible manager, but the barrier is equipped with a fail-safe system – if a critical condition for closure has been exceeded and the barrier has not yet been closed by the manager, an automatic closing procedure will start (such a system is implemented in the Eastern Scheldt Barrier in the Netherlands).

The barrier needs regular testing of the systems. At least monthly, the barrier will need to be closed under controlled conditions to test all critical systems.

An emergency power backup system is of critical importance, since the power supply might fall out during extreme storm conditions.

9. Pre-Feasibility Assessment – Effectiveness

This section contains outcomes from the first part of the pre-feasibility assessment of the barrier concept described in Section 8, addressing the question “will the barrier work to reduce flood risk?”

9.1 General methodology

The effectiveness of the barrier for flood mitigation was assessed by comparing its effectiveness against alternative flood mitigation measures. In the flood prone areas adjacent to the Avon River and the Estuary, the barrier effectiveness was tested by comparing stopbank / floodwall requirements with and without a barrier. In flood prone areas adjacent to the Heathcote River, the barrier effectiveness was tested by comparing house raising requirements with and without a barrier. Figure 19 below shows the steps completed to conduct this assessment. Each step is described in more detail in the following sub-sections.

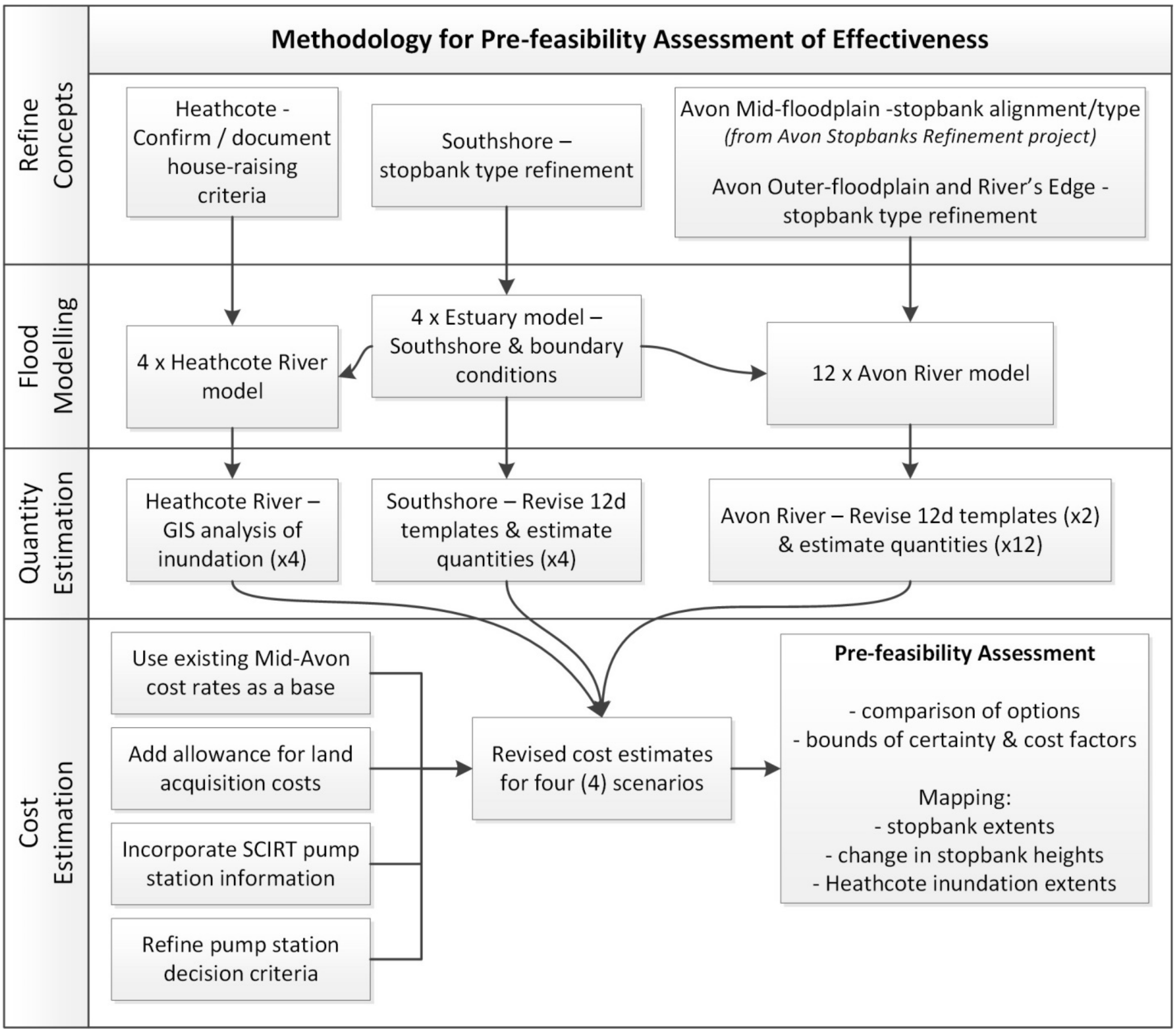


Figure 19 - Methodology for Pre-feasibility Assessment of Effectiveness

9.1.1 Sea level rise

An assessment of barrier effectiveness was considered under current climate conditions and also assuming 1 m of sea level rise. This is consistent with the barrier requirements described in Section 3.2, which are based on a report by Tonkin and Taylor on the *Effects of Sea Level Rise for Christchurch City Council* (Tonkin and Taylor, 2013). The Tonkin and Taylor report draws upon earlier guidance provided by the Ministry for the Environment in the report titled C*oastal hazards and climate change: A guidance manual for local government in New Zealand* (MfE, 2008).

This resulted in four scenarios being assessed:

- Without barrier, no sea level rise;
- With barrier, no sea level rise;
- Without barrier, 1 m sea level rise; and
- With barrier, 1 m sea level rise.

This assessment provides analysis of either extreme regarding sea level rise. Any subsequent work completed to assess barrier feasibility will need to consider intermediate sea level rise scenarios, including barrier operating procedures under these scenarios.

9.1.2 100 year rainfall and tide

In order to determine 100 year average recurrence interval (ARI) water levels, it was necessary to assess high water levels caused by both rainfall and tidal / storm surge effects. In order to conduct this assessment two models were run for each scenario:

- 100 year rainfall and 10 year tide; and
- 10 year tide and 100 year rainfall.

Upon completion of each set of model runs, the results were combined and the “peak of peaks” determined - representing the highest water level observed in either scenario.

The implementation of this approach is described further throughout the flood modelling section (Section 9.3) below.

9.2 Refine concepts

To provide a basis of comparison it was necessary to refine the non-barrier flood defence concepts. In the case of Avon and Southshore areas the flood defence measures assessed were mostly stopbanks, with some sections of floodwall along the southern shore of the Estuary where there is insufficient space available for stopbanks. In the Heathcote area the flood defence measure assessed was house raising.

Along the Avon River three stopbank alignments were assessed, one along the river’s edge, another along the outer floodplain and the third through the mid-floodplain. The river’s edge and outer floodplain stopbank alignments were adopted from the River and Tidal Flood Protection project (GHD, 2013).

The Avon River Stopbank Refinements project (GHD, 2015) undertook an exercise of rationalising the alignment and type of the stopbanks for the mid-floodplain option. This exercise included updating the stopbank types for various geotechnical conditions and refinement of the alignment due to various drivers such as protection of additional Council assets and minimising the impact on mature trees. This revised stopbank concept was adopted for this project to estimate Avon River mid-floodplain stopbank costs for the four barrier / sea level rise scenarios.

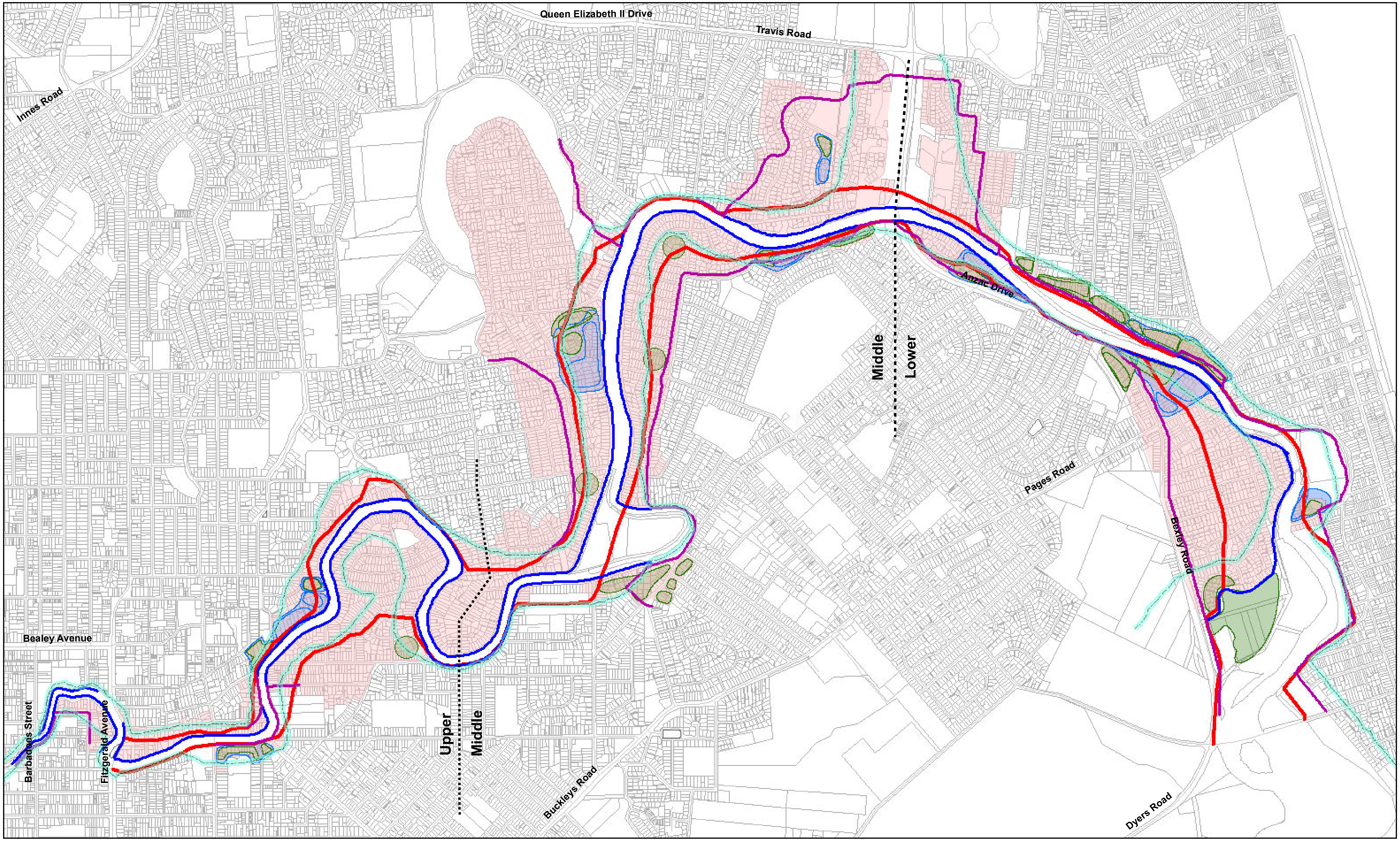
The Avon River Stopbank Refinements project revised the types of stopbanks proposed based on geotechnical considerations. In order to apply the refinements project's cost model to the river's edge and outer floodplain stopbank alignments it was necessary to review the available geotechnical information along the length of each alignment and assign "new" stopbank types as appropriate.

In Southshore the stopbank alignment from the River and Tidal Flood Protection project was adopted. As described above for the Avon River alternate stopbank alignments, it was necessary to reassess the relevant geotechnical information in order to assign "new" stopbank types along the Southshore stopbank for use in the cost model.

The figures on the following pages show the Avon River and Estuary stopbank and floodwall alignments used for the purposes of this assessment.

Cross-section drawings showing the three stopbank types used can be found in Appendix C.

For assessment of flood impacts along the Heathcote River it was necessary to determine which house would require individual mitigation measures. The Mayoral Flooding Taskforce established criteria for house-raising, however these criteria were in terms of post-quake frequency of inundation. In order to determine the number of houses requiring raising under the various barrier / sea level rise scenarios for the purposes of this assessment, it has been assumed that any house with an estimated floor level below the modelled flood surface in a given scenario will require raising.



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Metres

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

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- Lateral Spread Constraints
- Outer Floodplain Stopbanks
- Rivers Edge Stopbanks
- Mid Floodplain Stopbanks

Land Zoning

- Residential Red Zone

Stormwater Ponds

- Detention or first flush
- Wetland

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Christchurch City Council
Avon-Heathcote Barrier Pre-feasibility Study

Job Number	51-33273
Revision	A
Date	27 Jul 2015

Preferred Stopbank Alignment

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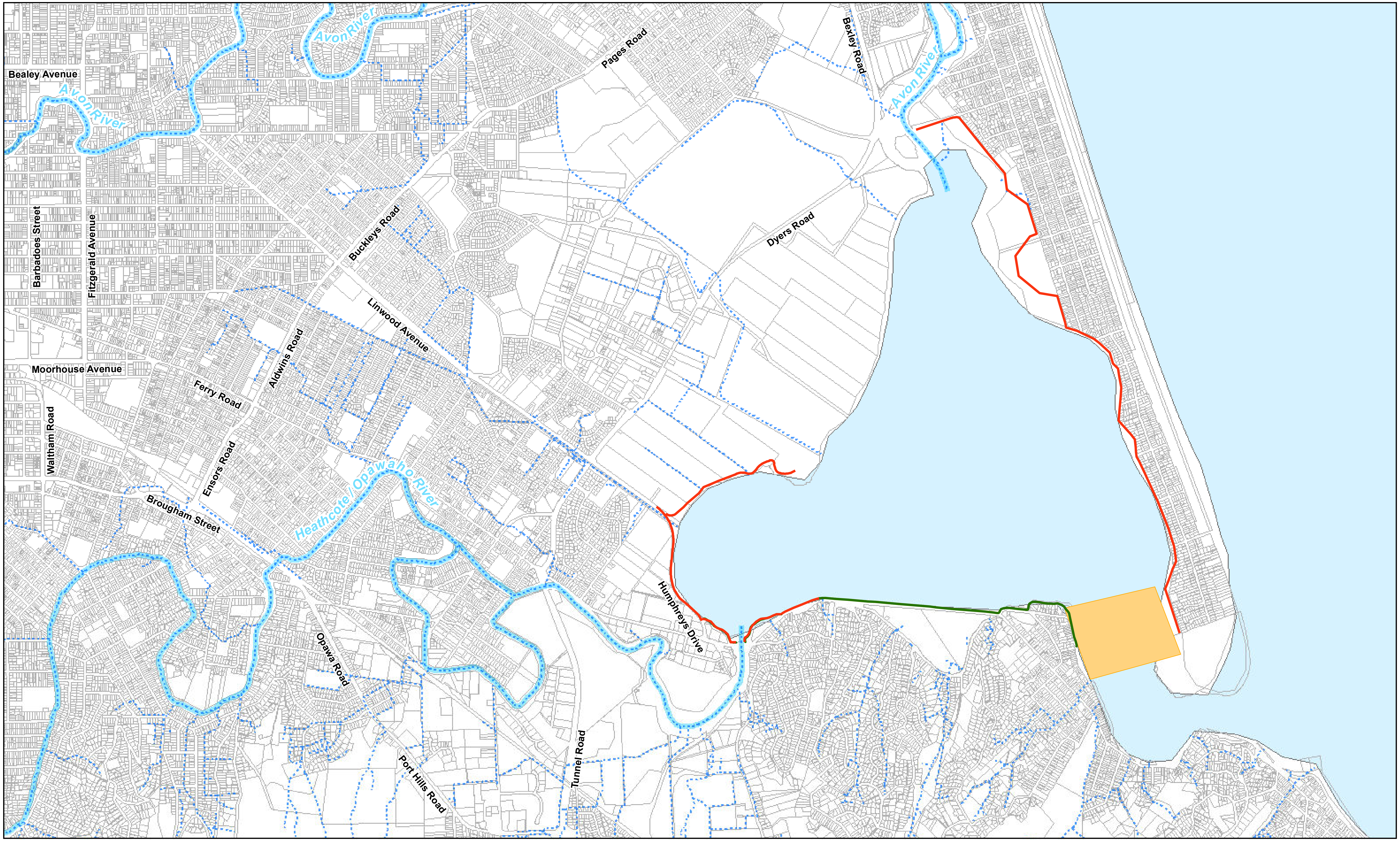
Data source: CCC: Red Zone DBH_TC_Zones_2012_10_31_PR_NZTM (Oct 2012), Land Parcels (July 2014), Stormater Ponds redzone dwg.dwg (Oct 2014): GHD: GHD_MidFloodPlainAlignments_20141028 (Oct 2014), Edited_Streets_RetainedRoads_20141031 (Oct 2014)



Paper Size A3

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Metres

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

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Legend

Option Design

- Stopbanks
- Floodwall
- Approximate Assumed Barrier Location
- Parcels

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Christchurch City Council
Avon-Heathcote Barrier Pre-feasibility Study

Job Number	51-33273
Revision	A
Date	14 Jul 2015

Concept Avon River Stopbank Alignments

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Data source: CCC: Parcels Layer. GHD Tidal Levels, Derived From Post Dec 2011 LIDAR Supplied by CCC, Existing Seawalls, Created by: Gareth Payne, Erika Tonson

9.3 Flood modelling

In the case of the Avon River and Estuary environs flood models were run in order to determine the extent and height of stopbanks required under the various barrier, sea level rise and stopbank alignment scenarios. For the Heathcote River environs the flood model was run to determine the extent and depth of flooding under the various barrier and sea level rise scenarios.

The effectiveness of the barrier for flood mitigation was assessed by simulating its operation during a 100 year return period fluvial flood. As an initial step, 10 year and 100 year ARI flows were extracted from existing results files for the Avon and Heathcote Rivers and input into the estuary model. The estuary model was then run for the various barrier and climate change scenarios to produce four sets of estuary boundary conditions consistent with the four scenarios described in section 9.1.1. The estuary model results were then fed back into the river models as a downstream boundary condition to simulate tailwater conditions with/without the barrier and 1 m of sea level rise. This process is described in more detail in the following subsections.

9.3.1 Estuary

The NIWA/ECan Avon Heathcote Estuary model uses the open source Delft3D hydrodynamic modelling software and has been set up to run in 2D (depth averaged) or 3D (5 vertical layer) modes. The model extends from Buxton Terrace on the Heathcote River and Gloucester Street on the Avon River out to approximately 15 km offshore from the estuary mouth. The model has a resolution of approximately 25 m in the estuary and 5-10 m through the estuary mouth. Further details about the model and its calibration are contained in Measures (2013).

Two versions of the estuary model were used representing the situation with and without the barrier. The baseline, no-barrier model used the existing post-earthquake model (Measures 2013). The barrier model was created by incorporating a number of changes:

- The bed elevation was modified to give a level bed elevation of -2.6 mLVD in the main channel at the location of the barrier. Over a 50 m distance either side of the barrier the bed was smoothed from its surveyed post-earthquake elevation to the sill elevation.
- The bed elevation was increased to 3 m at the location of the embankment connecting the barrier gates to the spit.
- ‘Dry points’ were specified at the locations of the barrier piers. A two gate, three pier arrangement was assumed in the model. The width of the piers was set equal to a single cell (approximately 7m). The differences between this assumed arrangement and the three gate, four pier arrangement that was finally adopted as our working example, are not sufficient enough to materially alter the findings.
- The barrier gate was simulated as a ‘3D gate’ structure in the model (see Deltares, 2014, for a description of how this type of structure is represented numerically). The bottom elevation of the gate was specified as a timeseries to represent the operation of the gate.
- Gate closure/opening from +2m LVD to -2.25m LVD was set to occur at a constant rate over a period of 30 minutes. This rate was based on the conclusion of the previous physical modelling study (HR Wallingford, 1970).

The Estuary model was used to generate 10 year and 100 year tidal conditions. River flow hydrographs for the 10 year and 100 year ARI floods were extracted from the Avon and Heathcote models at the location of the Gloucester Street and Buxton Terrace flow gauges respectively and used as inflows at these locations in the estuary model. The 10 year inflow was used for 100 year tidal run and the 100 year inflow was used for the 10 year tidal run (consistent with the approach described in Section 9.1.2). Inflows which enter the rivers downstream of the flow gauges were taken from the flow boundary conditions for the river models and input directly into the estuary model. This includes flows from the City Outfall Drain which is included within the Heathcote River model. No direct rainfall or stormwater/smaller catchment inflows directly to the estuary were included in the model as they represent a small portion of the total catchment area (3.8%) and would require additional hydrological analysis to develop inflow timeseries consistent with the river inflows. All river flows were based on the present day maximum probable development scenario.

Tide levels for the estuary model are specified at each end of the offshore boundary of the model. A tidal boundary was developed based on a spring tide experiencing surge which elevated it to a peak level of 1.762 mLVD, slightly lower than Goring's (2010) estimate of 20 year water level at Bridge Street Bridge and Ferry Road Bridge (1.826 and 1.768 mLVD respectively – see Table 3). The offshore tide level was set slightly lower than the desired level within the estuary to allow for river flow effects on water level. The peak of the surge tide was timed to coincide with the peak inflow from the rivers to the estuary (see Figure 22).

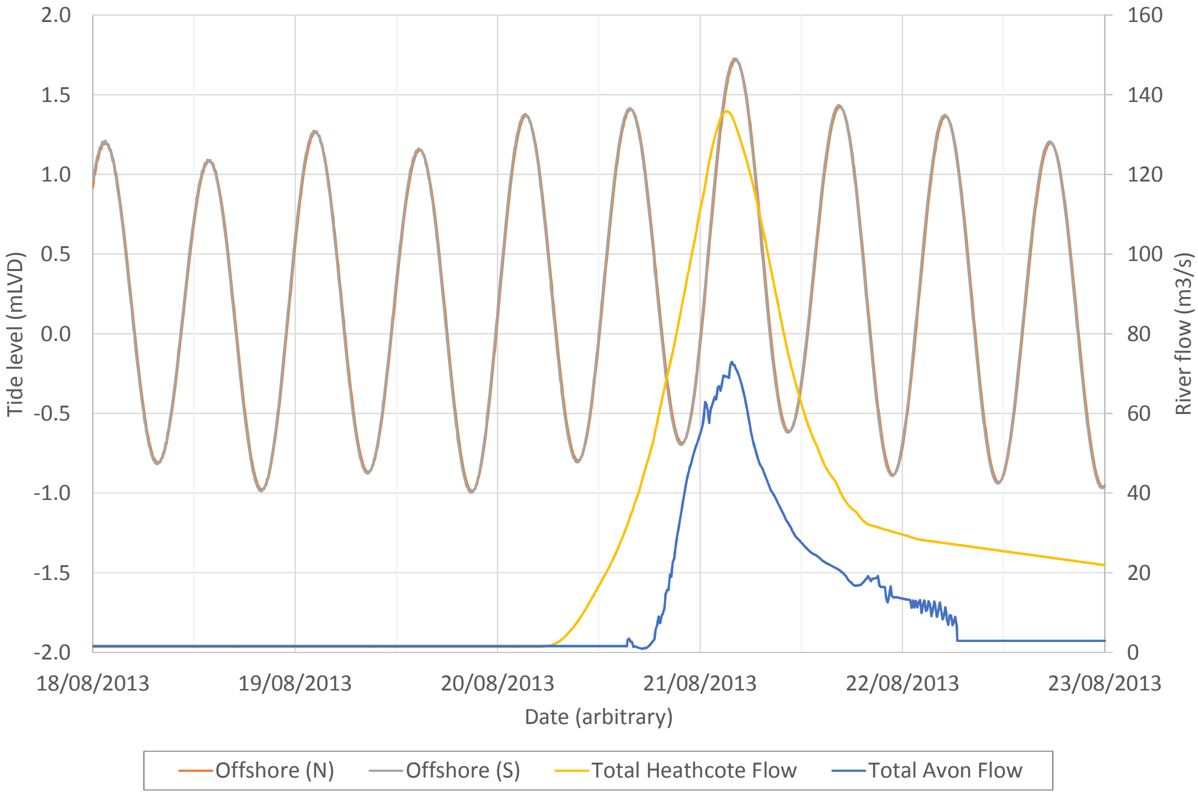

Figure 22 - Estuary model boundary conditions for the 100 year return period river flood, 10 year return period storm surge simulation

For the barrier closure scenario the barrier was set to close at low tide before the flood peak, reopen on the falling tide as the tide dropped below the level of the estuary then close again over the tide peak following the flood.

Figure 23 below shows the effect of the barrier on estuary water levels with 100 year river flows and a 10 year tidal surge. It is important to note that:

- The figure only shows levels for the downstream end of the Avon (at Bridge Street Bridge) for simplicity but level at the downstream end of the Heathcote River follows a very similar pattern.
- The modelled barrier is effective at supressing high tide throughout the estuary.
- Low tides are elevated at the river mouths by flood flow during the event (this is the cause of the difference between the orange and blue lines) – this is not accounted for in the boundary conditions of Council's current flood models.

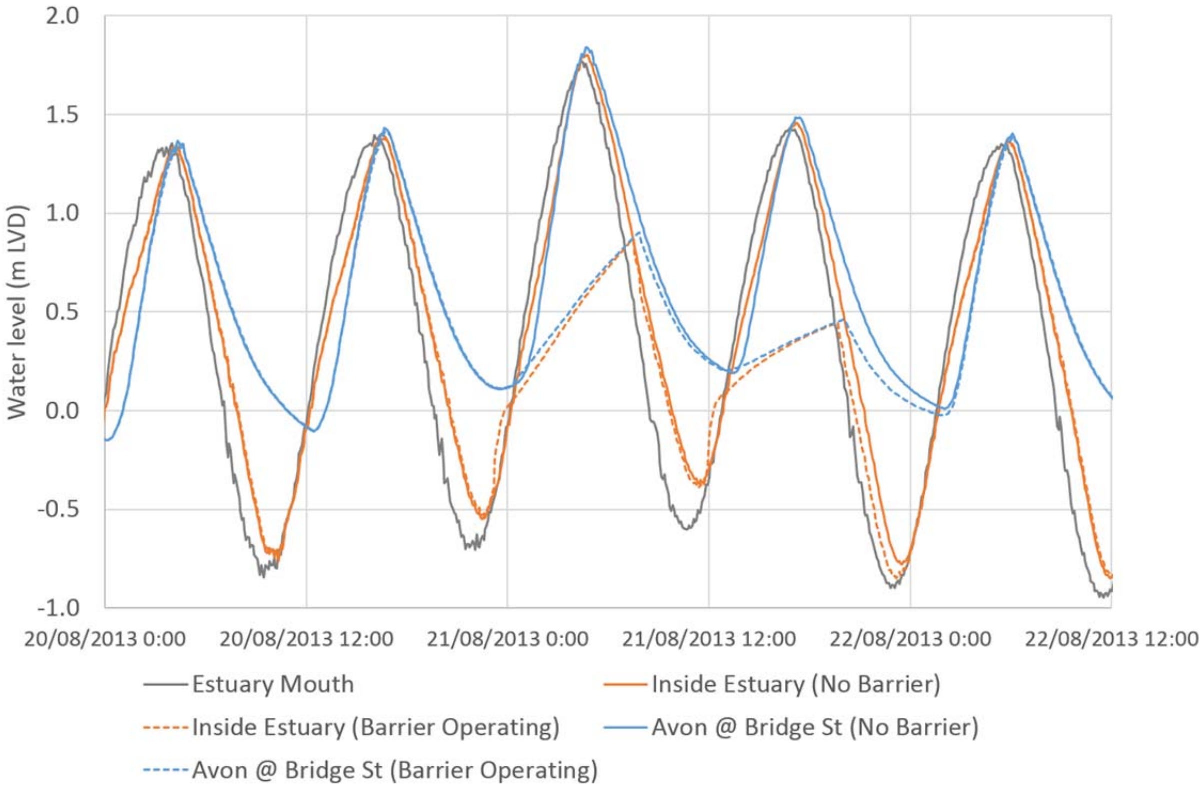

Figure 23 - Modelled estuary levels (with and without barrier, no sea level rise)

To assess the effectiveness of the barrier in the future, the 100 year flood was also simulated in the estuary model with and without the barrier for a 1 m sea level rise scenario. For this scenario the offshore boundary was raised by 1 m and all other boundary conditions, including the river flows, were kept the same. (Current day river flows were used as river flows with climate change allowance were unavailable for the Avon River at the time the modelling was carried out. Given the uncertainty associated with sea level rise estimates, the effect on estuary levels associated with changing flood flows as a result of climate change is likely to be small in the estuary model.) As the estuary water level exceeded stop bank levels during normal tide conditions before and after the flood it was assumed that the barrier operated on these tides as well to maintain a tide level inside the estuary below 1.6 m LVD.

Figure 24 below shows the effect of the barrier on estuary water levels during a 100 year river flows and 10 year storm surge event under a 1 m sea level rise scenario. It is important to note that:

- The barrier is still able to effectively control the high tide levels during a flood event with 1 m sea level rise.
- Tide peaks before and after the flood event have been concatenated at 1.6 m LVD for the barrier scenario on the assumption that the barrier closures would be increased in frequency and duration to maintain high water levels at present day thresholds. This is only one of various ways the barrier could be operated during normal (i.e. non-flood) conditions – see section 7.2 for further discussion of the different options for future barrier operation.
- With 1 m sea level rise the model shows that low water levels at the mouth of the Avon only increase by approximately 0.5 m. The reason for this is that with sea level rise the low tides are no longer elevated by river flows at the mouth of the rivers as the flow depth is greater. This change relies on the assumption that bed levels remain the same.

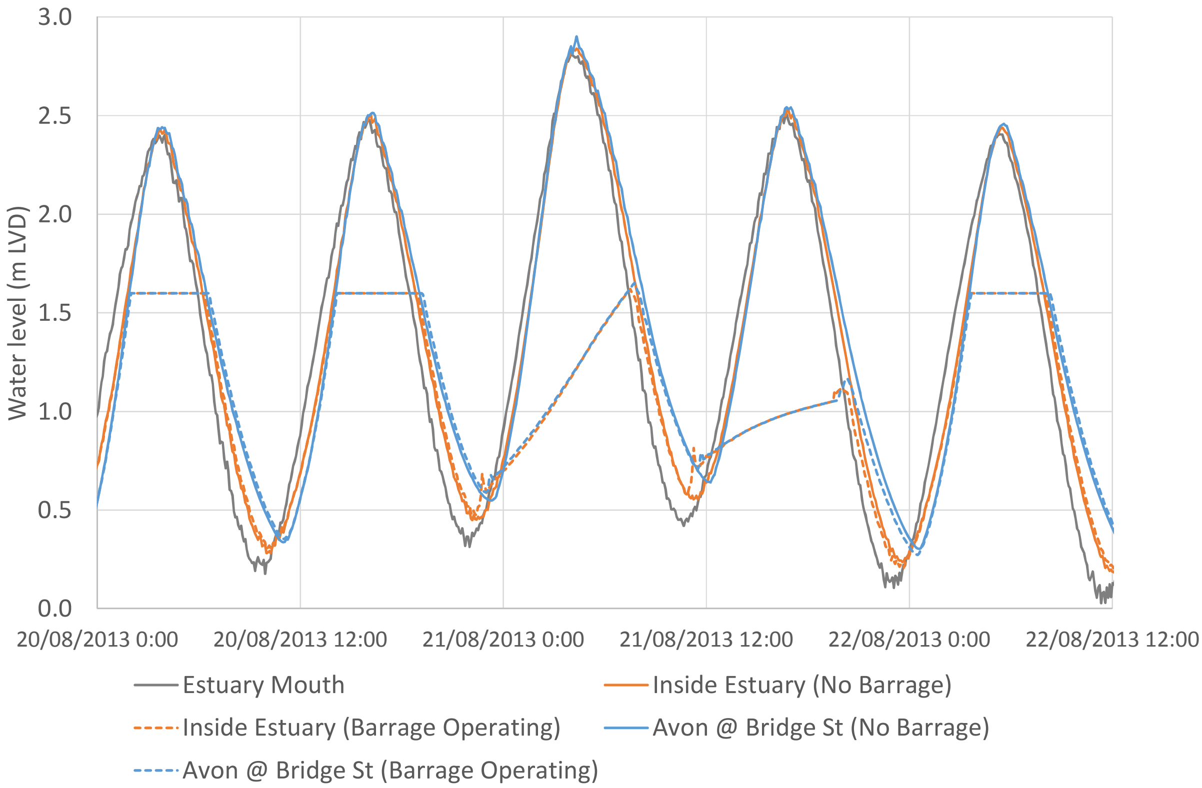

Figure 24 - Modelled estuary levels (with and without barrier, 1 m sea level rise)

9.3.2 Avon River

The Avon River was simulated using Council's existing flood model, a 1D-2D linked model constructed in DHI's Mike Flood software. The main channel of the river is simulated in 1D and is connected to a 2D model of the floodplain. To assess the benefits of the barrier twenty-four simulations were run to generate twelve sets of results. The twenty-four model runs consisted of:

- 2 x barrier scenarios (without barrier and with barrier)
- 2 x sea level rise scenarios (without sea level rise and with 1 m sea level rise)
- 3 x stopbank alignments (river's edge, mid-floodplain and outer-floodplain)
- 2 x rainfall/tide conditions (100 year rainfall / 10 year tide and 10 year tide / 100 year rainfall)

The "peak of peaks" was then taken for each matching set of rainfall/tide results to create a combined maximum result for each combination of barrier, sea level rise and stopbank alignment. The combination of attributes to generate the twelve sets of results is shown in Figure 25 below.

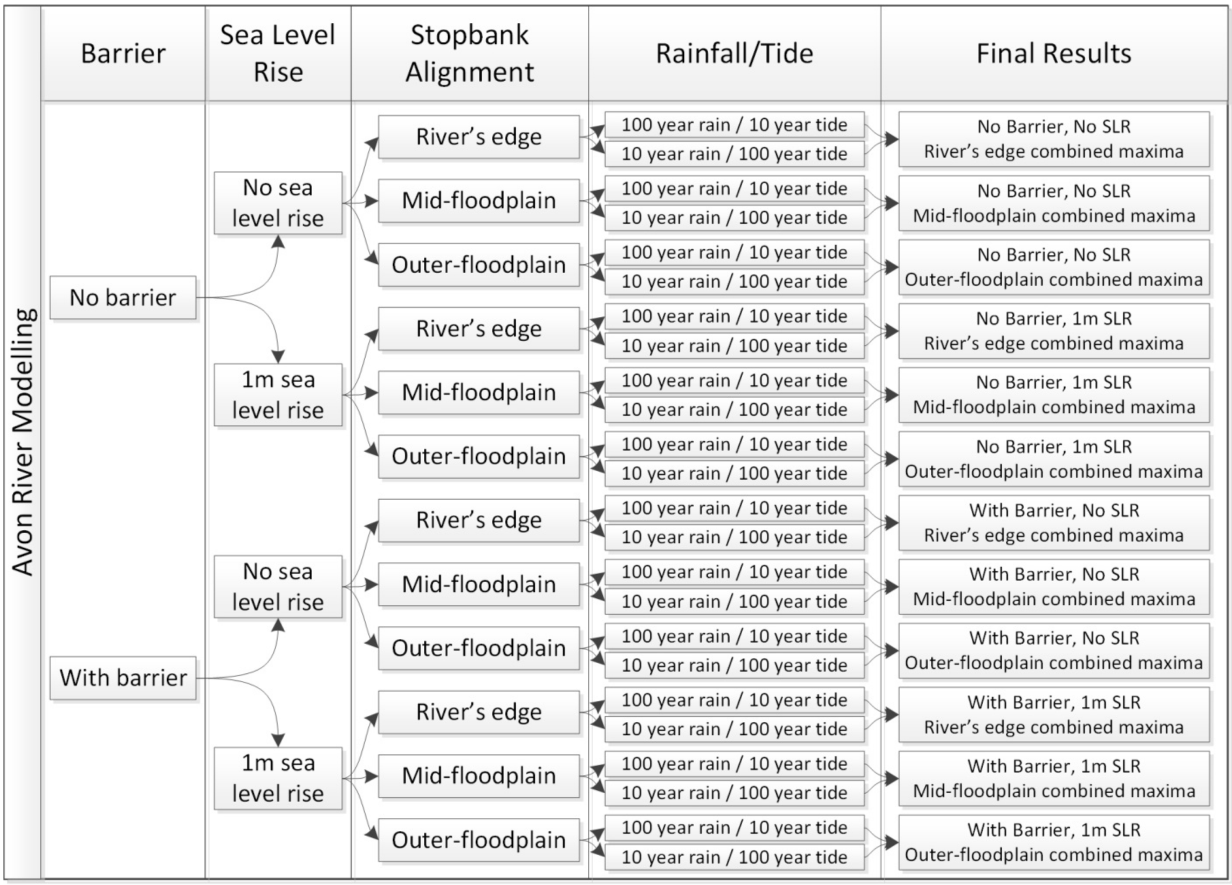

Figure 25 - Avon River Model Scenarios

Barrier, sea level rise and tide effects were simulated by altering the Avon River model's downstream boundary condition to match water levels predicted for the various scenarios by the estuary model. Stopbank alignments were simulated by placing "glass walls" in the model along the stopbank alignments. In other words infinitely high stopbanks were modelled in order allow an assessment of the height of stopbank required to contain all flows under a given scenario. In all other respects these simulations were identical to Council's previous simulations of flooding on the rivers.

Refer to Appendix D for river long sections showing the maximum flood surface for the various scenarios and stopbank alignments.

9.3.3 Heathcote River

Like the Avon River, the Heathcote River was simulated using Council's flood model, which is a 1D-2D linked model constructed in DHI's Mike Flood software. The main channel of the river is simulated in 1D and is connected to a 2D model of the floodplain. To assess the benefits of the barrier four model runs were completed, consisting of:

- 2 x barrier scenarios (without barrier and with barrier)
- 2 x sea level rise scenarios (without sea level rise and with 1 m sea level rise)
- 2 x rainfall/tide conditions (100 year rainfall / 10 year tide and 10 year tide / 100 year rainfall)

Only the 100 year rainfall / 10 year tide was modelled for the Heathcote River.

Unlike the Avon River where a variety of stopbank alignments were modelled, the Heathcote River has been modelled without stopbanks to provide an estimate of the flood impacts across the floodplain. This is to allow an assessment of the number of residential floor levels impacted under each scenario. This information will be used to calculate the potential cost of house raising as described in Section 9.4.3 below. Refer to Appendix C for figures showing change in flood depth and extent, with and without the barrier.

9.4 Quantity estimation

Various methods were used to estimate the quantum of work that would be required to implement flood defence measures under the various scenarios. This section describes the approaches used to estimate the quantity of physical work required to be undertaken in each of the three key areas.

9.4.1 Estuary

In order to estimate the potential benefit of a tidal barrier on flood conditions adjacent to the estuary, peak modelled estuary water levels were used to determine stopbank and floodwall requirements with and without a barrier. Stopbank and floodwall alignments were taken from the River and Tidal Flood Protection project (GHD, 2013), as per Figure 20 earlier in Section 9.

To inform the cost estimation process, heights, footprints and construction quantities for the Estuary stopbanks and floodwalls were determined using the following procedure:

- Stopbank/floodwall levels were determined for each of the four scenarios by buffering the estuary model flood levels out to the stopbank/floodwall alignments, then assigning a stopbank/floodwall height consistent with the adjacent estuary flood level plus 400 mm freeboard.
- Stopbank/floodwall profiles were calculated for each scenario using 12D (12D is a CAD tool which can be used to efficiently design three-dimensional works such as roads and embankments). "Templates" representing the various stopbank types (as determined in the concept refinement phase) were applied to create the profiles. Quantities of the various construction elements were then exported for use in cost estimation.

- Shapefiles representing the stopbank/floodwall footprints were also exported for use in the cost estimation phase.

9.4.2 Avon River

In order to estimate the potential benefit of a tidal barrier on flood conditions adjacent to the Avon River, peak modelled river levels were used to determine stopbank requirements with and without a barrier. Stopbank alignments were taken from the Avon Stopbank Refinements project (GHD, 2015), as per Figure 20 earlier in Section 9. As shown in Figure 20 and described earlier, three Avon River Stopbank alignments were assessed.

To inform the cost estimation process, heights, footprints and construction quantities for the Avon River stopbanks were determined using the following procedure:

- Stopbank levels were determined for each of the twelve scenarios by buffering the Avon River model flood levels out to the stopbank alignments, then assigning a stopbank height consistent with the adjacent flood level plus 400 mm freeboard.
- Stopbank profiles were calculated for each scenario using 12D (12D is a CAD tool which can be used to efficiently design three-dimensional works such as roads and embankments). "Templates" representing the various stopbank types (as determined in the concept refinement phase) were applied to create the profiles. Quantities of the various construction elements were then exported for use in cost estimation.
- Shapefiles representing the stopbank footprints were also exported for use in the cost estimation phase.

9.4.3 Heathcote River

The approach taken to estimate the benefit of a tidal barrier on flood hazard adjacent to the Heathcote River differs to the approach taken for the Estuary and Avon River because no substantial stopbanks are currently envisaged along the Heathcote River. Along the Heathcote River the potential benefit was estimated by comparing the number of residential floor levels likely to be impacted under the various scenarios.

To undertake this analysis the modelled flood surfaces were compared with Council's residential floor level data and a count obtained of the number of properties where the flood level exceeded the estimated floor level.

It is acknowledged that this method is simplistic in comparison the method adopted for the Avon and Estuary. Council is currently developing flood defence options for the Heathcote, which once further advanced will serve to improve upon the analysis presented here.

9.5 Cost estimation methodology

For the various modelled scenarios cost estimates have been broken into a number of elements: tidal barrier, stopbanks and floodwalls, house raising, stormwater infrastructure (i.e. pump stations, detention, outfall works) and land acquisition. The following subsections describe the approach applied to cost estimation of each element. For tidal barrier cost estimates and methodologies refer to Sections 8.3 and 8.4.

9.5.1 Stopbanks and floodwalls

Construction costs were estimated using the approach outlined in the Avon Stopbank Refinement report (GHD, 2015). This included allowances for preliminary & general (23% incl. profit), design (7%), MSQA (3%), consents (3%), staff time (1%) and contingency (20%).

Because bespoke rates were generated for the mid-floodplain alignment as part of the Avon River Stopbanks project, it was necessary to adapt these rates to the other Avon River stopbank alignments, as well as the estuary stopbanks. This was achieved by breaking the mid-floodplain alignment itemised cost rates into “Normal” and “Special” categories, where “Special” accounted for challenging construction conditions such as narrow construction corridors, live traffic conditions and constructing on the river’s edge.

9.5.2 House raising

To estimate the cost impact of this flooding, it was assumed that all impacted properties were raised at a cost of $150,000 per house. This is the cost that was determined by the Christchurch Mayoral Flood Taskforce in 2014.

9.5.3 Stormwater infrastructure

New and enlarged stopbanks, as well as increased estuary and river water levels will reduce the number of existing stormwater outfalls that can continue to function as gravity systems during flood events. In some cases this reduced outfall capacity could be mitigated by allowing for some storage of flood flows, generally near the outfall. In other cases it may be necessary to install or upgrade stormwater pump stations to provide adequate local drainage during flood events.

The River and Tidal Flood Protection project (GHD, 2013) made some simple assumptions regarding when a stormwater pump station would be required. For example, the effect of detention size on required pump capacity and vice versa was ignored. In order to improve upon the quality of cost estimates, pump station decision criteria were established which take into account inflow, tailwater level and land availability parameters to determine an optimised pumping/detention arrangement for each outfall. By revisiting these assumptions and allowing for detention of stormwater (whilst considering the costs of construction of detention and necessary land acquisition) the cost of stormwater pumping infrastructure associated with some stopbank options has been reduced. This has helped to quantify the reduction in required stormwater infrastructure required in the barrier scenarios (as lower tailwater levels increase gravity outfall capacity).

To inform the pump station / detention decision making process and cost estimation exercise, a revised stormwater pump station specification was developed. This basic specification was used to develop stormwater pump station costs for a range of pump station sizes from a minimum likely size to a maximum likely size. These cost curves were developed by breaking down the stormwater pump stations into the key elements, for example ground improvement, pumps, generators, valves, chambers, pipework, electrical, etc., across a range of sizes. Built-up stormwater pump cost estimates were then generated based on price estimates for each component based on NZ industry figures. Standard drawings for the generic pump station design can be found in Appendix F.

9.5.4 Land acquisition

No clear guidance was available on what land acquisition costs might be applied to Crown owned Red Zone Land used for flood mitigation purposes. To allow for proper assessment of the impact of land acquisition costs on cost comparisons, land acquisition costs have been reported separately.

In determining land acquisition costs the following assumptions have been made:

- Acquisition costs have been based on 2007 rating values for Residential Red Zone land and current rating values for Green Zone properties.
- Only land occupied by the footprint of the permanent works (i.e. stopbank, pump station, etc. footprints) need be acquired. i.e. land required for temporary works and access needn't be acquired.
- Partial sections can be acquired in the Residential Red Zone.
- When part of a Green Zone section of any type (including Council land) is required for construction purposes, the whole section must be acquired at the current rating value (total improved value, i.e. land and dwelling). Where less than 10% of the land is required it has been excluded from the calculations (to allow for very large land parcels and where minor realignments would be applied in detailed design).
- Council owned land in the Residential Red Zone can be used free of charge.

For the land acquisition cost estimates at 0% and 50% of ratings values, only the Residential Red Zone land has been discounted. Full rates for Green Zone land have still been applied.

9.6 Cost estimates – present day

9.6.1 Estuary

The barrier was found to reduce the length of stopbank required by 4.8km under present day climate conditions. This results in a cost saving of approximately $37M to protect against a 100 year fluvial/tidal combined maxima flood event adjacent to the estuary. Table 10 provides a summary of length and cost of stopbank requirements with and without a tidal barrier.

Table 10 Present day estuary stopbank/floodwall requirements with/without tidal barrier

Description	**Without barrier**	**With barrier**
Length (metres)	7,500m	2,700m
Stopbank/floodwall construction cost	$49.4M	$22.1M
Stormwater infrastructure	$4.3M	$0.8M
Total cost (excluding land)	*$53.7M*	*$22.9M*
Land acquisition cost (at 100% 2007 rating value)	$8.6M	$2.0M
Total cost (including land at 0% of 2007 value)	**$54.0M**	**$22.9M**
Total cost (including land at 50% of 2007 value)	**$58.1M**	**$23.9M**
Total cost (including land at 100% of 2007 value)	**$62.3M**	**$24.9M**

9.6.2 Avon River

The barrier was found to reduce the length of Avon River stopbank required by between 2.1km and 4.9km under present day climate conditions depending on the alignment chosen. This results in a cost saving of between $49M and $70M to protect against a 100 year fluvial/tidal combined maxima flood event adjacent to the Avon River. Table 11 provides a summary of length and cost of stopbank requirements with and without a tidal barrier for the three alignments considered.

Table 11 Present day Avon River stopbank requirements with/without tidal barrier

Description	**River's edge alignment**		**Mid-floodplain alignment**		**Outer-floodplain alignment**	
	Without barrier	**With barrier**	**Without barrier**	**With barrier**	**Without barrier**	**With barrier**
Length (metres)	22,200m	18,800m	13,900m	11,800m	15,700m	10,800m
Stopbank construction cost	$78.4M	$49.4M	$28.6M	$15.8M	$25.3M	$12.2M
Stormwater infrastructure	$41.9M	$12.3M	$35.2M	$12.4M	$32.8M	$7.9M
Total cost (excluding land)	*$120.3M*	*$61.7M*	*$63.8M*	*$28.2M*	*$58.1M*	*$20.1M*
Land acquisition cost (at 100% of 2007 value)	$18.0M	$7.0M	$22.7M	$9.4M	$19.6M	$6.7M
Total cost (incl Red Zone at 0% of 2007 value)	**$126.9M**	**$62.2M**	**$67.9M**	**$28.8M**	**$61.8M**	**$20.1M**
Total cost (incl Red Zone at 50% of 2007 value)	**$132.6M**	**$65.4M**	**$77.2M**	**$33.2M**	**$69.7M**	**$23.5M**
Total cost (incl Red Zone at 100% of 2007 value)	**$138.3M**	**$68.7M**	**$86.5M**	**$37.6M**	**$77.7M**	**$26.8M**

9.6.3 Heathcote River

Figures showing the change in depth and extent of flooding with/without a tidal barrier can be found in Appendix C. It is noted that the reduction in flood levels and extent in residential land is modest under present climate conditions, with only small areas of benefit around Woolston.

This scale of benefit is also reflected in the number of houses benefited by a tidal barrier under present climate conditions, with a 28 house reduction in impact during a 100 year flood event. This equates to a cost saving of $4.2M assuming a house raising cost of $150,000 per house. A summary of the benefit to residential houses can be found in Table 12 below.

Table 12 Present day Heathcote River residential flooding with/without tidal barrier

Description	**Without barrier**	**With barrier**
Number of houses	412	384
Cost to raise	$61.8M	$57.6M

9.7 Cost estimates – 1m sea level rise

9.7.1 Estuary

The barrier was found to reduce the length of stopbank required by 1.8km under a 1 m sea level rise scenario, and an average reduction in height of over 1m. This results in a cost saving of approximately $97M to protect against a 100 year fluvial/tidal combined maxima flood event adjacent to the estuary. The large reduction in stormwater infrastructure savings occurs as a result of avoiding the need for pump stations at the outfalls to several major drains. Table 13 provides a summary of length and cost of stopbank requirements with and without a tidal barrier.

Table 13 1 m sea level rise estuary stopbank/floodwall requirements with/without tidal barrier

Description	Without barrier	With barrier
Length (metres)	7,900m	6,100m
Stopbank/floodwall construction cost	$92.6M	$34.4M
Stormwater infrastructure	$29.8M	$1.9M
Total cost (excluding land)	*$122.4M*	*$36.3M*
Land acquisition cost (at 100% 2007 rating value)	$14.4M	$3.4M
Total cost (including land at 0% of 2007 value)	**$124.8M**	**$36.3M**
Total cost (including land at 50% of 2007 value)	**$130.8M**	**$38.0M**
Total cost (including land at 100% of 2007 value)	**$136.8M**	**$39.7M**

9.7.2 Avon River

The barrier was found to reduce the length of Avon River stopbank required by between 1.1km and 5.7km under a 1 m sea level rise scenario depending on the alignment chosen. This results in a cost saving of between $123M and $143M to protect against a 100 year fluvial/tidal combined maxima flood event adjacent to the Avon River. Table 14 provides a summary of length and cost of stopbank requirements with and without a tidal barrier for the three alignments considered.

Table 14 1 m sea level rise Avon River stopbank requirements with/without tidal barrier

Description	River's edge alignment		Mid-floodplain alignment		Outer-floodplain alignment	
	Without barrier	With barrier	Without barrier	With barrier	Without barrier	With barrier
Length (metres)	23,700m	22,600m	19,900m	14,200m	17,600m	14,400m
Stopbank construction cost	$182.7M	$103.1M	$82.9M	$25.4M	$63.3M	$19.1M
Stormwater infrastructure	$74.4M	$36.1M	$65.9M	$24.8M	$64.9M	$16.6M
Total cost (excluding land)	*$256.8M*	*$139.2M*	*$148.8M*	*$50.2M*	*$128.2M*	*$35.7M*
Land acquisition cost (at 100% of 2007 value)	$35.3M	$9.6M	$40.7M	$16.8M	$42.4M	$7.6M
Total cost (incl Red Zone at 0% of 2007 value)	**$272.5M**	**$140.5M**	**$157.4M**	**$53.6M**	**$141.0M**	**$35.7M**
Total cost (incl Red Zone at 50% of 2007 value)	**$282.3M**	**$144.7M**	**$173.5M**	**$60.3M**	**$155.8M**	**$39.5M**
Total cost (incl Red Zone at 100% of 2007 value)	**$292.1M**	**$148.8M**	**$189.5M**	**$67.0M**	**$170.6M**	**$43.3M**

9.7.3 Heathcote River

Figures showing the change in depth and extent of flooding with/without a tidal barrier can be found in Appendix C. The benefit to residential flooding is more substantial in the 1 m sea level rise scenario. There is a 780 house reduction in impact during a 100 year flood event. This equates to a cost saving of $117M assuming a house raising cost of $150,000 per house. A summary of the benefit to residential houses can be found in Table 15 below.

Table 15 1 m sea level rise Heathcote River residential flooding with/without tidal barrier

Description	Without barrier	With barrier
Number of houses	1632	852
Cost to raise	$244.8M	$127.8M

9.8 Cost comparison summary

Sections 8.3 and 8.4 provided a cost estimate for construction of a tidal barrier. The previous sections (9.1 to 9.7) have described the various methods used to estimate the potential benefit of a tidal barrier in terms of reduction in costs for other flood defence measures.

Table 16 Summary of cost comparison without/with tidal barrier

Description	Present day climate		1 m sea level rise	
	Without barrier	**With barrier**	**Without barrier**	**With barrier**
Tidal barrier	-	$310M	-	$310M
Estuary stopbanks/floodwall	$62.3M	$24.9M	$136.8M	$39.7M
Avon River stopbanks (mid-floodplain)	$86.5M	$37.6M	$189.5M	$67.0M
Heathcote River house raising	$61.8M	$57.6M	$244.8M	$127.8M
Total	**$210.6M**	**$430.1M**	**$571.1M**	**$544.5M**

Note 1: Estuary and Avon River costs include stormwater infrastructure (i.e. pump stations and detention storage.

Note 2: Table assumes 100% rating value paid for land acquisition.

The cost comparison presented in Table 16 shows that for the present day climate scenario the cost of a tidal barrier far outweighs the expected cost reduction for other defence measures. However in the 1 m sea level rise scenario the cost for flood defence with the barrier is slightly less than cost without a barrier.

The cost comparison in Table 16 makes certain assumptions regarding the cost of land acquisition and alignment of the Avon River stopbanks. These assumptions do no change the overall conclusion that a tidal barrier is unfavourable from a cost perspective in the current climate scenario, but may be cost comparable under a 1 m sea level rise scenario.

9.9 Limitations

When considering the cost comparisons presented in Section 9 the following limitations should be considered:

- Calculations regarding stormwater infrastructure costs assume that many existing stormwater outfalls are consolidated to allow fewer pump stations and detention basins to be used. This analysis did not take into account the cost of consolidating stormwater networks, i.e. the cost of diversion pipes or channels, or any other required network upgrades. In the case of the 100 year flood event analysed this does not change the outcome of the analysis because overland flows dominate in this scenario, and these overland flows will be effectively routed by the stopbanks. However, in order to maintain day-to-day levels of service, the pipe network would need to be modified.

- Calculations regarding stormwater infrastructure costs are reliant on some assumptions regarding acceptable flood levels on the residential side of the stopbanks. These flood levels are based on protecting houses with floor levels up to the current 95th percentile. Stormwater infrastructure costs (including associated land acquisition costs) increase by 20% on average if the 99th percentile is assumed.
- Pump station sizes and detention storage capacities have been estimated based on the assumption that Residential Red Zone land must be acquired at 100% of the 2007 rating value. If land could be acquired at a cheaper rate then stormwater infrastructure costs would reduce by more than the land value discount, as it would become favourable to construct larger detention basins, reducing pump station costs.
- House raising calculations in the Heathcote River area assumed that all houses could be raised. Due to foundation type it will not be possible to raise all houses.
- No consideration has been given to a range of other feasible flood management options including (but not limited to) river mouth pump stations, house tanking and managed retreat.
- No consideration has been given to the various environmental and social impacts and benefits. Depending on how these values are accounted for, consideration of these items could substantially influence the outcome of a comparison.
- This analysis has not taken into account the relative benefits with respect to management of residual risk (i.e. risk of flood defence failure) or tsunami risk.

10. Pre-Feasibility Assessment – Resilience

This section contains outcomes from the second part of the pre-feasibility assessment of the barrier concept described in Section 8. This assessment addresses the question will the barrier survive the local conditions and remain effective?

Background information and some preliminary analysis of the barrier pre-feasibility concept were drawn upon to assess the likely resilience of a barrier to a range of environmental factors which could potentially pose a risk to ongoing operation.

10.1 Storm conditions – terrestrial

Combined 200 year return period flows into the Estuary from the Avon and Heathcote Rivers and the City Outfall Drain are approximately 300 m^3/s. Given that there is sufficient storage within the estuary and that these flows are significantly smaller than the normal tidal flows (500-800 m^3/s, see Figure 26), terrestrial storm conditions pose no risk to an open barrier.

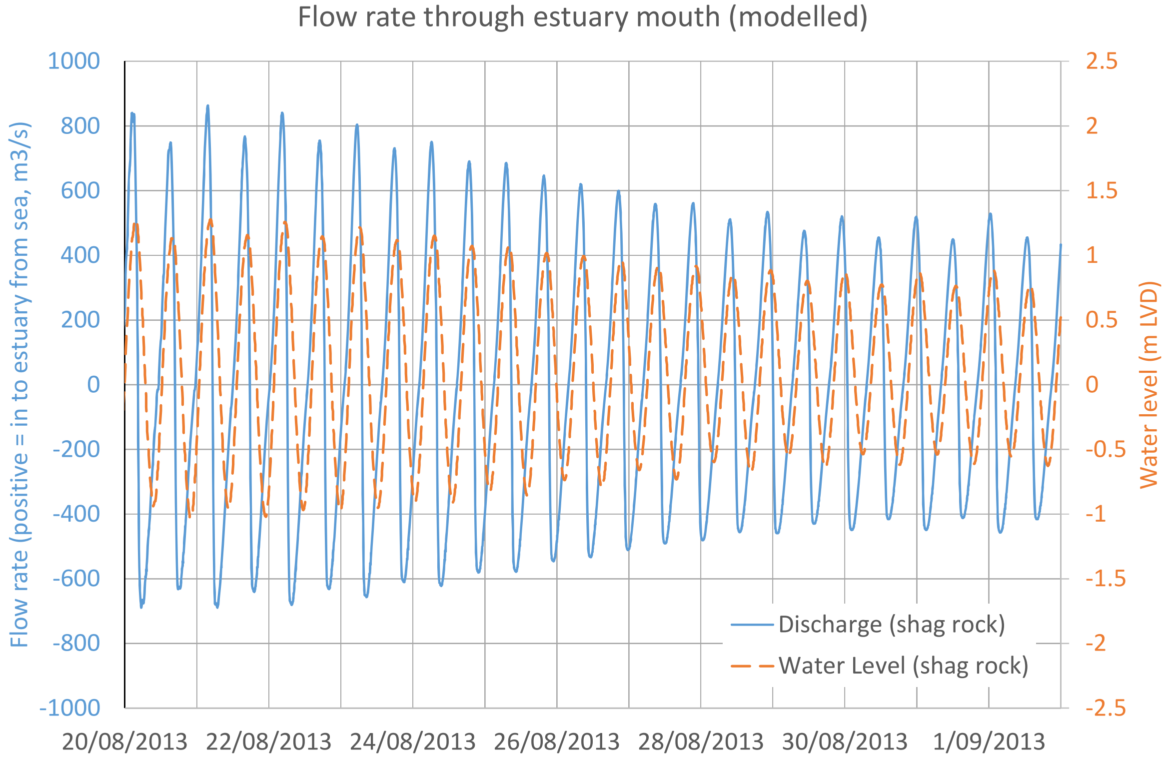

Figure 26 - Modelled flow rate through the estuary mouth

Local wind waves within the estuary are small (<0.5m), being limited by the depth and fetch and should pose little risk to the barrier.

10.2 Storm conditions – oceanic

The proposed location for the barrier is not currently exposed to waves from the sea but there is a risk that when the barrier is closed storm waves could propagate further into the estuary due to the reduced tidal flows. At present, even at high tide slack water, there is little propagation of sea waves into the estuary so it is considered unlikely that waves would pose a major threat to the barrier structure in the Redcliffs location.

Peak sea levels associated with storm surge are currently 2-2.2 mLVD[1] (Goring 2010). These levels pose little threat to the barrier with proposed crest height of 3.4 mLDV. Sea level rise will increase surge levels but a barrier crest level of 3.4 mLVD is sufficient to provide approximately 0.5 m freeboard for the maximum expected surge with 1 m sea level rise. It would be possible to design the barrier such that further sea level rise could be accommodated in future.

Consideration was also given to the potential for failure of the barrier arrangement due to overtopping of the sand spit remote from the barrier location (for example in the vicinity of New Brighton). Tonkin and Taylor (2013, p.43) addressed the likelihood of this occurring, concluding that "[a] rise in mean sea level is not expected to have any effect on inundation risks from storm events due to the existing dune crest elevations being above predicted storm surge levels."

10.3 Spit and mouth morphology

The location of the proposed barrier has been historically very stable from a morphological perspective. Findlay and Kirk (1988) and Bryan et al (2008) document major morphological changes to the spit tip and tidal channels but at the location of the proposed barrier none of those documented spit and channel configurations were significantly different to the current configuration. This historic stability at the site selected for the barrier suggests that the barrier is unlikely to be affected by morphological changes which impact its effectiveness under the current climate and sea level regime.

As described in Section 3.5.1 accelerated sea level rise is likely to increase the tidal prism volume, hence increasing the size of the estuary channels, mouth and tidal deltas. With increasing tidal prism flows rates through the barrier structure would increase but so to would the submerged cross sectional area of the structures opening (as a result of increased water depths over the sill). With 1 m sea level rise the tidal prism is expected to increase by five million m^3 (Tonkin and Taylor 2013), a 60% increase over the current average tidal prism (Measures 2013). The submerged (half tide) cross-sectional area of the barrier opening would increase by 38% as a result of the same sea level rise. Modelling shows that the proposed barrier easily passes normal tidal flows with very little restriction to the flow under current sea levels (approximately 1 cm reduction in tidal range within the estuary when open). It is not anticipated that the barrier would struggle to pass the additional flows resulting from sea level rise and given that the barrier ties into an engineered embankment to the east and a hard sea wall to the west it is very unlikely that the increased flows and increasing channel sizes could outflank the structure.

As well as increasing tidal prism sea level rise is also likely to cause retreat of the shoreline along the Brighton Spit. Based on analysis by Tonkin and Taylor expected retreat is 30-90 m. Given that the spit is

[1] Storm surge analysis at the mouths of the Avon and Heathcote Rivers but at high tide the water level within the estuary is relatively flat and very similar to the level at the estuary mouth except for wind setup effects.

currently over 250 m wide at its narrowest point and the dunes backing the foreshore are 5-9 m high it is unlikely that sea level rise would result in a breach of the spit.

Hicks and Hume (1996) estimated that ebb delta volumes should increase by a factor of 1.32 times any increase in their tidal prism volumes, This indicates a 79% increase in the Avon Heathcote ebb delta volume, which (assuming an existing ebb delta volume of approximately 1 million m^3 based on Hicks and Hume's relationship between ebb delta size and tidal prism volume) equates to an additional 0.8 million m^3 of sand needing to be sourced from the adjacent beach system. This will create a further shoreline retreat beyond that estimated by Tonkin and Taylor - we estimate 20 m assuming the sand deficit is secured from a 2 km span of shore with a height of 20 m between the offshore profile closure depth and the dune crest.

Flood delta volume is also expected to increase as a result of climate change increases to the tidal prism. Whilst this will likely result in greater sand movement through the barrier structure on each tide it is unlikely to result in significant deposition within the structure as the slight flow constriction caused by the structure will accelerate tidal velocities and flush the sills clear.

Consideration was also given to the risk of barrier failure due to increased groundwater movement through the spit. The maximum head difference is likely to be in the order of 2.0 m but only 1 m to the mud flats behind the spit. With a minimum spit width of 250 m this gives a temporary groundwater slope of about 1:250, which is not likely to be of concern.

10.4 Geotechnical stability

The placing of the dunes will cause some natural consolidation of the underlying estuarine soils. The underlying estuarine soils are still likely to be liquefiable during strong earthquake shaking and could settle and spread laterally when liquefaction occurs. This is most likely to occur near to the channel and barrier and the spread dune could cause constriction of the channel at the barrier. For example the most severe lateral spreading along the Avon River caused a ~ 5 m constriction of the river. This could be mitigated by treating the estuarine soils near to the barrier abutment and under the dunes with soil improvement, such as Landpac. The gates and embankment (dune) will have differing ground treatment requirements in order to achieve the necessary geotechnical stability. Beneath the gates it is anticipated that ground improvement works would be required, whilst beneath the dune dynamic compaction should be sufficient.

Ground improvement beneath the gates and abutment will need to be reasonably extensive, utilising a technique such as DSM (Deep Soil Mixing).

Landpac dynamic compaction is relatively inexpensive to carry out consolidation and ground improvement over large areas at up to 5 m depth, and could be carried out under the entire sand-dunes embankment. Landpac has been trialled and used successfully for ground improvement for a large subdivision at Prestons, north of Christchurch City. Its use at this site is assessed as being viable, but once the subsurface investigations are assessed, may require trials to confirm its acceptability.

There is sufficient confidence at this stage to say that there are ground improvement options readily available in New Zealand to allow the construction of the conceptual barrier structure. Future stages of work would need to include subsurface investigations, such as drill-holes, cone penetration tests (CPTs), and geophysical profiling (e.g. Multichannel analysis of Surface Waves (MASW) and seismic refraction / reflection) to investigate the soil profile and properties and confirm the required ground improvement methodologies.

10.5 Tsunami

A 200 year return period tsunami in open ocean could have an amplitude of 5 m (Plover, 2013); in the estuary, the tsunami wave will be strongly attenuated. For the pre-feasibility concept design a tsunami wave height of 2 m was assumed. The barrier would be designed and constructed to withstand such an event. Even if it was overtopped, by a tsunami wave, the height of the wave on the other side would be strongly reduced. Any subsequent stages of work would need to examine this topic in greater detail, both with respect to the resilience of the structure and potential risk mitigation benefits assuming the barrier could be closed in time.

11. Pre-Feasibility Assessment – Impacts

This section contains outcomes from the third part of the pre-feasibility assessment of the barrier concept described in Section 8, addressing the question "will the impacts of building the barrier be acceptable?"

11.1 Hydrodynamics

In order to investigate the effect of the barrier on morphology when it was in the open position, normal tidal flows were simulated using the Delft3D estuary model of Measures (2013) described in section 9.3.1. Tidal flows were simulated for a whole spring neap cycle. The modelling showed that the proposed barrier has very little effect on tidal flow rates or tidal range within the estuary. The effects quantified by the model include:

- Currently the peak flood and ebb flow over the sandbanks where the proposed embankment is to be constructed ranges from 10 m^3/s during neap tides to 60 m3/s during spring tides. This represents only 3-8% of the total flow. This flow would be blocked completely by the embankment and forced through the gate structure.
- The restriction posed by the open gate structure has a very small impact on tidal range within the estuary causing an approximately 1 cm drop in high tide levels and a negligible effect on low tide levels.
- Closure of the gate has very little impact on peak water levels outside the barrier (i.e. Moncks Bay and Redcliffs). Transient water levels following closure are raised up to 100mm but as closure occurs when the tide is low this does not pose a flood risk. This is consistent with work from previous physical modelling (HR Wallingford, 1970) that suggested gradual closure over 30 minutes prevented problematic surge effects.
- The gate has almost no effect on salinity within the estuary or the rivers when in the open position.
- The barrier locally influences maximum bed shear stress lowering this in the shelter of the embankment and piers, and slightly increasing it just upstream and downstream of the gate (see Figure 27).

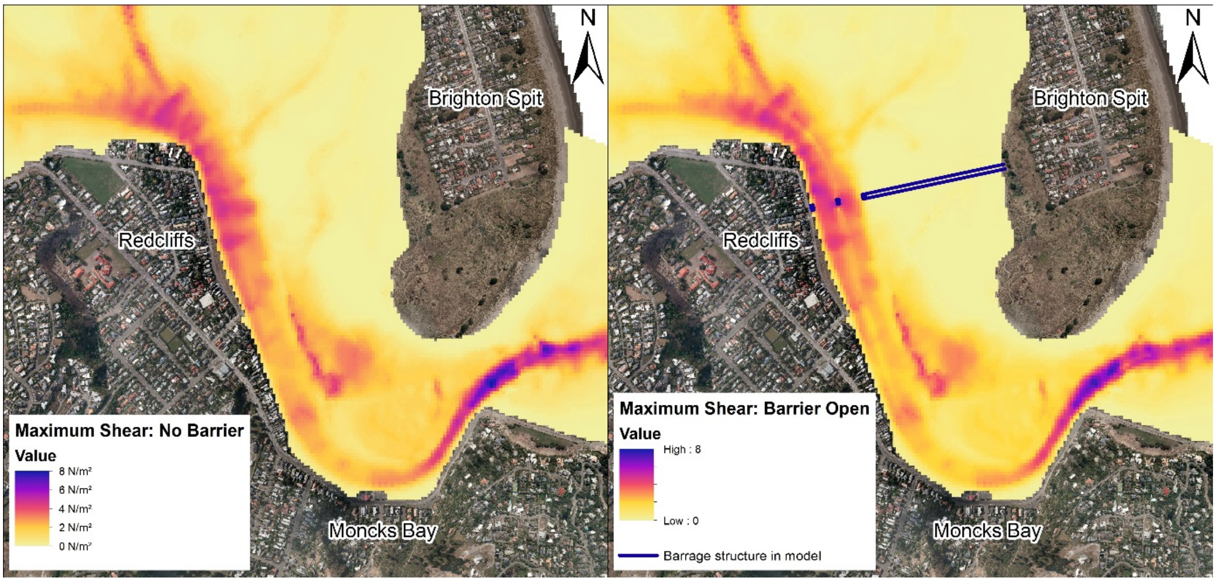

Figure 27 - Maximum bed shear stress with (right) and without (left) the barrier during normal tidal conditions (barrier open)

11.2 Morphology

As indicated by the hydrodynamic modelling the barrier does have a local effect on bed shear stress around the structure and on the main tidal channel on both sides of the structure. This will have a local effect on morphology as the channel adjusts; however, the magnitude of effects is expected to be relatively small given that the structure presents little obstruction to flow or sediment when it is open. Local effects will include: potential scour around the piers and sill of the structure due to tidal flows, deposition of sediment and increased vegetation in the backwaters created by construction of the embankment, and slight scouring of the main tidal channel as a result of the embankment focussing all flow through the gates.

When the barrier is closed during floods (at low tide) it will suppress high tide water levels within the estuary. This will increase time-averaged gradient of the river channels where they enter the estuary, causing increased bed shear stresses and bed erosion. From a flood risk point of view this erosion could be beneficial by helping to reduce flood levels further upstream although it also has the potential to cause bank erosion.

As well as suppressing water levels in the estuary, the barrier closures will stop most of the tidal flows in and out of the inlet throat, which will reduce the capacity of the tide to clear sand swept into the throat by ocean waves. Since river flood events are often accompanied by high coastal wave events, this temporary cessation of tidal flows will allow the build-up of sand in the throat of the estuary during the period while the barrier is closed. Following re-opening of the barrier, this sand will be flushed seaward but there may be a time lag during which the throat is partially blocked. With current sea levels, however, barrier closure would be infrequent and for relatively short duration and it is not anticipated that sufficient sand would build up during closure to present any issues.

As sea levels rise, barrier closures are likely to become more frequent and of longer duration. Long duration closures over multiple consecutive tides during periods of high wave energy could allow problematic sand build-up across the mouth of the estuary which could take a long time to flush. Complete closure of the mouth is however considered very unlikely as significant tidal flow would still occur on every tide (when the barrier is opened around low tide).Frequent barrier operation could also trigger a change in the morphology of the spit tip or Sumner Bar – whilst this is unlikely to impact barrier effectiveness it could result in impacts on the Sumner or Scarborough beaches, or on properties vulnerable to coastal erosion near the spit tip.

Construction of the barrier would require temporary works that partially obstruct flow in the main channel. Most likely, this would involve either blocking half the channel at a time with a cofferdam to allow construction of the piers and sill on the bed of the estuary or smaller sized temporary works to build the sill from rock revetments directly in the water. During this construction phase the temporary works would cause major obstruction to the main channel increasing velocities and causing scour on the bed and banks of the remaining section of channel as well as deposition in the backwaters sheltered by the temporary works. There is a risk that the morphological change during the construction phase could have significant long term impacts if the channel position moved enough to destabilise from its current stable position. Detailed analysis and modelling would be required to investigate this. This risk could be managed by reducing the time the temporary works would be in place and considering construction of temporary bank protection to limit channel migration. For example, by constructing much of the embankment and armouring its tip prior to temporary works at the gate site the embankment could serve to limit lateral migration of the main channel.

11.3 Ecology and water quality

The proposed barrier and embankment seem likely to have minimal medium to longer term effects on the estuary's ecology and water quality impacts based on available modelling results and assuming appropriate barrier operations (see Section 11.1 for a summary of modelled effects on tide levels, salinity etc.) . Construction effects of both the proposed barrier and embankment seem generally manageable to a local scale. Development of an embankment at the eastern end offers the opportunity to introduce different habitat and communities to this area, enhancing some biodiversity values. Also, the proposed barrier opens the opportunity to influence the estuary's future biodiversity and ecosystem values as it manages inundation due to sea level rise.

Based on modelling results of effects on hydrodynamics, the proposed design appears unlikely to compromise the estuary's recognised high biodiversity and ecosystem values. The hydrodynamic modelling indicates that this barrier and embankment design retains the estuary's connectivity with the sea over the full tidal range and when open has little impact on the tidal water level changes and salinity regimes, both fundamental to estuarine biodiversity and ecosystem sustainability. Thus, under normal circumstances, the proposed barrier will provide ready exchange of water and biota between estuary and sea. When used for flood protection (rainfall or sea level induced), it can create near-natural low tides (vertical water fall and duration of emersion) while exchanging water with the sea, allowing characteristic estuarine salinity regimes to continue and migrations of organisms (e.g., phytoplankton, invertebrate larvae, whitebait) between the estuary and sea.

Effects of freshwater impoundment within the estuary by the proposed barrier during rainfall-induced flood protection seems acceptable because most estuarine organisms and communities can tolerate significant exposure to freshwater. (e.g., Jones and Simons 1982; Shumway and Marsden 1982;

Partridge and Wilson 1987, 1988; Pechenik et al. 2003; McLeod and Wing 2008; Hicks et al. 2010). This tolerance is increased by periodic emersion, and the proposed barrier appears to allow near- natural low tides to achieve this and allow tide-related ecosystem processes (e.g., bird feeding, microphytobenthos photosynthesis, etc.) to continue. Stormwater impoundment effects on water quality and sedimentation are likely to be small as even without a barrier stormwater is impounded in the estuary by the high tide allowing settlement to take place.

With the proposed barrier providing good connectivity to the sea and operated to create near natural tides within the estuary, the estuary's ecosystem should adjust to sea level rise, primarily through medium-term, up-shore (and up-catchment) migration of individual species and their communities. The extent of this migration will be determined by the maximum tide level set via the proposed barrier's operations. This controlled high water level will truncate the estuary's tidal amplitude and reduce the area of intertidal habitat within the estuary. The proposed barrier provides an opportunity for managing the frequency and duration of immersion and exposure to saline water on the estuary's shores, key factors driving the composition of the estuary's intertidal biodiversity and communities.

Given the proposed barrier's apparent effectiveness in maintaining the estuary's ecosystem values, the key next steps should include more comprehensive investigation of the effects of sea level rise on the estuary's biodiversity and ecosystem values and the potential for the proposed barrier to maximise these to benefit all stakeholders.

The effects of the barrier on ecology in the future are largely dependent on decisions around how the operating philosophy is adapted in response to sea level rise. Section 7.2 outlines several different possible options for future operation. The effect of these different options would be:

- Retain present day trigger levels: With a 1 m sea level rise and retaining the present day trigger level, the estuary's tidal volume (and flood water holding capacity) reduces as sea level rise continues, so that freshwater comprises more of the estuary's high tide water. This increase is anticipated to be even greater if rainfall intensity increases, as predicted. By retaining present day trigger levels, the estuary will become increasingly dominated by freshwater tolerant communities as the truly estuarine communities are supplanted. The full implication of this change for the estuary's biodiversity and ecosystem values is uncertain, but potentially significant.
- Retain present day operating frequency: This scenario seems likely to have considerably less effect on the estuary's biodiversity and ecosystem values. The intertidal volume and area will be constrained only by landward topography and a full range of tidal submersion-emersion will exist on most shores. The fresh-sea water balance will adjust to a natural equilibrium, and high shore communities will migrate landwards in parallel with low shore communities, driven by the natural, typically estuarine tidal-salinity regime advancing inland with sea level rise.
- Combined approach: The consequences of a combined approach for the estuary's biodiversity and ecosystem values seem likely to lie somewhere between those outlined for the two operation regimes described above.

11.4 Landscape and visual amenity impacts

Landscape and visual amenity assessment is the consideration of the change to the appearance of the landscape once the proposal is fully implemented. These changes are assessed according to the viewing audience. This will be local residents who can see parts of the proposal from their properties, and motorists, pedestrians and cyclists using local roads and public spaces. The construction of a barrier in the proposed general Redcliffs locality will have an unavoidable visual impact on the surrounding area due to the topography of the land, and the positioning of surrounding dwellings in an amphitheatre type arrangement. The impacts will be most pronounced from the residential suburbs of Redcliffs and Moncks Bay. The Southshore Spit Reserve will offer some screening of the barrier site from the Southshore residential area. The proposed embankment could appear relatively natural in relation to the surroundings; however, the gate structure itself will have a significant visual impact. Aside from the residential development in the surroundings, the subject site is currently a natural environment that would be impacted significantly by the proposed structure.

As a barrier structure will not be able to be screened due to its solid nature, and the large size of it, consideration will need to be had towards either making the structure recessive through chosen materials and or by creating an architectural feature which is interesting to look at. It is expected that the local community would have strong opinions in relation to the loss of amenity and natural character of the area. The properties located along Beachville Road will also be affected by a proposed increase in height of the existing seawall from 2 m to 2.4 m (and eventually 3.4 m with 1 m of sea level rise), which will also have adverse visual amenity effects by reducing views to the estuary. It is also noted that a proposed seawall replacement by the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) in late 2014 was strongly opposed by various groups including the Christchurch Yacht Club, the Redcliffs Residents' Association and the Ihutai Avon-Heathcote Estuary Trust.

Various planning policy documents support this assessment through identification of the site as an area of high natural value and landscape amenity. Relevant planning documents have been reviewed, and a summary is provided below of the some key landscape issues associated with the planning documents and the barrier proposal.

- As previously mentioned in Section 3.5.1, the entire estuary is identified as being an area of Significant Natural Value in the *Regional Coastal Plan*. This overlay is focused on achieving the sustainable management of the coastal environment by protecting and enhancing Areas of Significant Natural Values and areas of high natural, physical, heritage or cultural value (Objective 6.1). As a result of this, the erection of structures in this area is a non-complying activity.
- Under the *Christchurch City Plan* the land bordering the South Brighton spit, and the land bordering Sumner Beach is zoned Conservation 1a. This zone is focused on the protection of the integrity, functioning and resilience of the coastal margin. The land bordering the southern part of Sumner Beach has a special amenity area overlay (ref 35 and 18).
- The Proposed Christchurch Replacement District Plan identifies further important landscape values within the study area:
  - Outstanding Natural Features - Avon/ Heathcote Estuary and Christchurch Coast, South Brighton Spit and Estuary Entrance. It is likely that any land-based structures (i.e. elements of the barrier located above mean high water springs) within these areas are likely to be a non-complying activity under this plan.
  - Areas of at least high natural character in the Coastal Environment - Avon/ Heathcote Estuary and Christchurch Coast, including South Brighton Spit. Buildings/structures are likely to be a discretionary activity in these areas.

- Noting the various district plan notations and our own assessment on site, the Redcliffs alignment may be regarded as being a slightly more suitable location than more seaward options initially considered for this pre-feasibility assessment, given it is clear of more of these district plan notations. Furthermore, we consider that the naturalness of the coastal environment is less pronounced at the Redcliffs alignment than the alternative seaward option alongside Shag Rock which has high natural character. Therefore, selecting the Redcliffs site reduces the potential effects on the natural character of the coastal environment, however significant natural character impacts will still arise.
- In addition to the landscape and amenity values identified in the statutory planning documents, there are various master plans for the urban area including estuary side public spaces which provide evidence of the importance of the amenity of the area to the public. These include the Avon Heathcote Estuary Ihutai Estuary Edge Master Plan 2010, the Main Road Master Plan (Part of the Ferry Road / Main Road Master Plan) Phase Two – Ferrymead Bridge to Marriner Street, Sumner, and the Sumner Village Centre Masterplan. There are a number of reserves along the water's edge that have been identified to be preserved for public amenity and birdlife and some with plans for improvements. These reserves may be affected by the placement of a barrier in terms of amenity and space. Examples of particular areas of interest for preservation and improvements include:
- Beachville Reserve and Council owned and deeds land – along the Redcliffs coastline opposite the spit. This is to be protected from development due to sea level rise, wave action and storm surges.
- A desire to maintain a coastal pathway for a multi-modal non-motorised route along the waterfront.

In summary, the landscape values of the estuary and surrounding areas are immeasurably important, and the construction of a barrier structure and embankment across it at the Redcliffs site will have significant impacts on this. It is expected that the local community will have strong concerns over the proposal for a barrier in this location due to the values they hold in relation to the estuary including the landscape/amenity issues.

11.5 Cultural impacts

The Treaty of Waitangi provides for the exercise of kawanatanga (governance) by the government, while actively protecting the rangatiratanga (possession) of tangata whenua in respect of their natural, physical and spiritual resources. The Resource Management Act identifies tangata whenua in relation to a particular area; as the Hapu or Iwi that holds mana whenua (territorial rights) over that area. Te Rununga o Ngai Tahu is the Tangata Whenua within the Hagley/Ferrymead boundary.

Mahaanui Kurataiao Limited is a resource and environmental management advisory company who represent the interests of the mana whenua of the area. This body produced the Mahaanui Iwi Management Plan 2013 (IMP) which is the main document for the management of cultural values in the study area. This plan outlines those values and matters important to the local iwi. The Ihutai catchment and estuary (the Avon-Heathcote estuary) has been identified as an area of immense cultural and historical importance to tangata whenua. The plan sets out objectives and policies for the management of the area. These address urban development and loss of indigenous biodiversity, open space and pressure on Te Ihutai (the estuary). The plan also identifies silent files in the area which are sites that have specifically been identified as significant/sacred (wahi tapu) to the mana whenua. Map SF1 in the management plan identifies any silent files in the Christchurch area covered by the IMP. There are not any specific sites identified within the study area.

The closing of the barrier has the potential to increase the duration of stormwater/wastewater contamination of the estuary before tidal/saline flushing. This has the potential for adverse effects the health and abundance of Mahinga Kai. These potential effects would need to be carefully considered in terms of the cultural impacts as well as previously discussed ecological effects.

It is anticipated that Iwi would have significant interest with the construction of a barrier in the Avon-Heathcote (Ihutai) estuary as the whole estuary is of great importance to them. Thorough consultation with iwi would be required for the project. The IMP is therefore a key document that must be considered in the planning of the tidal barrier.

11.6 Heritage and archaeology impacts

In addition to the importance of the role Iwi should have in the planning of the barrier, there are also many New Zealand Archaeological Association recorded archaeological sites within the study area. An authority to disturb or destroy the sites from the New Zealand Archaeological Association under the Historic Places Act 1993 will likely be required, and these sites should therefore be taken into account when selecting a precise location for the barrier, and specialist archaeological input would be necessary if the project proceeds. It is highly likely that the placement of the barrier will affect an archaeological site. This would have irreversible effects.

There are two heritage sites within close proximity to the site, listed in the New Zealand Heritage List (formerly the register). The more west of the two sites is Moncks Cave which is located on Main Road. The second is a historic house located at 5 Clifton Terrace, Sumner. Neither of these sites would be affected by the placement of the barrier at the Redcliffs site.

11.7 Recreational / social impacts

As discussed in Section 3.2 there are a range of recreational users of the estuary who will be adversely affected by the provision of a barrier and embankment. Any of the craft that launch upstream of the proposed Redcliffs barrier location and which regularly traverse from the estuary to the ocean, will be able to pass through the barrier except when it is required to be closed during a significant storm/tidal event. In present day, this is likely to be 2 or 3 times in a year. This includes P-class dinghies, optimists and similar one or small two person single hull sail boats, wind surfers and kite surfers, kayaks and paddleboards and beach craft. When the gate is closed these craft would be able to be dragged/carried over an embankment – although given the barrier would generally be closed only in storm conditions it is unlikely that many recreational users will be using the estuary while the barrier is closed. Any other larger craft are able to launch/anchor at the Christchurch Yacht Club downstream of the proposed Redcliffs barrier location, so will not be affected by it.

The provision of a barrier and embankment that incorporates a walking and cycling path would likely have a positive effect in terms of active recreation in the area as it would open up a new route, and access to the spit.

It is noted that the local community have a vested interest in the recreational opportunities in the area based on previous consultation carried out for the Beachville Road/Redcliffs Park section of the Christchurch Coastal Pathway. Suggestions from the community included matters such as keeping carparks at the Beachville boat ramp for vehicles with boat trailers and including the proposed bike skills/scooter area adjacent to the coastal pathway on Beachville Reserve in the plan. It is expected that the community will have opinions on the provision of a barrier in terms of the effects on recreation– some may favour it and others may be concerned in relation to the social impacts of connecting two previously unconnected suburbs with different socio-economic compositions. A social impact assessment would greatly assist the understanding of the social and recreational impacts.

11.8 Construction effects

The effects of the construction phase of the barrier would need to be considered separately to those effects post construction. Construction effects could include, but is not limited to the following:

- Construction traffic and the effects of this on the surrounding road network and communities is important to consider. The surrounding land uses to the proposed barrier site are residential communities which would be sensitive to increased traffic movements to and from the area.
- Noise and vibration effects will arise during the construction of the barrier, due to the necessity to use large mechanical equipment that is likely to generate elevated levels of noise and potentially vibration at the nearest residences. As such, there are likely to be some temporary noise impacts over the construction phase of the project, which will have an adverse effect on the surrounding residential communities.
- Dust and sediment or sedimentation effects may result from earthworks in dry conditions, stockpiling of materials including material placement and removal, and smoke and odour from diesel machinery and truck exhausts. This could have adverse effects on both the health of estuary and on surrounding properties.
- As discussed in section 9.3.2 hydrodynamic and morphology effects on the estuary as well as sediment and ecological impacts during construction would need to be considered.

11.9 Operational Noise

Post construction, it is expected there will be some noise effects resulting from the operation of the barrier. This would be intermittent while the barrier is either opening or closing, and would only occur occasionally when a storm is expected. This noise is likely to be minimal, therefore having minor adverse amenity effects on surrounding residential landowners.

11.10 Operational traffic

The proposed barrier will have minimal effects on traffic in the area when the construction phase is complete, as it is not intended to provide access for vehicles over the barrier. Access will be restricted to pedestrians and cyclists. However, it is possible that in the event of an emergency the barrier would be able to be open to vehicles, in order to provide an emergency link to or from the South Brighton.

11.11 Contaminated Land

The area of land of the South Brighton Spit is identified on Environment Canterbury's Listed Land Use Register as it is listed as a former landfill site (No: ACT 0949, G3 Landfill site). Consent may be required under the NES for earthworks on that side of the estuary, as this land is potentially contaminated. A further assessment of the risk to the environment and human health will be required by contaminated land specialists in order to conclude the scale of effects and the required mitigation measures for this.

11.12 Consultation

At this pre-feasibility stage, some key stakeholders have been informed of the barrier project. This includes the Canterbury Earthquake Recovery Authority (CERA) and the Department of Conservation (DOC). The extent of contact with these stakeholders has been informing them of the preparation of this pre-feasibility report. We envisage that full consultation will be carried out if the project proceeds any further. Environment Canterbury has also been informed, and has been involved in the initial workshopping and providing technical inputs to the pre-feasibility reporting stage.

11.13 Monitoring

The scale and significance of the activity's effects are such that monitoring will be required. Under clause 6(1)(g) of schedule 4 of the RMA, a description of how and by whom the effects will be monitored if the activity is approved is required.

11.14 Consideration of alternatives

Due to the scale of adverse effects expected to be generated by the proposal, there is a statutory requirement under Clause 6(1)(a) of schedule 4 of the RMA, to consider possible alternative locations or methods for undertaking the activity. Other alternatives for the protection of Christchurch from the effects of flooding, storm surges and the effects of rising sea level may include the following, by way of example:

- The provision of stop banks along the rivers in the city;
- Retreating development and existing land use away from the coast and waterways through rezoning, and land purchase, creating retention and removing obstacles to river flow;
- Modification to buildings in flooded areas to accommodate floodwaters;
- Filling of land; and
- The do nothing option.

It's important to note that this proposal could not realistically proceed through to any RMA consenting process without the Council having first assessed all alternative options and comparing the barrier proposal and its costs and benefits, in relation to the alternatives.

11.15 Consentability

We have identified a number of potentially significant environmental effects identified with respect to the barrier proposal. Consenting the proposal under a traditional RMA consent process is likely to be very difficult, particularly given our initial scoping work has identified a number of Non-Complying Activity consents potentially being required including:

- The erection or placement of a structure within an Area of Significant Natural Value under the Regional Coastal Plan.
- The erection of a structure within an Outstanding Natural Feature under the Proposed Christchurch Replacement District Plan (potential requirement – rules not confirmed yet).

For a Non-complying Activity to be approved, it is necessary to satisfy the section 104D(1) threshold test requiring adverse effects to be no more than minor, OR, the proposal being consistent with the objectives and policies of the relevant planning documents. There are no planning documents which promote or recognise the need for a barrier in Christchurch, so no policy support available to balance out the various environmental protection provisions which would be relevant. Accordingly, Regional Coastal and potentially District Plan changes to facilitate the project would be one option to provide a facilitative consenting framework. Alternatively (preferably) an Order in Council under the Canterbury Recovery Act 2011 is likely to be necessary to facilitate this major flood recovery project that relates to earthquake related flood recovery. It is noted that the existing Canterbury Earthquake (Resource Management Act) Order 2011 (SR 2011/34) provides for fast-tracked RMA approvals for land remediation works as follows:

"s4(2) The applications to which this order applies are those made under-

(a) Section 88 of the Act for resource consents to undertake land remediation work:

(3) This order only applies to applications lodged with-

(a) Christchurch City Council

s5(1)In this order, unless the context otherwise requires,-

land remediation work *means work undertaken, for the purpose of the Canterbury Earthquake Response and Recovery Act 2010*

(a) To protect, stabilise, or remediate land affected by the Canterbury earthquake for either or both of the following purposes:

(i) to enable use of the land or of adjacent land or structures to be resumed:

(ii) to protect the land or adjacent land or sturctures from damage, including damage arising from erosion, liquefaction, subsidence, slippage, or falling rocks or debris caused by the earthquake; or

(b) to repair or reconstruct infrastructure; or

(c) to provide for flood protection."

This Order in Council overrides the standard RMA process as follows:

- It deems the land remediation applications to be non-notified irrespective of the level of environmental effect and whether there are any affected parties;
- Its enables the consent authority to grant a consent for a non-complying activity even when the effects are more than minor and the proposal is contrary to objectives and policies in relevant planning documents;
- It sets out a truncated consultation process whereby affected parties/landowners have a 10 working day period to provide written comments on the proposal, but without providing any opportunity for a hearing or right of objection/appeal.

We do not consider the scope of the existing Order in Council SR 2011/34 is sufficient to fast track consenting of a barrier proposal as currently drafted. A barrier, while providing for flood protection, is not in our view the type of land remediation work envisaged by the Order in Council – rather we consider this envisaged direct land based work on damaged land. However, some relatively minor amendments to this existing Order could be a way to facilitate the consenting of a barrier.

12. Future Stages

As discussed in the final section, this Pre-Feasibility Study has concluded that there are no clear impediments to the construction of a tidal barrier in the Avon-Heathcote Estuary. This study has also concluded that a tidal barrier would not resolve Christchurch's flood risk challenges in isolation, it would need to be implemented in conjunction with other engineering and/or policy initiatives. What remains unclear from this study is whether a tidal barrier is a favourable option when considered as part the larger mix of options.

As such, future stages of a barrier implementation would need to consist of 3 elements. The first element would consider the benefits, impacts and costs of a barrier as part of a more catchment wide flood management strategy for different future scenarios. The second element would be to engage with the community to gain feedback on the flood management options available. The third element would work to develop the barrier concept toward implementation if it remains a favourable concept following the options comparison and community engagement.

12.1 Flood Management Options Report

Prior to further development of the tidal barrier concept it is necessary to understand what role (if any) the barrier would play in the management of flood hazard in Christchurch. This will involve further consideration of the potential benefits, impacts and costs of the tidal barrier in comparison with the other defence or flood storage options available, as well as other policy options relating to adaptation (e.g. adaptation of existing and/or new houses) or planned retreat (e.g. land use planning controls on future and/or existing development in affected areas). Also non-structural options to reduce extreme water levels in the rivers by adding retention (e.g. use of Red Zones) and removing obstacles to the flow – creation of "room for the river" are worth to be considered in this context. Now could be the right time to make future-proof decisions on zoning and land development taking into account long term scenarios; in which urban development goes hand in hand with sustainable flood management. It will also be necessary to take into account a more detailed analysis of the impact construction of a tidal barrier would have on the implementation requirements and timeframes for other flood management strategies. In order to allow this comparison and consideration of synergies, the tidal barrier concept will require further analysis with respect to the following:

- Flood alleviation benefits of a tidal barrier and the consequential effects on the required extent of other flood management options;
- Social and Environmental impacts and benefits under future operating scenarios for the barrier, the embankments and other options;
- Broad financial (construction and operational) costs of the barrier and other flood management options – drawing on existing information available within the Council where available;
- Institutional and organisational analysis on future roles, responsibilities and capabilities of authorities and organizations in flood management in the estuary;
- Analysis on the non-structural options to reduce damage and to increase resilience of population. Key question is what is the required level of protection provided by structures would be, besides what can be established by the non-structural options. Not all has to be solved structurally.

- Consultation with the public and stakeholder organisations.

It will be necessary to clearly define per location the challenges in flood management so the scope of options consideration and geographic extent of the Options Report is clear.

The Flood Management Options Report will be partly be based upon information from existing reports on option development which have been prepared by the various teams within Council over the past years, including:

- Avon-Heathcote Barrier Pre-Feasibility Study (this report);
- District Plan Review – options considered for land use planning to manage river and coastal flooding in Christchurch;
- River and Flood Tidal Protection Study;
- Mayoral Flood Taskforce Reports;
- Avon Stopbank Refinements Report;
- Estimated costs for adaption options across the affected areas; and
- Several combinations of the above.

The Options Report shall outline in a cohesive and transparent way the process of option development, The report will be presented in a simple and clear manner which is suitable to use as the basis for early public engagement on high level flood options for the affected areas of Christchurch, before any decision is made by the Council on a preferred option for flood management.

12.1.1 Tidal barrier impact on flood defence options

As a part of a wider study of flood management options it will be necessary to consider the potential benefits that a tidal barrier as part of a catchment wide flood management strategy may have on other flood mitigation types. This question was addressed in part in Section 9, but considerable further work is required to address the limitations highlighted in Section 9.9.

12.1.2 Environmental impacts under future operating scenarios

This report concluded that environmental impacts of a tidal barrier under present day operating conditions are likely to be limited, with increasing impacts occurring as frequency of barrier operation increases. It was the general opinion of the report authors that environmental impacts of a permanently closed tidal barrier are unlikely to be acceptable from a community / consenting perspective. However, in order to test this hypothesis it will be necessary to assess the likely environmental impacts for a range of operating scenarios. These impacts can then be considered as part of a larger flood management strategy.

Ecology

At this stage ecological research needs will include:

1. Predicted natural changes in habitat areas with sea level rise (and climate change) from 2015 to (for example) 2030, 2050 and 2070. This should aim to determine the rates at which different key physical habitats will develop (e.g., salinity regimes, mudflats, salt marsh habitats, etc.) and the areas of these habitats available at each time.

2. Model the natural ecological responses (distributions, sustainable population sizes, standing crop, total annual production, etc.) of key elements of the biota (e.g., marsh plants, seabirds, cockles, mud snails, crabs, pipi, wedge shells, etc. (or total biodiversity)) to sea level rise using information from 1.
3. Replicate 1., for the same times and habitats, but under likely barrier operating regime for each time.
4. Replicate 2., based on habitat predictions under 3.
5. Replicate 3-4 for different barrier scenarios.

This information will provide a baseline of likely change regardless of the barrier and will serve to get stakeholders thinking about the estuary as an evolving system, not a static one, and one that will be changed by sea level rise (and climate change). Being able to compare predicted natural outcomes with barrier-managed outcomes will provide all stakeholders with a far better basis for evaluating likely impacts and preferred options.

Morphology

As described in the assessment of impacts a barrier has the potential to impact bed levels causing feedback effects on flows. These morphological impacts include local impacts around the barrier, impacts at the estuary mouth and in its main channels, impacts on the ebb-tidal delta and beaches either side of the estuary mouth, and potentially impacts on bed levels in lower reaches of the Avon and Heathcote rivers. As well as morphological impacts of a barrier ongoing morphological changes to the spit and its tip and local changes around a barrier have the potential to impact barrier effectiveness.

The analysis described in this pre-feasibility report qualitatively describes potential morphological impacts to and from a barrier but much more detailed analysis is required in order to quantify expected changes. Quantitative analysis is required for:

- Changes in morphology expected as a result of sea level rise without a barrier.
- How different barrier configurations and operating philosophies would impact morphology, including the effects of sea level rise.
- How temporary works associated with barrier construction would affect morphology.

In order to investigate the morphological impacts of the barrier a numerical morphological modelling study is recommended. A morphological model predicts sediment transport and bathymetric change over time and could be used to quantify potential impacts of different barrier designs and operating philosophies. Morphological models consist of a core hydrodynamic model, extended to include calculations of sediment transport and their feedback onto bed levels over time. For the Avon Heathcote Estuary it is important any morphological modelling includes the combined effects of waves, tides and river flows.

In order to have certainty in model outputs it is important that morphological models, including their hydrodynamic and sediment transport components are calibrated to observed data. For the Avon Heathcote Estuary this may require:

- **Focussed short term data collection campaign:** This would likely form the first stage of a morphological modelling study and would include deployments of instrumentation within and around the estuary such as ADCPs and turbidity sensors. It would also involve manual data collection activities such as suspended sediment sampling and bathymetric survey of the estuary and ebb tidal delta.

- **Increased medium-long term data collection:** Current data collection relevant to understanding estuary morphology includes regular coastal profile monitoring, flow monitoring on the Avon and Heathcote Rivers, sea level monitoring (ECan/NIWA Sumner sea level recorder) and offshore wave monitoring (ECan/NIWA banks peninsular wave buoy). In order to better inform understanding of morphology and allow improved analysis of barrier morphological impacts it is recommended to carry out additional monitoring activities for as long a duration as possible in advance of a morphological modelling study (ideally several years):
  - **Time-lapse camera(s):** Installing a fixed time-lapse camera or cameras overlooking the estuary mouth area would collect data on short-medium term morphological changes. Image processing routines could be developed to rectify imagery and extract daily shoreline position timeseries for a range of tidal water levels.
  - **Regular cross-section monitoring:** Similar to the current shoreline profile monitoring it is recommended that regular (monthly-yearly) cross-section monitoring is undertaken for the estuary mouth, the mouths of the Avon and Heathcote rivers, and at the location of the proposed barrier.

12.1.3 Visual impact assessment

The Options Report will need to provide visualisation material to illustrate all flood management options so that the general public can understand the visual impacts of the various options available. If possible, it may be useful if this material can be available in an electronic form so it is suitable for online / interactive engagement techniques.

12.1.4 Social impact assessment

A draft Social Impact Assessment should be prepared prior to consultation, which will inform the consultation approach needed and can then be developed further, following engagement with the community on the flood management options available to the City.

12.2 Consultation

Given the tidal barrier will be such a high profile and controversial project, early engagement with the public is essential to ensure there is sufficient public and political support for the project, before confirming the project is the best option and proceeding to concept design. The key reason that comprehensive early engagement is important for this project is the affected community is not necessarily the same as the community which will benefit from a barrier. Furthermore, the environmental effects are varied and complex for a barrier, so it’s important that the Council *“brings the community on the journey”* and approaches decision making on the wider financial, social and environmental feasibility of the project in a very open and transparent manner.

The key information required for the consultation aspect of this project will be around:

1. Defining the challenges of flood protection now and in the future
2. Setting out the options and combinations
3. Confirming high level costs to ratepayers on the various options (including life cycle costs)
4. Setting out flood management effectiveness for the options

5. Summarising high level environmental effects – scoping level of information
6. Providing visualisations for the options so people can better understand the concepts

Consultation would seek to obtain feedback on the preferred flooding management strategy and set out the next steps and opportunities for further involvement.

Given that the Council is currently working on a public engagement process for an overall Natural Hazards Strategy (NHS) for Christchurch (including Banks Peninsula), it could be useful to link the necessary consultation for the Avon-Heathcote flooding options (i.e. this project) with the wider NHS engagement as the discussion with the community is essentially the same, and this project would also assist with providing a real life example of the options available to manage natural hazards in one part of the city.

12.3 Tidal Barrier Concept Design

If upon completion of an overarching Flood Management Options Report a tidal barrier is considered to be required then the next stage will be to develop a confirmed concept. As this pre-feasibility study only developed a concept in order to test feasibility, rather than a concept intended for progression through subsequent design phases, the first step of the next phase will need to include reconsideration of both the barrier location and the barrier type/configuration.

This study also only addressed two climate scenarios, the present day scenario and 1 m sea level rise scenario. The Flood Management Options report will have considered a range of operating scenario, their impacts and sought community and stakeholder feedback regard the various operating options. Having received further guidance on these matters more detailed consideration will be possible regarding the type and location of a barrier structure.

In order to assist with the reconsideration of location/configuration and ultimately inform the concept design process a number of key tasks will need to be completed. These tasks are summarised under each of the following sub-headings.

12.3.1 On-site geotechnical investigations

Investigations to date have relied upon existing geotechnical and geological data and mapping. Once potential barrier sites have been reconfirmed it will be necessary to undertake site investigation works to confirm the validity of the existing data. This stage of work would need to include subsurface investigations, such as drill-holes, cone penetration tests (CPTs), and geophysical profiling (e.g. Multichannel Analysis of Surface Waves (MASW) and seismic refraction / reflection) to investigate the soil profile and properties and confirm the required ground improvement methodologies. Due to submerged nature of much of the area of interest, some of these investigations will need to be undertaken from a boat or barge.

12.3.2 Combined river flood and storm surge modelling study

To determine the effectiveness of the barrier, both now and in the future when the expected climate change has taken place, a sophisticated model complex would be required, where the entrance to estuary, the estuary itself and the rivers are combined to a single model. Only this way a consistent analysis of the impacts and effectiveness of the tidal barrier can be obtained. Furthermore, an extensive

Joint Probability analysis would be required to determine the appropriate combinations of storm and rainfall discharge from the rivers giving the design probability of occurrence.

12.3.3 Tsunami modelling study

A tidal barrier would almost certainly be position where it has the potential to be impacted by tsunami and mitigate the upstream effects of a tsunami. A tsunami modelling study would be required to address both of these issues, i.e. what structural requirements need to be applied in order to ensure that the structure is resistant to tsunami and what design / operational features could be incorporated to maximise the potential tsunami hazard reduction.

12.3.4 Dam break assessment

A tidal barrier structure would be classified as a large dam by the New Zealand Society of Large Dams (NZSOLD), and as such would require a dam break assessment in order to assess the likely impacts (in terms of loss of life) in the event of a failure. This assessment would inform the structural design requirements of the tidal barrier.

12.3.5 Development of a consenting strategy and initial enactment

A number of specialist environmental assessment reports will need to be commissioned for consenting purposes. These are likely to include the following disciplines:

- Coastal processes
- Hydrology and flooding
- Aquatic (coastal and river) ecology
- Terrestrial ecology
- Avian ecology
- Social impact assessment
- Economic impact assessment
- Archaeology and heritage
- Cultural impact assessment
- Traffic impact assessment
- Hydrogeology (effects on groundwater)
- Geotechnical including settlement
- Noise and vibration effects
- Erosion and sediment control
- Contamination
- Lighting
- Navigational safety

The range and scope of the specialist environmental assessment reports may need to be reviewed following the consultation phase, in order to ensure a comprehensive assessment that addresses all potential concerns likely to be raised by the community through the consenting process.

12.3.6 Ongoing community and stakeholder consultation

A further consultation phase would be required once a draft consent application was available. This may include the wider public or potentially just key stakeholders.

12.3.7 Concept design development

On the basis of the wider Flood Management Options report, outcomes from community and stakeholder consultation, and the investigations described above under this concept design phase it would be possible to develop a concept design for a tidal barrier.

At this stage the concept would confirm the location, type and operating philosophy of the tidal barrier. This would allow for preliminary concept design drawings to be developed and a revised cost estimate prepared with an approximately ±20% level of confidence.

13. Conclusions

As described at the outset of this report, Council is seeking to answer a range of questions relating to pre-feasibility of a tidal barrier in the Avon Heathcote Estuary. Responses to these questions are presented below.

What form would a barrier take?

There are a variety of forms that were assessed as being viable for a barrier in the Avon Heathcote Estuary. Based on preliminary assessment against a range of criteria a pre-feasibility barrier concept was developed which consists of gates, an embankment and abutments.

The vertical lift gate structure would be approximately 170 m wide spanning the main channel, anchored to the Redcliffs shoreline at one end and the newly constructed barrier embankment at the other. The gate structure's main component parts would include:

- A concrete sill founded in the channel floor at approximately -2.6 m LVD;
- Three bays approximately 50 m wide each;
- Each bay containing a 50 m wide gate, 6 m high, lifted clear of the water when the barrier is open;
- One gate could potentially be lifted 2 m clear to allow passage of kayaks and other small craft;
- Four 9 m high piers holding the gates, one at each side and two at 50 m intervals across the channel; and
- A walkway attached to the piers to allow maintenance access and potentially a public pedestrian/cycle link.

The embankment would be a constructed dune linking one end of the gate structure to the spit at Southshore. It would be approximately 430 m long and up to 200 m wide. In time as vegetation establishes and material migrates naturally the dune will resemble and extension of the existing reserve. The crest height would be a minimum of 3.4 m LVD, with some higher undulations to promote a natural look. The walkway from the gate structure could be extended across the dune to complete the link between Southshore and Redcliffs.

The abutment would be an augmentation of the existing flood defences at Redcliffs to connect the gate structure with the 2.9 m contour. Specific options for achieving this have not been determined as a part of this study, however options are likely to include increasing the heights of the existing sea wall coupled with localised raising of road levels.

Where would a barrier be best located?

In order to maximise estuary storage volume and limit the length of the barrier, assessment of location options was limited to the area close to the estuary mouth. Within this area there were two potential location options identified. The "Redcliffs Option" would span from somewhere along Beachville Road in Redcliffs to inner side of the spit in Southshore. The "Shag Rock Option" would span from somewhere near Shag Rock on the south side of the estuary mouth to somewhere near the tip of the spit in Southshore. These two options were assessed against a range of criteria and the Redcliffs option determined to be favourable.

Will a barrier work?

The pre-feasibility barrier concept will work from constructability and resilience perspectives. The concept could be constructed using resources and techniques that are available in New Zealand.

Resilience of the completed concept was considered with respect to a range of environmental risk factors. None of the risk factors was considered likely to undermine the functionality of the barrier within the relevant timescales.

What are the benefits of a barrier?

An assessment of barrier effectiveness was conducted by modelling estuary water level reductions and consequent river flooding reductions for a 100yr storm event. These model results have been analysed to assess the effect of a tidal barrier on the required extent of other flood mitigation measures under present day and 1 m sea level rise scenarios.

The cost / benefit comparison shows that for the present day climate scenario the cost of a tidal barrier far outweighs the expected cost reduction for other defence measures. However in the 1 m sea level rise scenario the cost for flood defence is comparable with the cost for flood defence without a barrier. This analysis does not take into consideration a tidal barrier's benefits relative to a full range of mitigation options (i.e. other engineering or planning options), nor does it assess value associated with environmental and social benefits/impacts, or give consideration to residual risk or tsunami risk.

Despite these limitations, it is possible to conclude that tidal barrier has sufficient flood management benefits under a 1 m sea level rise scenario to warrant further consideration as part of a wider flood management strategy. However, under present day climate conditions a tidal barrier is unlikely to offer sufficient benefit. Further work is required to address the limitations discussed above and determine at what stage (with respect to sea level rise) a barrier may become beneficial.

What are the potential costs for construction and whole of life for a barrier?

The estimated construction cost of the pre-feasibility concept (including barrier gates a dune embankment and flood defences for a 1km stretch along Redcliff) is approximately NZ$310. This cost includes a 25% construction contingency and 10% allowances for both design and consenting.

Operation and maintenance cost estimates are 1-5% of the capital cost per annum for the gate structure (($1.5M to $7.0M pa) and 1% of the capital cost per annum for the embankment ($0.25M pa).

When will a barrier be required and how long will it last in the face of sea level rise (durability and flood risk)?

As described in answer to the question of "What are the benefits of a barrier?" the immediate flood risk reduction benefits of a tidal barrier are limited, especially when cost is taken into consideration. Further analysis of intermediate sea level sea rise scenarios (i.e. more than 0 and less than 1 m) will be required to address the question of when a barrier would be required.

In terms of durability, a barrier constructed today could be readily future proofed to allow adaptation to sea level rise of 1 m or more.

In terms of managing future flood risk, as sea levels rise, it will become a matter of adapting the future barrier operating philosophy to balance the benefit of flood protection against potential environmental impacts of more frequent barrier operation. The factors involved are complex and further detailed investigation will be required to establish the optimal 'balance'.

What impacts will a barrier have?

A tidal barrier would have impacts on morphology, ecology and water quality, landscape and visual amenity, cultural value, heritage and archaeological values and recreation.

The barrier will have a local effect on morphology but given that the structure presents little obstruction to flow or sediment when it is open the effects will be small. Infrequent closures, as expected to be required in the present day scenario, are likely have little effect. Frequent barrier operation could trigger a change in the morphology of the spit tip or Sumner Bar potentially resulting in impacts on Sumner or Scarborough beaches, or on properties vulnerable to coastal erosion near the spit tip. Temporary works during construction have the potential to cause a significant disturbance to the position of the main tidal channel.

The ecological impact of infrequent barrier operation is low as most estuarine organisms and communities can tolerate exposure to freshwater providing near natural low tides are allowed to occur. However, unnatural manipulation of the estuary's water level, over more than a few successive days is incompatible with sustaining the ecosystem. In future constraining the high water level (to mitigate the flood effect of sea level rise) would result in reduced tidal amplitude, which shortens the intertidal range within the estuary. Ecological effects of this high water restraint will depend upon the barrier control regime implemented. Opportunities exist to develop barrier operating regimes which complement estuarine adaptation to sea level rise.

Effects on landscape and visual amenity will be unavoidable and significant in magnitude. There are a number of planning and policy documents which recognise the need to protect the landscape and visual amenity values in the estuary from inappropriate development. The proposal is likely to receive mixed reactions within the community with those adversely affected by the visual impact being different from the communities likely to benefit from the structure. Cultural value impacts will arise as the estuary location is recognised as being of significant value to local iwi – the scale of the cultural effects can only be determined in consultation with iwi. Effects on archaeological values are likely, as there is a high concentration of archaeological sites within the general area. There is an opportunity for positive recreation effects, particularly improved access for walking and cycling, through enabling access over the barrier – but in turn, this has the potential to generate social impacts through connecting Redcliffs with Southshore. There will also be an effect on recreational boating within the estuary, but these effects are not considered to be significant and can be mitigated to a certain extent through sensitive barrier design.

What are the risks associated with construction and operation of barrier?

Risk analysis at this stage has been largely focussed on impacts to morphology, ecology and water quality, landscape and visual amenity, cultural value, heritage and archaeological values and recreation. These risks are described in the previous question.

Safety risks to contractors and the general public during construction and operation of a tidal barrier should be further investigated during development of a barrier concept design. These investigations would need to include safety in design processes and a dam break assessment.

What other investigations are required to consent and construct a barrier?

This study has also concluded that a tidal barrier would not resolve Christchurch's flood risk challenges in isolation, it would need to be implemented in conjunction with other engineering and/or policy initiatives. What remains unclear from this study is whether a tidal barrier is a favourable option when considered as part the larger mix of options.

As such, future stages of a barrier implementation would need to consist of 3 elements. The first element would consider the benefits, impacts and costs of a barrier in comparison/conjunction with the other available flood management options. The second element would be to engage with the community to gain feedback on the flood management options available. The third element would work to develop the barrier concept toward implementation if it remains a favourable concept following the options comparison and community engagement. The list of activities/investigations likely to be required for design and consenting purposes at the concept design phase includes:

- On-site geotechnical investigations
- Tsunami modelling study
- Dam break assessment
- Development of a consenting strategy and initial enactment, which would include a number of specialist environmental assessment reports:
    - Coastal processes
    - Hydrology and flooding
    - Aquatic (coastal and river) ecology
    - Terrestrial ecology
    - Avian ecology
    - Social impact assessment
    - Economic impact assessment
    - Archaeology and heritage
    - Cultural impact assessment
    - Traffic impact assessment
    - Hydrogeology (effects on groundwater)
    - Geotechnical including settlement
    - Noise and vibration effects
    - Erosion and sediment control
    - Contamination
    - Lighting
    - Navigational safety

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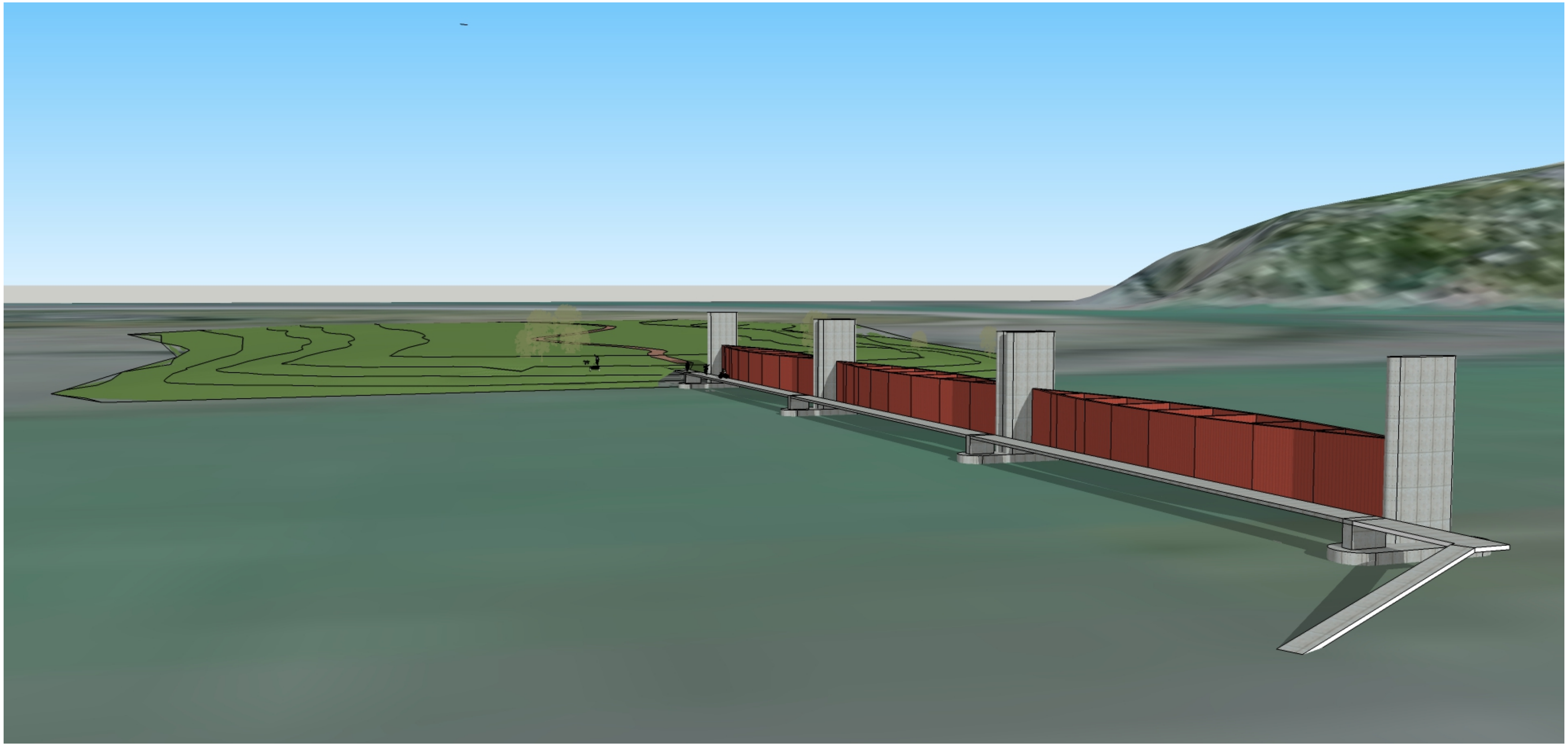
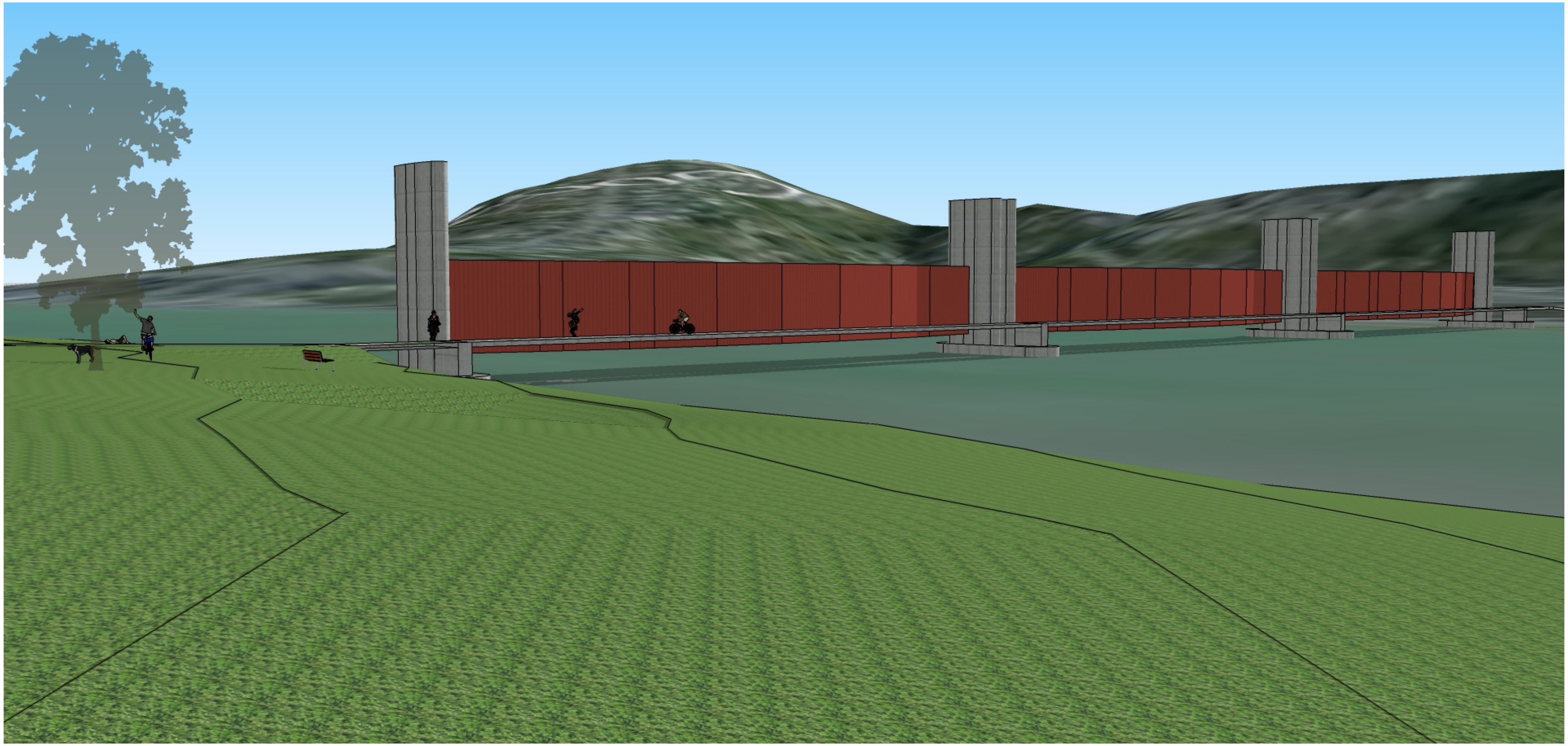
Appendix A

Visualisations





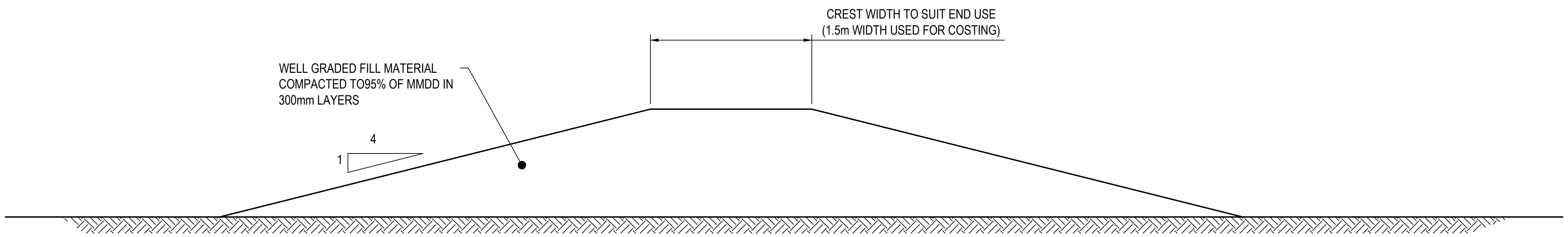
Appendix B

Construction Cost Estimate Breakdown

CCC Barrier Pre-Feasibility Construction Estimate					
Item	**Description**	**Quantity**	**Unit**	**Rate**	**Amount**
1	**Preliminary and General**		**20%**	**$ 43,260,159**	**$ 43,260,159**
2	**Embankment**				
2.01	Sand	206400	m^3	$ 77	$ 15,858,400
2.02	Geotextile	8839	m^2	$ 9	$ 79,547
2.03	Rock RipRap	5303	m^3	$ 246	$ 1,301,921
2.04	Planting	1	LS	$ 1,000,000	$ 1,000,000
2.05	Landscaping	1	LS	$ 500,000	$ 500,000
	Subtotal Embankment				**$ 18,739,868**
3	**Barrier**				
3.01	Sheetpiling	19392	m^2	$ 550	$ 10,665,600
3.02	Dewatering	864	day	$ 1,200	$ 1,036,800
3.03	Excavate and Dispose Sill Area	19550	m^3	$ 189	$ 3,686,571
3.04	Piling	48300	m	$ 550	$ 26,565,000
3.05	GAP65 Foundation	7820	m^3	$ 211	$ 1,650,020
3.06	Reinforcing Sill	1759500	kg	$ 4	$ 7,038,000
3.07	Concrete Sill	11730	m^3	$ 500	$ 5,865,000
3.08	Formwork Pier	5240	m^2	$ 230	$ 1,205,200
3.09	Reinforcing Pier	3018000	kg	$ 4	$ 12,072,000
3.1	Concrete Pier	17960	m^3	$ 500	$ 8,980,000
3.11	Pier Steel End Protection	43960	kg	$ 7	$ 312,116
3.12	Fabricate Steel Barrier	600406	kg	$ 15	$ 9,066,134
3.13	Deliver Barrier to Site	3	LS	$ 60,000	$ 180,000
3.14	Install Barrier	3	LS	$ 339,600	$ 1,018,800
3.15	Access Deck T Beams Formwork	1590	m^2	$ 230	$ 365,769
3.16	Access Deck T Beams Reinforcing	171291	kg	$ 4	$ 685,163
3.17	Access Deck T Beams Concrete	489	m^3	$ 480	$ 234,913
3.18	Install T Beams	1	LS	$ 679,200	$ 679,200
3.19	Formwork Access Deck	68	m^2	$ 230	$ 15,640
3.2	Reinforcing Access Deck	32640	kg	$ 4	$ 130,560
3.21	Concrete Access Deck	272	m^3	$ 480	$ 130,560
3.22	Access Deck Barriers and Handrail	340	m	$ 1,182	$ 401,820
3.23	Deck Surface	1360	m^2	$ 50	$ 68,000
3.24	Mechanical Barrier	1	LS	$ 20,000,000	$ 20,000,000
3.25	Electrical/Control Barrier	1	LS	$ 2,000,000	$ 2,000,000
3.26	Control Building	1	LS	$ 1,500,000	$ 1,500,000
3.27	Excavate and Dispose Channel Area	36975	m^3	$ 189	$ 6,972,429
3.28	Geotextile	14790	m^2	$ 9	$ 133,110
3.29	Rock RipRap Channel Area	36975	m^3	$ 246	$ 9,077,363
	Subtotal Barrier				**$ 131,735,767**
4	**Stop Bank Flood Protection**				
4.01	Pit Run	60000	m^3	$ 106	$ 6,372,000
4.02	Geotextile	11068	m^2	$ 9	$ 99,612
4.03	Rock RipRap	6641	m^3	$ 246	$ 1,630,312
4.04	Topsoil	3446	m^3	$ 114	$ 391,865
4.05	Basecourse	3000	m^3	$ 100	$ 300,000
4.06	AC Pavement 50mm	10000	m^2	$ 45	$ 450,000
4.07	Drainage Works	1	LS	$ 2,500,000	$ 2,500,000
	Subtotal Flood Protection				**$ 11,743,789**
5	**Contingency & Miscellaneous**		**30%**	**$ 54,081,371**	**$ 54,081,371**
	Total Pre-Feasibility Construction Estimate				**$ 259,560,954**

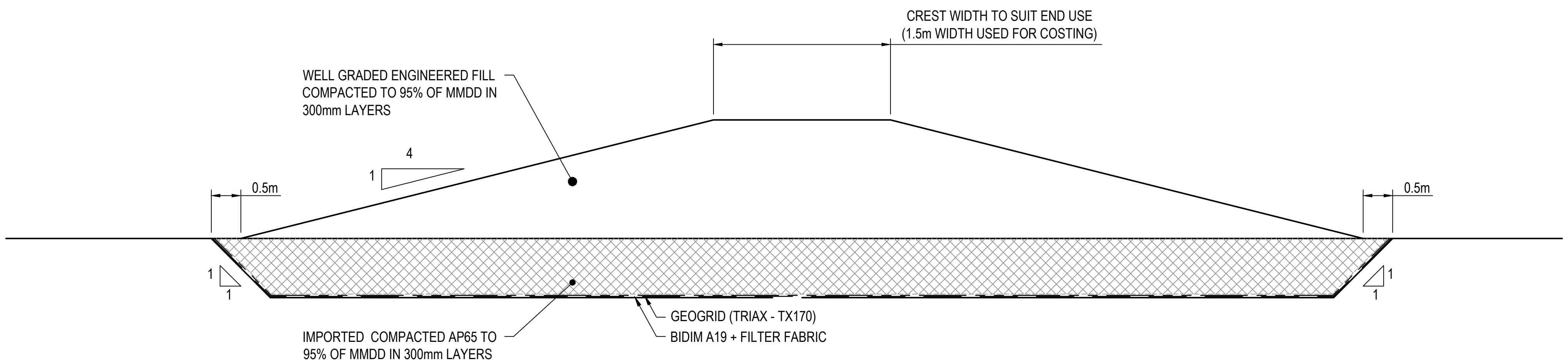
Appendix C

Stopbank Types



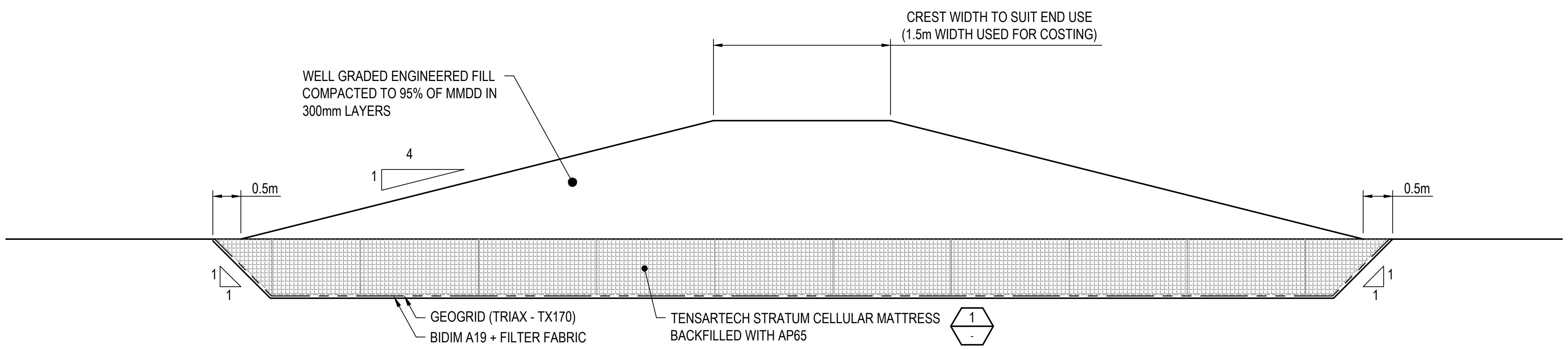
STOPBANK TYPE 1 - NO FOUNDATION

SCALE 1:50



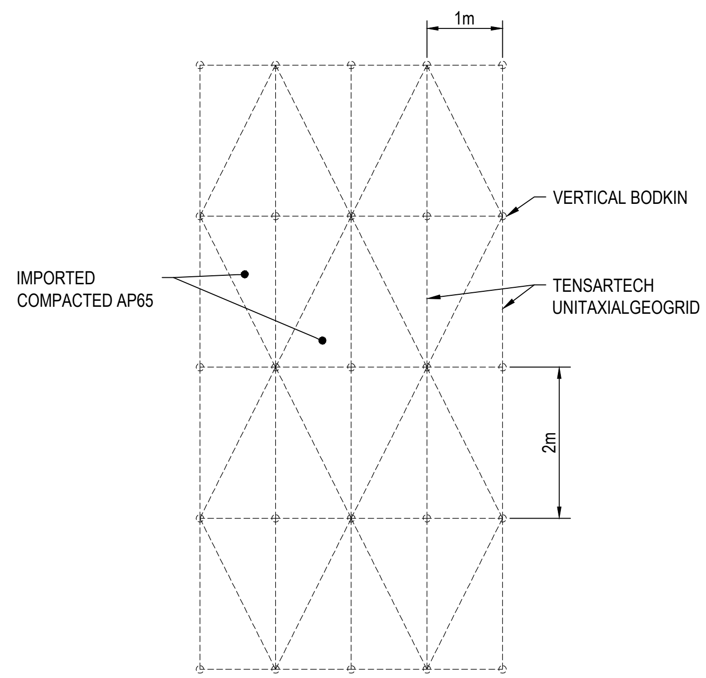
STOPBANK TYPE 2 - GRAVEL RAFT FOUNDATION

SCALE 1:50



STOPBANK TYPE 3 - GEOCELL FOUNDATION

SCALE 1:50



PLAN VIEW OF TENSARTECH
STRATUM CELLULAR MATTRESS

1 DETAIL
-
SCALE 1 : 50

PRELIMINARY

rev	description	app'd	date
A	INITIAL ISSUE		

CHRISTCHURCH CITY COUNCIL
RIVER & TIDAL FLOOD PROTECTION NEEDS

AVON RIVER
UPDATED TYPICAL SECTIONS

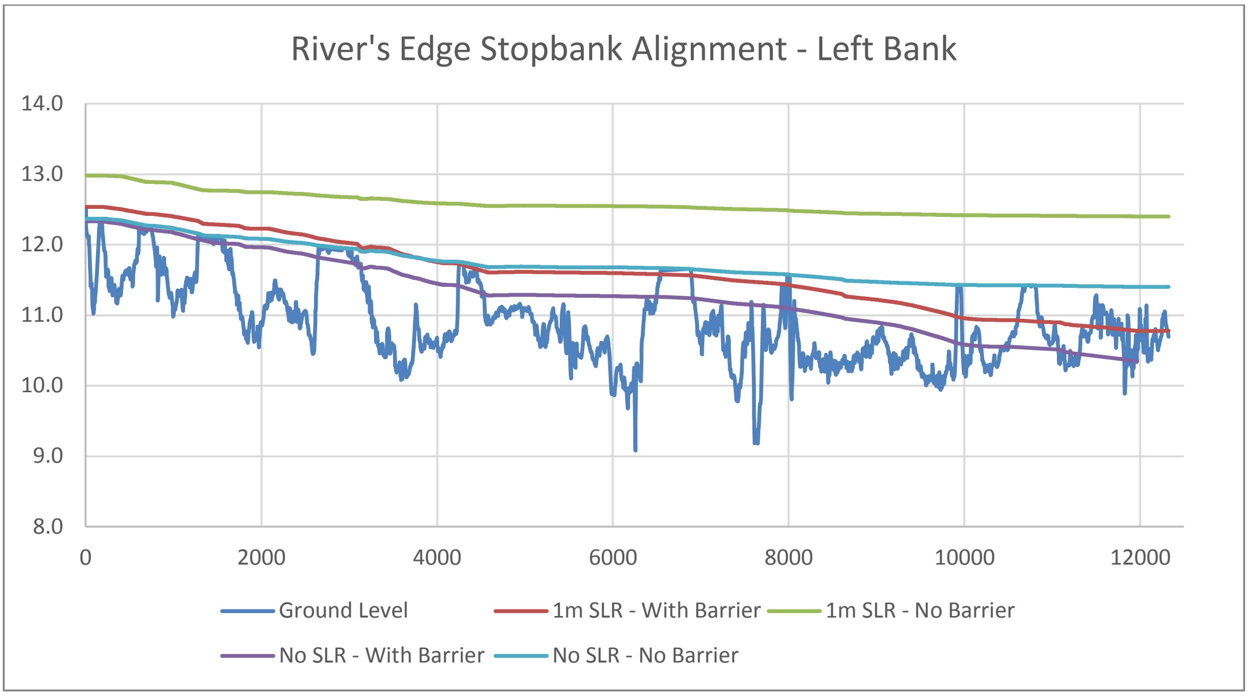
GHD
226 Antigua St
Christchurch 8011, New Zealand
T 64 3 378 0900 F 64 3 377 8575
E chcmail@ghd.com W www.ghd.com

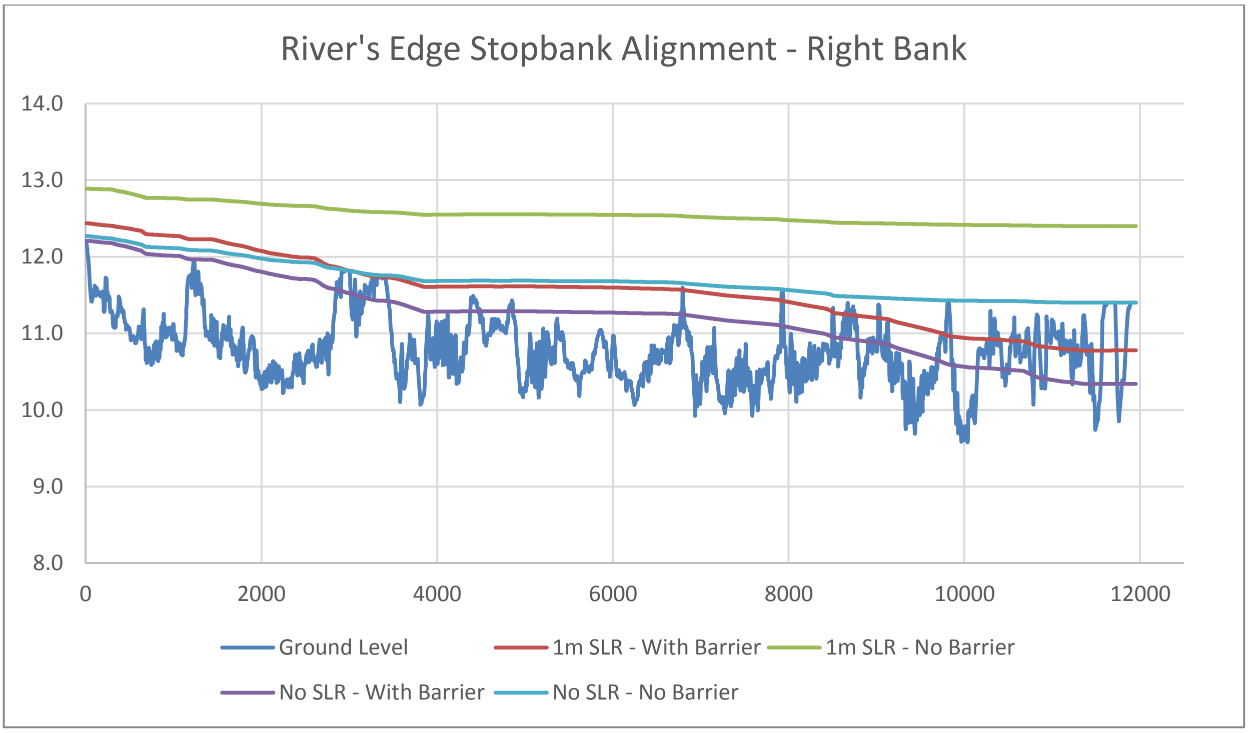
scale 1:50 for A1 job no. 51-3104603
date DECEMBER 2014 rev no. A

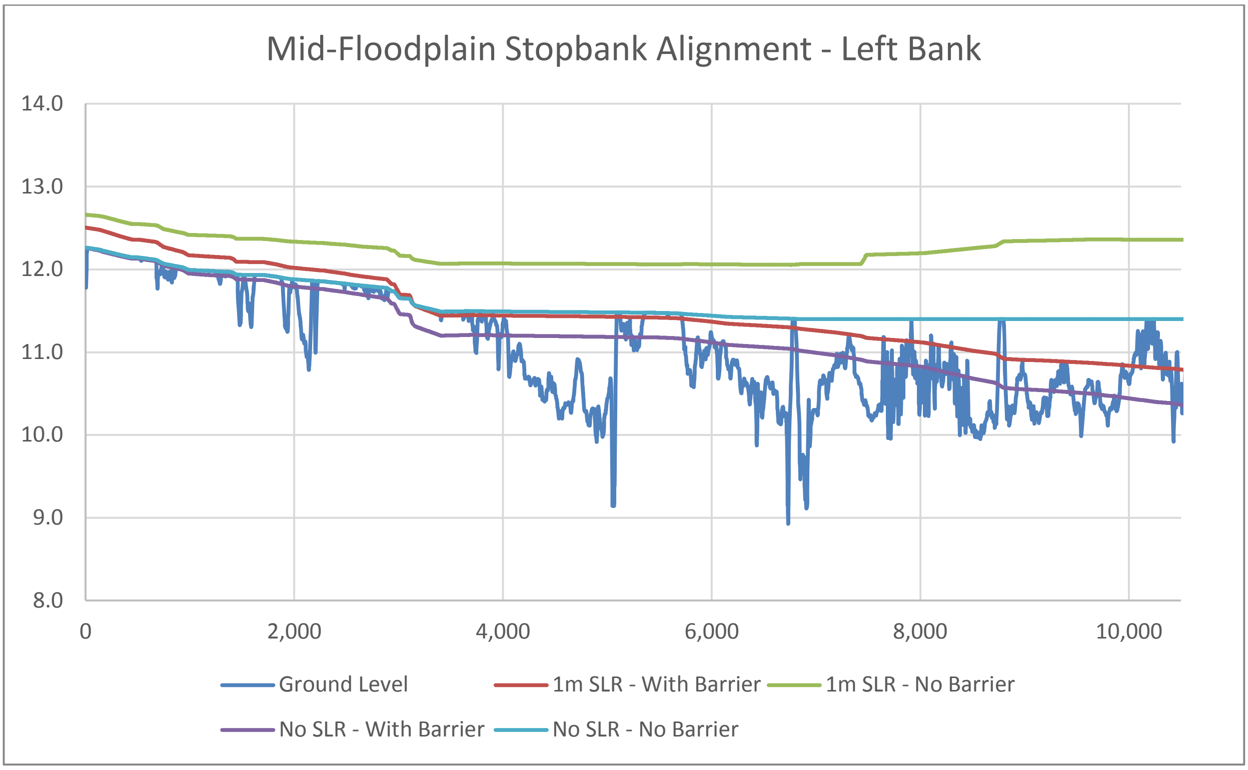
approved (PD) SK001

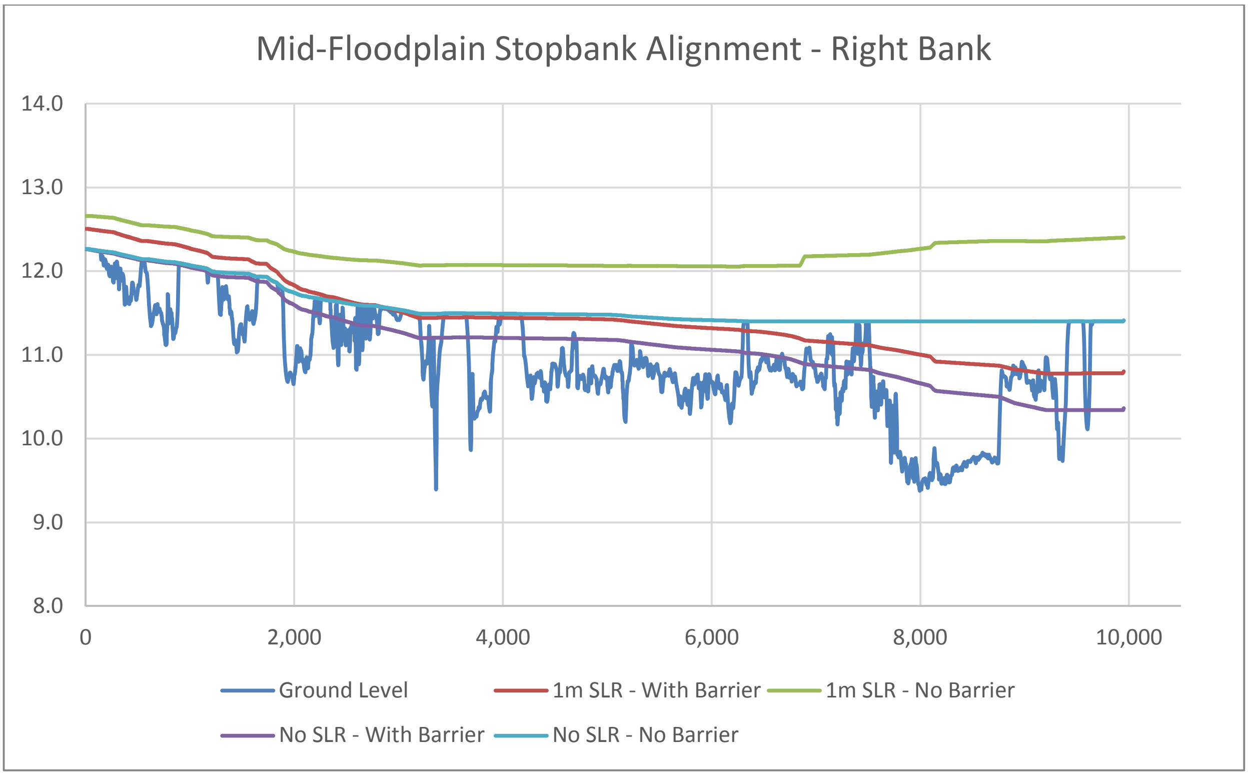
Appendix D

Avon River Long Sections


River's Edge Stopbank Alignment - Left Bank
14.0
13.0
12.0
11.0
10.0
9.0
8.0
0
2000
4000
6000
8000
10000
12000
Ground Level
1m SLR - With Barrier
1m SLR - No Barrier
No SLR - With Barrier
No SLR - No Barrier


River's Edge Stopbank Alignment - Right Bank
14.0
13.0
12.0
11.0
10.0
9.0
8.0
0
2000
4000
6000
8000
10000
12000
Ground Level
1m SLR - With Barrier
1m SLR - No Barrier
No SLR - With Barrier
No SLR - No Barrier

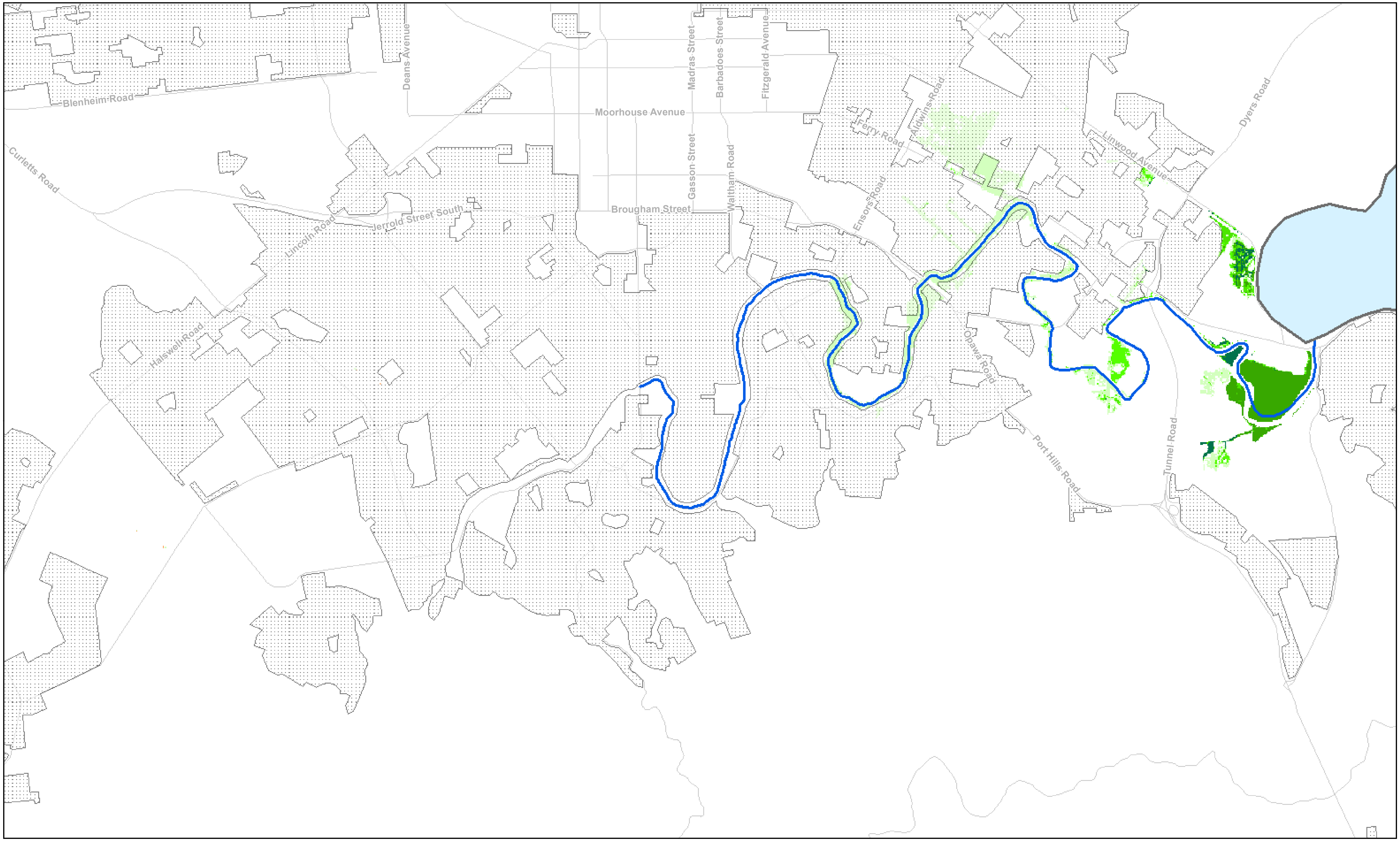




Note that the disjointed nature of the Outer-Floodplain stopbank alignments make them impractical to plot on a graph. The water surface profiles / stopbank levels are similar, but slightly lower than those shown above.

Appendix E

Heathcote River Flood Extents



Paper Size A3

0 145 290 580 870 1,160

Metres

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

Heathcote Change in Flood Depth With Barrier (NoSLR)

- 0.3 - 0.4
- 0.2 - 0.3
- 0.01 - 0.2
- -0.01 - 0.01
- -0.2 - -0.01
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -1.225 - -0.5
- Residential zone

GHD

Christchurch City Council

Christchurch City Council
Avon-Heathcote Barrier Pre-Feasibility Study

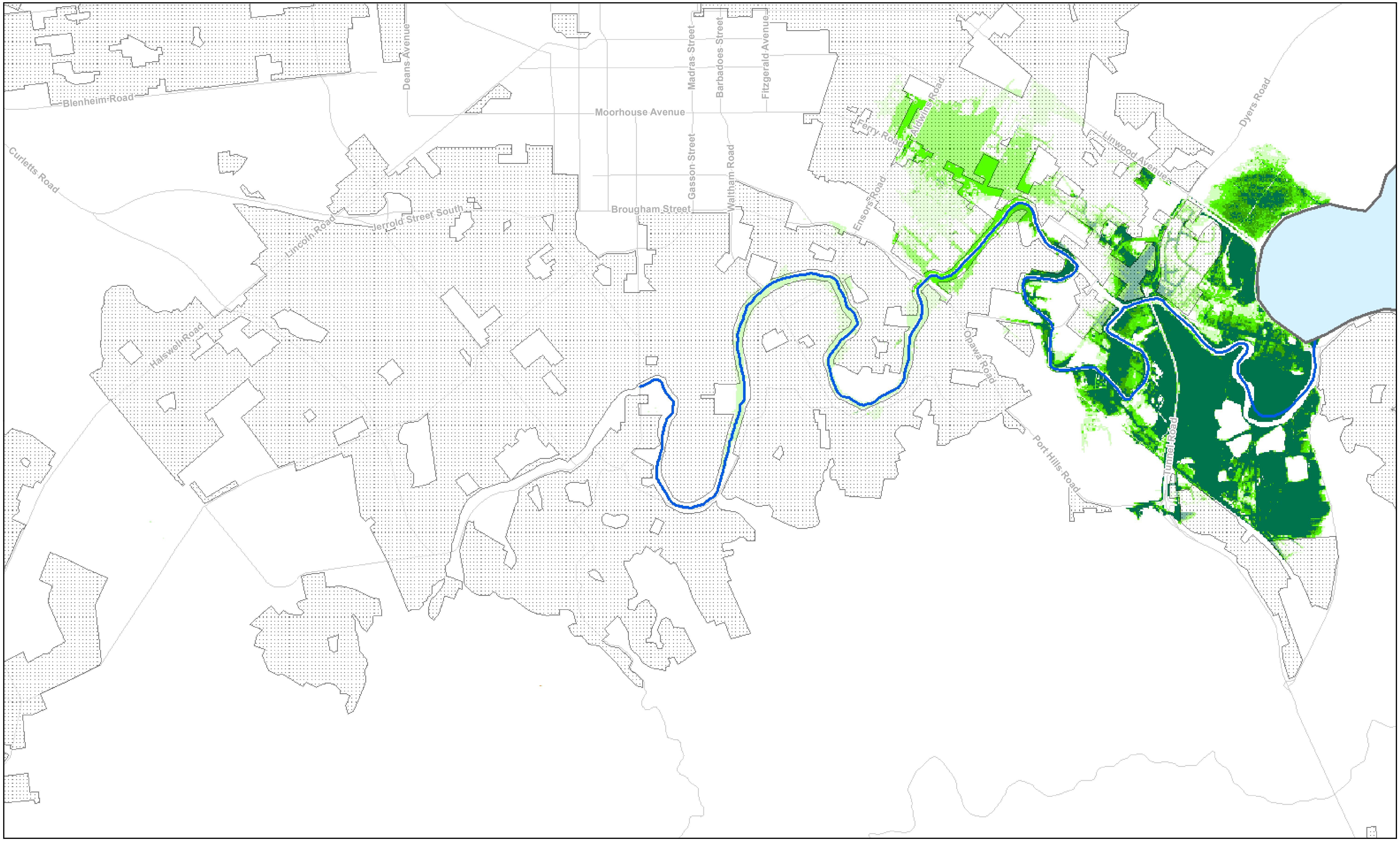
Change in Flood Depth with proposed Barrier for the post-earthquake 100 year flood (no SLR)

Job Number	51-33059
Revision	B
Date	29 May 2015

G:\51\33059\GIS\Maps\Mxd\51_33059_G004_RevB_Heathcoth_flood_map_DepthDifference_1mSLR.mxd

GHD House, 226 Antigua Street, Christchurch 8011, PO Box 13468, Christchurch 8141 New Zealand T 64 3 378 0900 E chcmail@ghd.co.nz W www.ghd.com

Data source: LINZ; nz-mainland-residential-a. GHD; x001_Avon_River, NZ_Coastal_Mask_follow_estuary-and-FMA_27082013, Heathcote_100yrRF10yrTS_Barrage_MaxDepth_NZTM_Poly_03, Heathcote_100yrRF10yrTS_Erase, Strategic_Roads_NZTM. Created by:tpowell



Paper Size A3

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Metres

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

Heathcote Change in Flood Depth With Barrier (with 1m SLR)

- 0.3 - 0.4
- 0.2 - 0.3
- 0.01 - 0.2
- -0.01 - 0.01
- -0.2 - -0.01
- -0.3 - -0.2
- -0.4 - -0.3
- -0.5 - -0.4
- -1.225 - -0.5
- Residential zone

GHD
Christchurch City Council

Christchurch City Council
Avon-Heathcote Barrier Pre-Feasibility Study

Change in Flood Depth with proposed Barrier for the post-earthquake 100 year flood (1m SLR)

Job Number	51-33059
Revision	B
Date	29 May 2015

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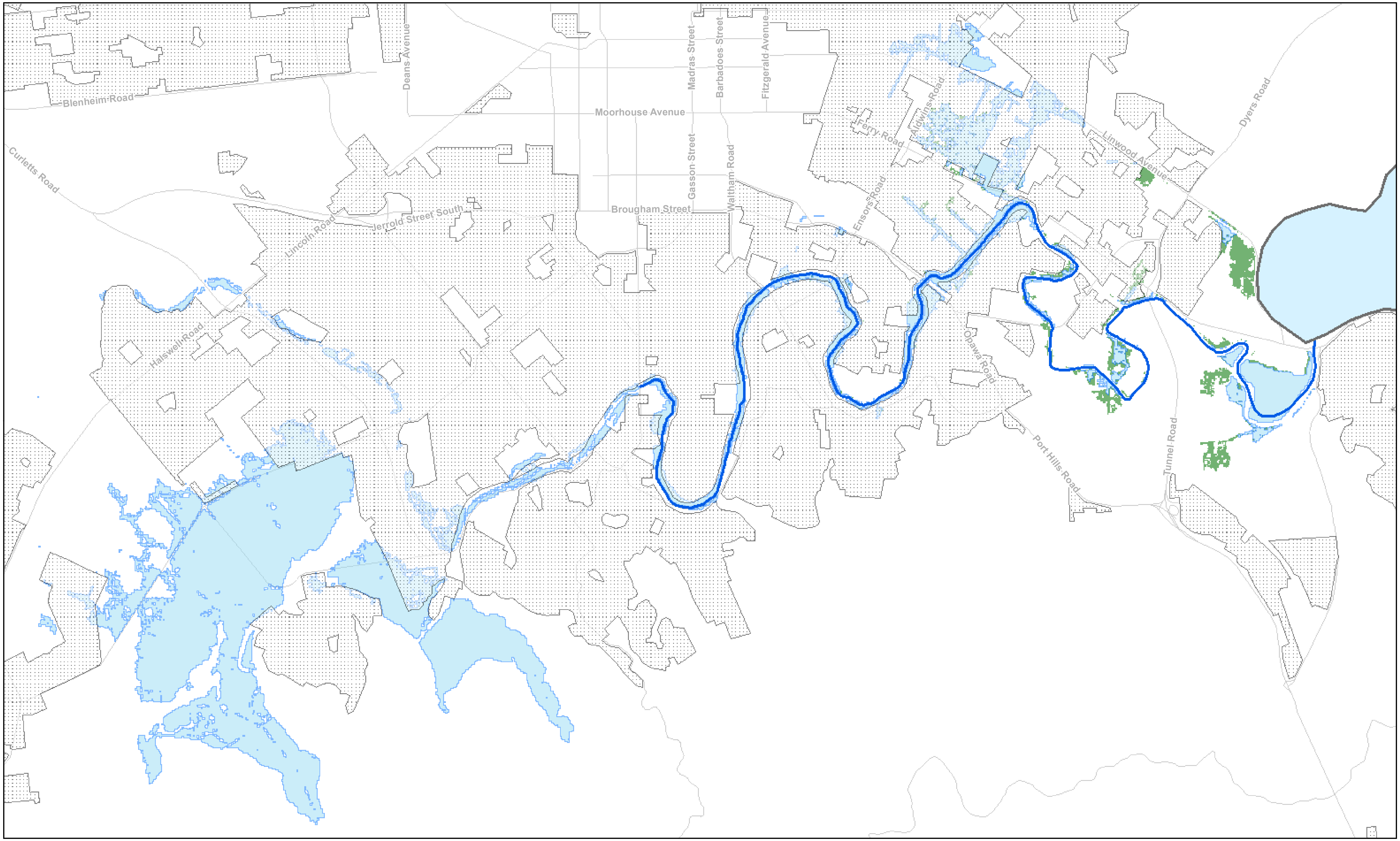
GHD House, 226 Antigua Street, Christchurch 8011, PO Box 13468, Christchurch 8141 New Zealand **T** 64 3 378 0900 **E** chcmail@ghd.co.nz **W** www.ghd.com

Data source: LINZ; nz-mainland-residential-a. GHD; x001_Avon_River, NZ_Coastal_Mask_follow_estuary-and-FMA_27082013, Heathcote_100yrRF10yrTS_Barrage_MaxDepth_NZTM_Poly_03, Heathcote_100yrRF10yrTS_Erase, Strategic_Roads_NZTM. Created by:tpowell



Paper Size A3

0 145 290 580 870 1,160

Metres

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

Heathcote Inundation Extent with Barrage (No SLR)

Reduction in Flood Extent due to Barrier

Residential zone

GHD

Christchurch City Council

Christchurch City Council
Avon-Heathcote Barrier Pre-Feasibility Study

Change in Inundation Extent with proposed Barrier
for the post-earthquake 100 year flood (No SLR)

Job Number	51-33059
Revision	B
Date	29 May 2015

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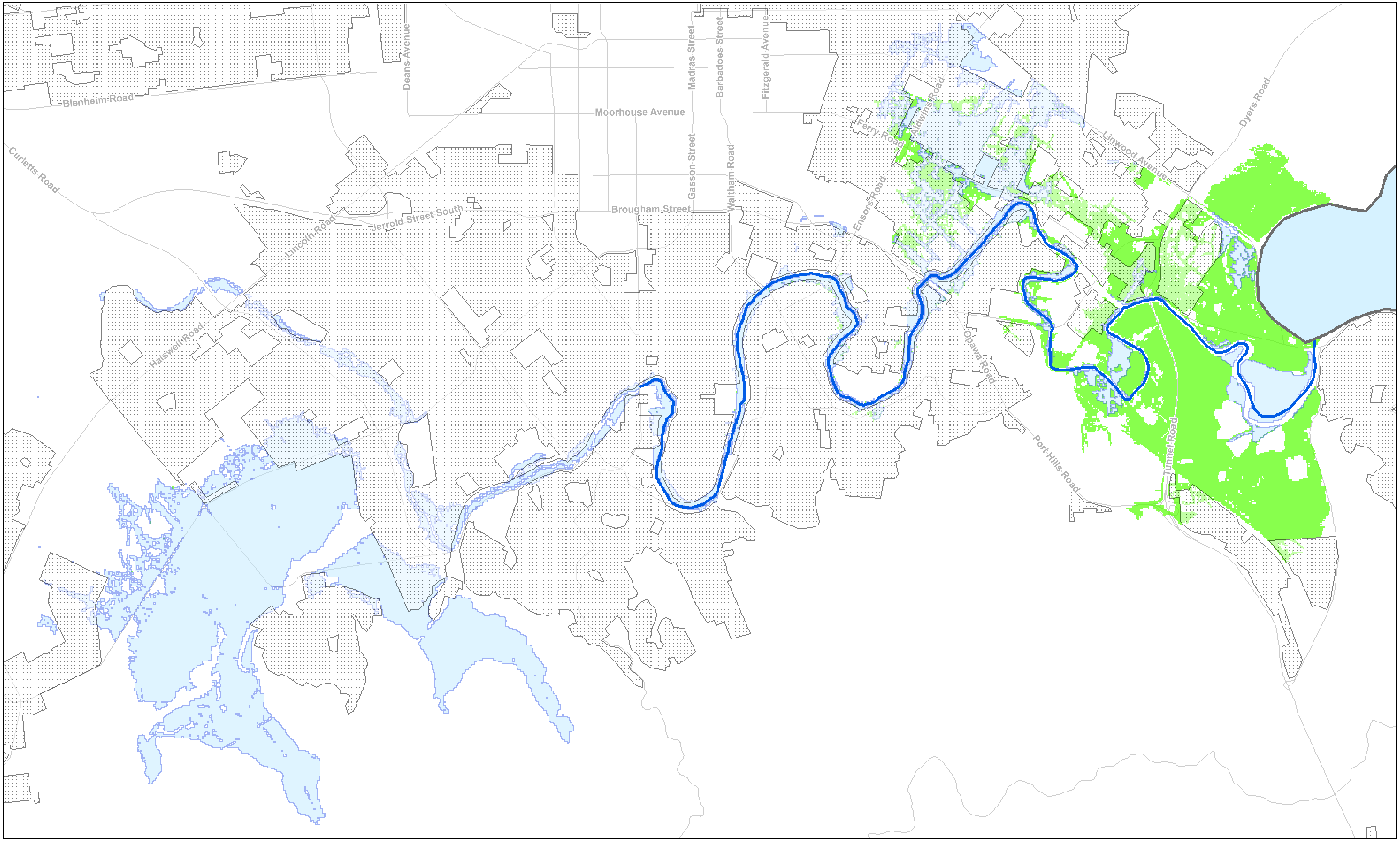
GHD House, 226 Antigua Street, Christchurch 8011, PO Box 13468, Christchurch 8141 New Zealand T 64 3 378 0900 E chcmail@ghd.co.nz W www.ghd.com

Data source: LINZ; nz-mainland-residential-a. GHD; x001_Avon_River, NZ_Coastal_Mask_follow_estuary-and-FMA_27082013, Heathcote_100yrRF10yrTS_Barrage_MaxDepth_NZTM_Poly_03, Heathcote_100yrRF10yrTS_Erase, Strategic_Roads_NZTM. Created by:tpowell



Paper Size A3

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Metres

Map Projection: Transverse Mercator
Horizontal Datum: NZGD 2000
Grid: NZGD 2000 New Zealand Transverse Mercator

N

- Heathcote Inundation Extent With Barrier (1m SLR)
- Reduction in Flood Extent due to Barrier
- Residential zone

GHD

Christchurch City Council

Christchurch City Council
Avon-Heathcote Barrier Pre-Feasibility Study

Job Number	51-33059
Revision	B
Date	29 May 2015

Change in Inundation Extent with proposed Barrier for the post-earthquake 100 year flood (with 1m SLR)

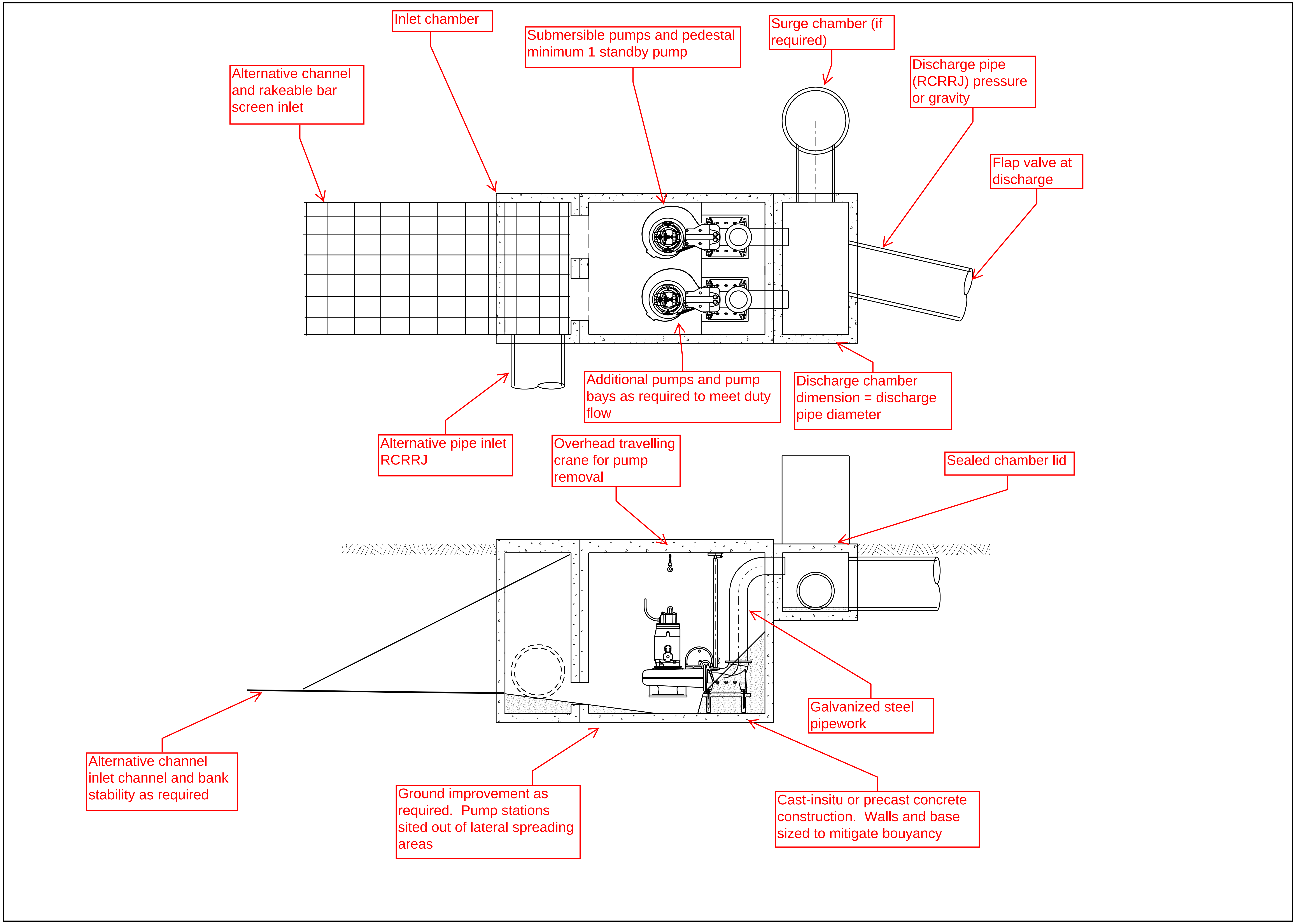
G:\51\33059\GIS\Maps\Mxd\51_33059_G001_RevB_Heathcoth_flood_map_Extent_SLR_1m.mxd

GHD House, 226 Antigua Street, Christchurch 8011, PO Box 13468, Christchurch 8141 New Zealand T 64 3 378 0900 E chcmail@ghd.co.nz W www.ghd.com

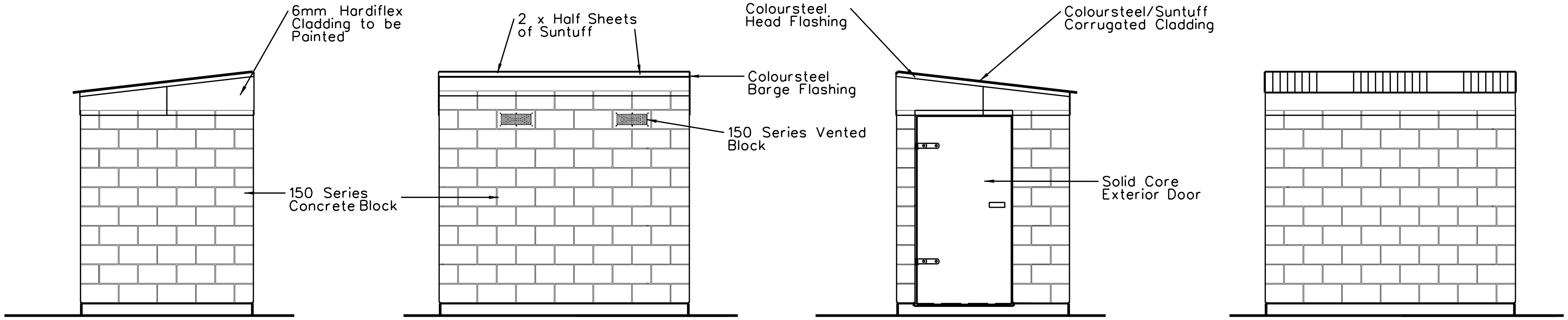
Data source: LINZ; nz-mainland-residential-a. GHD; x001_Avon_River, NZ_Coastal_Mask_follow_estuary-and-FMA_27082013, Heathcote_100yrRF10yrTS_1mSLR_Barrage_MaxDepth_Poly_02, Heathcote_100yrRF10yrTS_1mSLR_Erase, Strategic_Roads_NZTM. Created by:tpowell

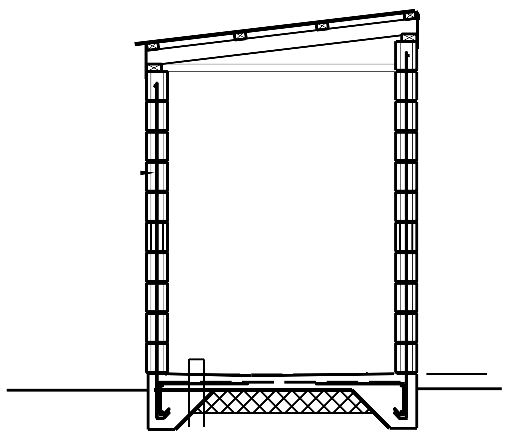
Appendix F

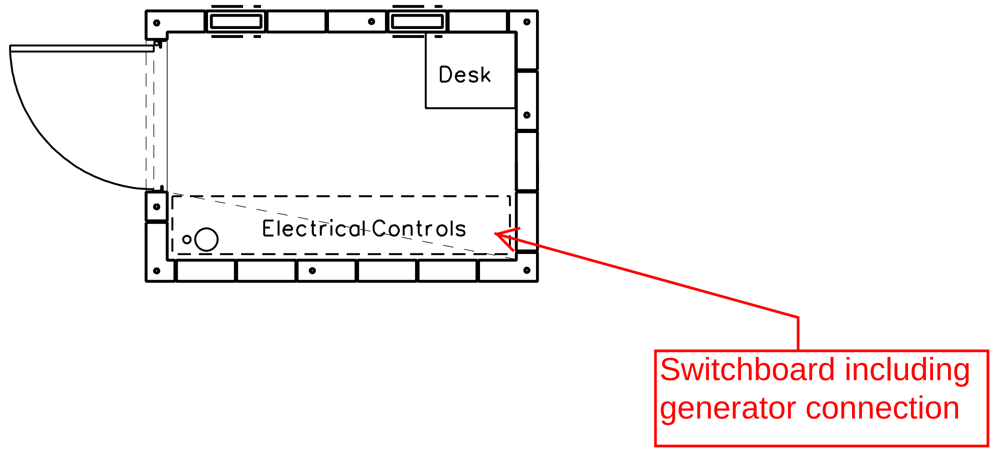
Standard Pump Station Drawings



Inlet chamber
Submersible pumps and pedestal minimum 1 standby pump
Surge chamber (if required)
Alternative channel and rakeable bar screen inlet
Discharge pipe (RCRRJ) pressure or gravity
Flap valve at discharge
Additional pumps and pump bays as required to meet duty flow
Discharge chamber dimension = discharge pipe diameter
Alternative pipe inlet RCRRJ
Overhead travelling crane for pump removal
Sealed chamber lid
Galvanized steel pipework
Alternative channel inlet channel and bank stability as required
Ground improvement as required. Pump stations sited out of lateral spreading areas
Cast-insitu or precast concrete construction. Walls and base sized to mitigate bouyancy


6mm Hardiflex Cladding to be Painted
150 Series Concrete Block
2 x Half Sheets of Suntuff
Coloursteel Barge Flashing
150 Series Vented Block
Coloursteel Head Flashing
Coloursteel/Suntuff Corrugated Cladding
Solid Core Exterior Door




Desk
Electrical Controls
Switchboard including generator connection

GHD

GHD Building
226 Antigua Street, Christchurch 8013
T: 64 3 378 0900 F: 64 3 377 8575 E: chcmail@ghd.com

Document Status

Rev No.	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
0	Matt van der Peet Richard Measures	Martin Dasler	M Dasler	Martin Dasler	M Dasler	23/7/15
1	Matt van der Peet Richard Measures	Martin Dasler	M Dasler	Martin Dasler	M Dasler	27/7/15