New Zealand Climate Change Research Institute
DTU Management Engineering

# Preparing for Sea Level Rise
# An Adaptive Managed Retreat Case Study

## Master Thesis

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By
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## Approval

This thesis has been prepared over six months as a collaborative project between Victoria University Wellington (VUW) and the Technical University of Denmark (DTU). The research took place in New Zealand. Guidance from the New Zealand research team consisting of Dr Judy Lawrence from VUW and Dr Rob Bell from NIWA as the direct supervisors for the research. Supervision in Denmark consisted of Dr Martin Drews from DTU Management Engineering guiding and making sure this research complies with DTU standard for a thesis.

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# Abstract

Low-lying coastal areas of New Zealand are increasingly exposed to sea-level flooding and sea level rise (SLR) has been indicated as one of the key factors affecting low-lying coastal communities in New Zealand. SLR causes increases in groundwater levels, in turn reducing the discharge capacity of gravity-based two water infrastructure. Other impacts from climate change like changes in precipitation patterns cause increased discharge to the drainage systems. This requires adaptation of two water infrastructure and raises the issue of how local government can maintain levels of service for the two waters as the impacts of climate change worsen over the coming decades(and beyond). The adaptation option being explored in this study is retreat of two waters infrastructure (waste water and storm water) and how it could be implemented in a managed way. This includes exploring the interface between water services and the community retreat.

To encompass this deep uncertainty, rather than pre-selecting a scenario, a dynamic adaptive approach is used to develop a range of alternative pathways to achieve the desired objective or level of service. Long term retreat was investigated for the Petone / Alicetown two water infrastructure by using Dynamic Adaptive Pathway Planning (DAPP). A mix of quantitative and qualitative input was used to determine adaptation thresholds (AT's) for the system. This was achieved by investigating two water asset exposure using an exposure assessment in conjunction with ground-thruthing findings with local experts.

By using a DAPP approach to frame retreat in different areas it was found to be a suitable approach to address uncertainties arising from SLR when implementing a two water retreat strategy. This was possible using a combination of an area specific retreat strategy (1), area specific pathways (2), area specific retreat phases (3), signal land use changes (4) and identify pathway conflicts and synergies. Pathway portfolios were developed with a portfolio of actions, planning and land use implications and failure conditions. This was useful for determining pathway / portfolio changes. This enabled (1) separation of retreat phasing from the pathways and (2) visualization of the effects between these pathways.

It was found that by using a systematic approach combining adaptation pathways, retreat phases and signalling land use changes by using long-term planning over potentially different pathway portfolios, could minimize disruption, signal land use changes and allow for gradual budget adjustments. The development of this 'routine' provides a structured approach for managed retreat of two water infrastructure. Compensation plays an important role in addressing the inequity of signaling restrictive land use planning (e.g. closed zoning to further development). Timely discussions around compensation and limiting development in vulnerable areas is therefore important for fitting retreat in a long term threshold based approach. Creating amenity for the community by repurposing areas could help overcome the social feasibility barrier. In the end retreat is a socio-political issue, what has been developed in this study is a way to inform and improve the decision making process for relevant stakeholders, authorities and the community.

# Acknowledgements

**Dr. Judy Lawrence**, Senior Research Fellow, New Zealand Climate Change Research Institute, School of Geography, Environment and Earth Sciences, Victoria University of Wellington

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# Contents

# 1 Introduction

Recent investigations in New Zealand seek to document how climate change is likely to affect coastal communities, e.g., by means of sea level rise (SLR) and enhanced risk of coastal flooding, rising groundwater and combined rainfall, river flood and storm-tide occurrences. Sea level rise has been indicated as one of the key factors affecting low-lying coastal communities in New Zealand (Ministry for the Environment, 2017; Local Government New Zealand, 2016; Paulik et al., 2020; Hughes et al., 2020 (In Press)). Negative consequences induced by SLR include more frequent flooding, increased erosion and increases in groundwater levels, saltwater intrusion, liquefaction and drainage problems.

Climate change impacts for New Zealand as a result of SLR threaten coastal infrastructure, communities and low-lying ecosystems (Rouse et al., 2017). Low-lying coastal areas of New Zealand are already exposed to extreme sea-level flooding (present-day 1/100 year event). This affects 0.8 percent of the land area of New Zealand but exposes approximately 72,000 residents or 1.6 percent of New Zealand's population (Paulik et al., 2020). Infrastructure exposure to climate change in New Zealand was investigated by Local Government New Zealand (Local Government New Zealand, 2019a, 2019b). It became clear that three waters (waste water, water supply and storm water) have the greatest exposure of the investigated infrastructure. Local Government New Zealand (2019b) found that the replacement value of three waters infrastructure exceeds the replacement value of exposed roads and buildings.

New Zealand's national coastal hazards and climate change guidance uses a scenario approach to assimilating SLR projections into land-use planning and engineering design, with the primary purpose of stress-testing adaptation options and actions (Ministry for the Environment, 2017; Lawrence, Bell, et al., 2018). Scenarios track with some certainty to mid century then there is a widening (or deep) uncertainty in SLR later this century and beyond e.g. in the next 100 years, which is the planning period required by the New Zealand Coastal Policy Statement-2010. The 4 scenarios in the guidance (Appendix 1) cover a range of SLR from 0.55 to 1.36 m by 2120 which primarily depends on how global emissions will track and the emergence of polar ice-sheet instabilities.

To encompass the deep uncertainty from mid century, rather than pre-selecting a scenario (which could be the best estimate, a most-likely scenario, or a worst case), a dynamic adaptive approach is used to develop a range of alternative pathways to achieve the desired objective or level of service. Monitoring the system performance, relative to those objectives, through early signals and triggers (decision points), informs stakeholders and the community when an alternate pathway will need to be implemented. While this approach has been applied to communities generally or large-scale projects (e.g. the Delta project in The Netherlands), little research has been undertaken on its applicability as a framework for addressing the adaptation of stormwater and wastewater networks (other than Kapetas and Fenner, 2020; Manocha and Babovic, 2017).

This study focuses on the Petone and Alicetown area, located in Lower Hutt in the Wellington region, which can be seen in Figure 1.1. The area was historically developed in the early settlement part of the late 19th and early 20th centuries to the point where the flood plain is now largely urbanized, also shown in Figure 1.1. Damaging earthquakes have impacted the area a few times (e,g, 1855, 2013, 2016), arising from fault lines through the wider Wellington region. A major fault line (the Wellington Fault) runs through through the west boundary of the Petone area (Greater Wellington Regional Council, 1996). Compared to its adjacent areas, there is also an increased risk of liquefaction, ground shaking and tsunami inundation hazard (Greater Wellington Regional Council, 1996). The area is located in between a river mouth and the Wellington harbour area. What becomes apparent when looking at the project area is how the urbanized area of Petone is trapped between an incline at the western Hutt road, the floodplain and the proximity of the coastline. The area is characterized by being located in a river valley where the 54 km long Hutt river meets the Wellington Harbour area. The width of the estuary is 4.5 km wide at this point (Lawrence et al., 2011). The esplanade, a major road link, runs along the coastline with some vegetated dunes present. There is also a tidal interaction with the Hutt river.

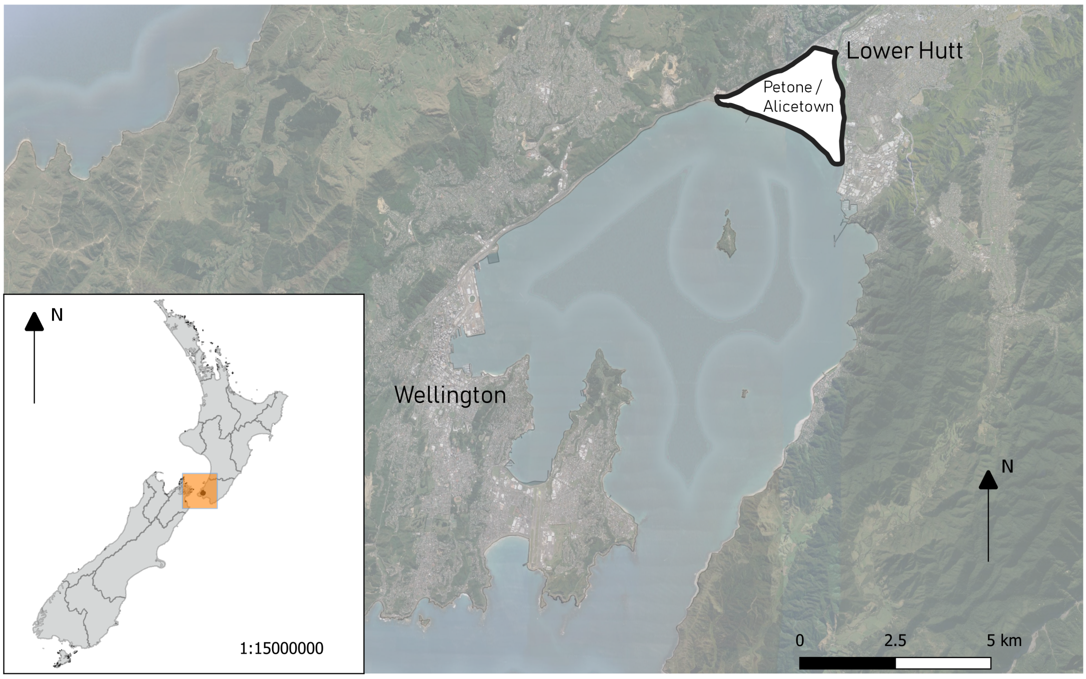

Figure 1.1: Study Area

Flooding has been an issue historically in the area, where ten major floods have occurred between 1855 and 2000, and more recently the 2004 Hutt river floods (Lawrence et al., 2014). Traditionally flood risk-reduction options comprise structural protection measures like levees and stop banks, creating a legacy problem where citizens have an unrealistic perception of flood risk and the expectation that the area will continue to protect them for all floods going into the future. The Petone area was identified as the most vulnerable geographic unit together with the Seaview area, a reclaimed area located next to Petone, for the Hutt City Council (Daysh, 2019). This is despite the presence of one of New Zealand's largest flood protection schemes (Lawrence et al., 2014). Paulik et al. (2020) and Paulik et al. (2019) show that Wellington is among the cities with the highest pipeline exposure for all three waters infrastructure in New Zealand and with the highest replacement costs.

This raises the issue of how local government can maintain levels of service for the two waters as the impacts of climate change worsen over the coming decades (and beyond) to reflect the plausible futures during the lifetime of the asset. Local government has a mandate[1] to address the effects of climate change, when assessing the delivery of services and for the wellbeing of communities. This broadly includes planning by avoiding and mitigating adverse effects of hazards, flood risk reduction, and delivery of water services. To date the approach taken by the local government is to address impacts of flooding on the three waters infrastructure as they emerge (Controller and Auditor-General, 2020). This strategy may appear to suffice in the short term (provided any inevitable service failures can be acceptably managed) but may compound the impacts in the long term as the effects of sea level rise become more apparent. A strategy that can be developed to anticipate those impacts can be explored along a number of pathways before the adaptation threshold materializes. The adaptation option being explored in this study is managed retreat of two waters infrastructure (waste water and storm water) and how it could be implemented in a managed way. This includes exploring the interface between water services and the community retreat. This implies adaptation of two water infrastructure is not exclusively a technical issue, but rather, encompasses a socio-political issue about residents adapting to the changing climate and SLR. This study focuses on adapting the two water infrastructure. In this context my research question is as follows:

*How could the retreat of two water infrastructure (Stormwater and Wastewater) in the Petone and Alicetown Area be managed alongside a community retreat from the coast, considering and defining;*

- 1) What levels of Service (LoS) are appropriate while transitioning towards adaptation thresholds?
- 2) How long should two waters services be maintained?
- 3) What measures and actions are appropriate to maintain L.o.S and do they coincide with adaptation thresholds?
- 4) What leads - service withdrawal or resident withdrawal?

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[1] Resource Management Act sections 6(h), 7(i), 31; Local Government Act requires ongoing planning through 10-year council Long-Term Plans (LTPs) and longer 30-year local government Infrastructure Plans and Section 125 requires local government to assess the provision of water and sanitary services

# 2 Background

This chapter provides background on managed retreat relevant to the study and helps focus the study by discussing relevant concepts and literature grouped by topic (Appendix 3). The first section focuses on classification of adaptation types addressing SLR in coastal regions, as discussed in the Intergovernmental Panel on Climate Change (IPCC) (2019). The second section discusses pathways to one of those types, managed retreat. The third section discusses the DAPP approach used to frame systematic retreat from the coastline focusing on how pathways for 2-waters infrastructure could transition to managed retreat (and eventually re-purposing of the area). The last section discusses the consequences and adaptation options for coastal Urban Drainage systems impacted by SLR. It concludes by discussing the implications for the Petone study area and this study.

## 2.1 Types of Adaptation Options

Adaptation options in response to SLR according to IPCC (2019) are shown in Figure 2.1, where the five most commonly used policy approaches are shown. In this context, these responses are implemented to protect communities from the effects of SLR, where mostly a combination of increased water levels and wave impact is considered during increasingly extreme events. Negative consequences of SLR include more frequent flooding, increased erosion and increases in groundwater levels, saltwater intrusion, liquefaction and drainage problems.

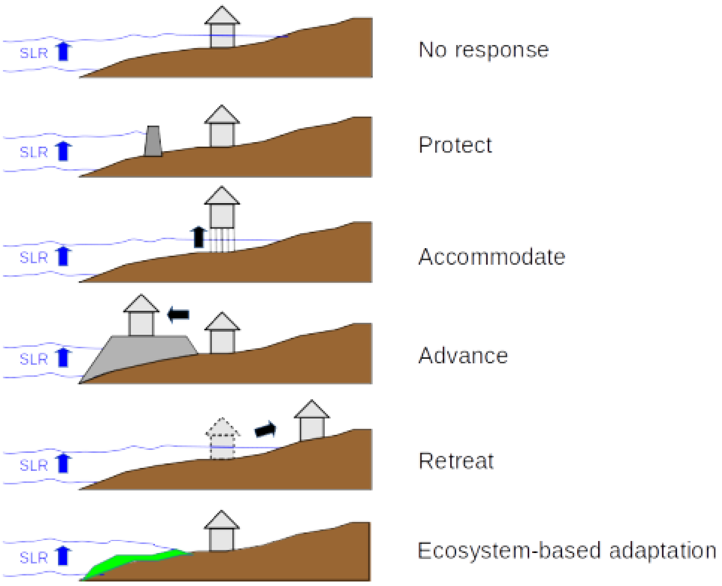

Figure 2.1: Sea level rise adaptation options, adapted from (IPCC, 2019, p. 4-87)

Rouse et al (2017) outlines the advantages and disadvantages that arise from each of the four most commonly considered adaptation policies:

- Do nothing, advantage is that it would result in low cost and effort for the present generation. Disadvantages include that there is no future certainty for any of the actors, projected impacts would occur with consequences for people, property and infrastructure, ignores risks for future generations

- Protect, advantage is that hard engineering provide immediate protection for high value infrastructure, soft engineering aligns with natural processes and allows for cyclic erosion. Disadvantage is that this approach is expensive, assumptions might lead to a mis perspective of the risk, direct coastal squeeze and physical impacts on adjoining beaches
- Accommodate, advantage is that it works with physical processes by retrofitting measures like raising floor levels, removing current risk. Disadvantage is moderate costs depending on retrofitting, based on static risk assumptions, requires change in expectations of use/service levels, requires careful communications because it has limits as SLR is ongoing
- Retreat, advantage is that it allows for a dynamic risk, it allows ecosystem resilience to be maintained and seeks to remove risk. Disadvantage is that is potentially expensive to implement due to relocation of infrastructure, compensation costs and likely community resistance, it also needs a long term timeframe to be implemented without major community disruption.

Advance in a coastal engineering context is commonly achieved by land reclamation and ongoing beach nourishment. Since the foreshore is a highly dynamic zone, advance methods are expensive to implement (usually associated with a protect method) and to maintain, and therefore only being considered for large cities (e.g the U-wall option for Manhattan, NY). Ecosystem based disaster risk reduction seeks to work with natural processes, e.g. coastal ecosystems, rather than work against them resulting in a higher adaptive capacity and lower costs on a life cycle basis then traditional engineering solutions when applied in an appropriate setting (de Vriend et al., 2015; Lange et al., 2016). The major disadvantage of ecosystem based adaptation is its experimental nature and not yet being integrated with shoreline and hydraulic protection guidelines which means quantification of its benefits is immature. Advances in research with the aid of numerical modelling will start to push these solutions to a more common approach to adaptation.

## 2.2 Managed Retreat

This section focuses on introducing managed retreat and provides a background on the importance of considering managed retreat as an adaptation option for low-lying coastal areas, given that the sea level will continue rising at a rate that is uncertain. Managed retreat can be defined as ”an adaptive approach to risk reduction, where people, activities and assets are strategically relocated away from hazardous locations” (Hanna et al., 2017, p. 3). In relation to the research question this would comprise two water infrastructure assets.

Implementation barriers to managed retreat are becoming increasingly identified in the literature. (Gibbs, 2016) recognizes that although there are a lot of studies that take managed realignment into account, there is a lack of implementation of these studies and little on-the-ground experience. It also acknowledges that ‘’Evidence of climate change impacts is rapidly increasing but there is unfortunately little change to the speed of adaptation by governments and individuals’’ (Mills et al., 2016).

Currently there are three district Councils in New Zealand implementing cases of managed retreat as a response to a range of hazards (Hanna et al., 2017) These include a relocation of council assets due to coastal erosion risk, voluntary retreat as a result of a damaging debris flow and a voluntary purchase of properties for making room for the river as part of a flood risk reduction project.

Hanna et al. (2018) identified several key implementation barriers for managed retreat in New Zealand. They concluded that implementation of managed retreat is difficult due to a lack of national policy guidance, legislative mechanisms and implementation support. In addition to this, funding the sequence of steps to achieve managed retreat is found to be uncertain and voluntary retreat the only tool currently able to incentivise managed retreat. When combined with withdrawal of service, it is also perceived to be compulsory (Hanna et al., 2018). Hino et al. (2017) concluded that managed retreat is favoured for longer timeframes, approx. >25 yrs. This agrees with (Rouse et al., 2017) for traditional protection projects, where it states that building levees result in high maintenance costs, environmental damage and increases development in hazardous areas from residual risk. In short, the following four retreat categories are identified (Hino et al., 2017):

- Post Disaster, there is mutual agreement as risk is perceived to be not tolerable, there is high political will and there is a high cost benefit
- Greater Good, Risk is perceived tolerable therefore resident opposition must be overcome, there is high political will and high cost benefit
- Hunkered Down, mandatory resettlement, risk is perceived to be tolerable, there is low political will and there is a low cost benefit
- Migration Risk is perceived intolerable and there is low political will and low cost benefit, e.g. remote settlements where there is an emphasis on self-reliance

Siders et al. (2019) concluded that managed retreat is often ad hoc and focused on risk reduction which is treated as isolated from broader societal goals. They reason that without guiding policies, ad hoc managed retreat fails and misses opportunities to contribute to societal goals. They recommend strategic retreat, aimed at contributing to these societal goals. Identified barriers making managed retreat difficult to implement in practice include profitable, short term economic gains in coastal development, imperfect risk perceptions, subsidized insurance rates and disaster recovery costs, misaligned incentives between residents, local officials and national governments and a preference for the status quo (Siders et al., 2019).

A recent thesis project by Olufson (2019) investigated two recent examples of managed retreat in order to identify what kind of components would be included in managed retreat, how they could be sequenced and how these different components could be grouped to assist those implementing managed retreat. The following sequence of grouped components are identified in (Olufson, 2019):

- Community Engagement - engagement and consultation on adaptation options and managed retreat implementation
- Planning and Preparing - planning and rule changes, planning for reduces Los and development restrictions on at risk areas, monitoring and establishing trigger points
- Enabling Investment, Property Acquisition - new community investment in the form

of alternative land for relocation and development of new community facilities, Public infrastructure L.o.S. reduction and maintenance reduction

- Active Retreat - Public infrastructure relocation (replacement/redevelopment of public infrastructure elsewhere, relocation of critical facility structures and relocation of community facilities), privately owned infrastructure relocation (private companies begin to reduce/remove/relocate infrastructure and covenants on property are activated), private property relocation and abandonment (relocation/abandonment of residential and commercial property and providing temporary housing), removal of marine structures
- Cleanup - demolition, land rehabilitation and maintenance

## 2.3 Dynamic Adaptive Pathway Planning (DAPP)

A systematic way of managing retreat from the influence of coastal processes and SLR is required to answer the research questions. Dynamic Adaptive Policy Pathways (DAPP) (Haasnoot, 2013) is a Decision Making under Deep Uncertainty (DMDU) method, where the planning is dynamic to account for uncertainties and change over time by exploring alternative strategies. Policy actions have an uncertain design life and might fail sooner or later to be effective as boundary conditions change with an Adaptation Tipping Point (ATP) (Haasnoot et al., 2019), which from now on will be referred to as Adaptation Threshold (AT). The concept has been adopted in Ministry for the Environment coastal hazards and climate change guidance (2017) for a New Zealand context and developed as Dynamic Adaptive Pathway Planning (DAPP), which is the terminology utilized in this study. The ability to incorporate uncertainties and explore alternative strategies makes it a suitable approach to investigate the research questions.

*'' DAPP explores alternative sequences of decisions (adaptation pathways) for multiple futures and illuminates the path dependency of alternative strategies. It opens the decision space and helps to overcome policy paralysis due to deep uncertainty. There are different routes that can achieve the objectives under changing conditions (like 'different roads leading to Rome')."* (Haasnoot et al., 2019, p. 71-1)

The aim of DAPP is to adapt and transition current static and time bound planning to decision making that enables adjustments (Lawrence, Bell, et al., 2018). This is required due to a combination of deep geophysical and socio-economic uncertainties. Accordingly, involvement of stakeholders is critical; for example as facilitated using a simulation game (Lawrence and Haasnoot, 2017) and through collaborative decision making (Kench et al., 2018). Based on Haasnoot et al. (2019), the development of a DAPP approach consists of the following components:

- Framing
- Analysis
- Actions
- Evaluation of actions and options
- Development and selection of adaptation pathways
- Specify and implement strategy
- Monitoring and review

As can be seen from Figure 2.2, pathway changes occur when a certain hazard increment, in this case SLR, is reached and current management fails to meet objectives of the strategy. This is an adaptation threshold point (ATP), where another adaptation option (pathway) can be initiated. Adaptation thresholds are defined as the conditions under which a policy will fail to deliver on objectives. (Haasnoot et al., 2019).

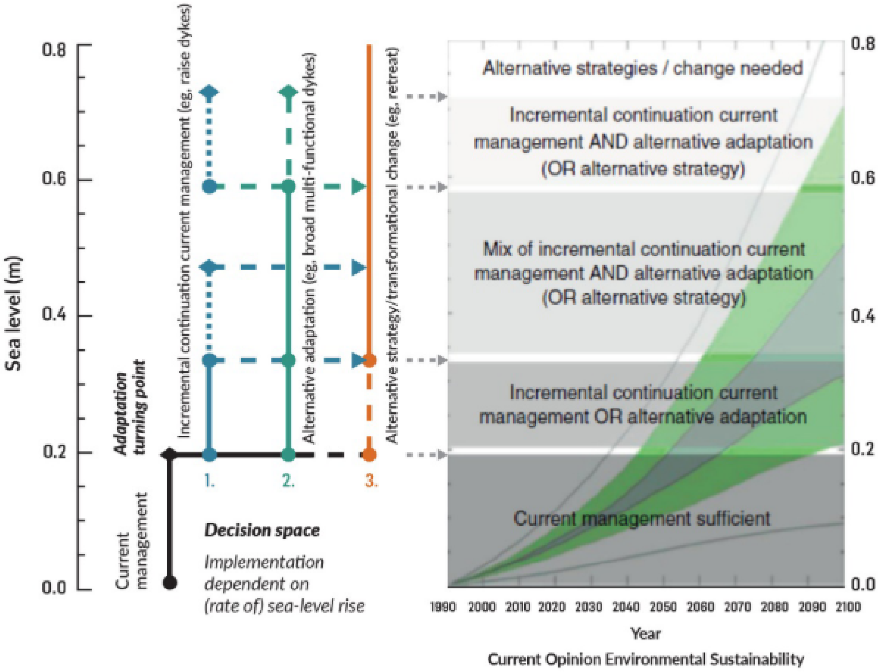

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Figure 2.2: DAPP Approach, adapted from (Werners et al., 2013, p. 337)

AT's are defined as the threshold where boundary conditions are exceeded, e.g. due to an increasing hazard and new actions are needed to ensure acceptable performance levels. This can be technical, environmental, societal or economic standards (Manocha and Babovic, 2017; Haasnoot et al., 2019). In Babovic et al. (2018), this adaptation threshold is found by modelling the system and placing it under increasingly larger stress. Adaptation thresholds can also be identified through moderation processes using scenarios with different conditions representing the stress similar to sensitivity testing.

Signals and triggers in the DAPP warn and initiate pathway changes respectively. As can be seen in Figure 2.3, as performance of an asset starts to decrease, a signal is established evaluating and warning for decrease in asset performance, signalling an adaptation threshold is approaching. After a continuing decrease of asset performance due to changing outside boundary conditions, a trigger is reached to change or implement an option on a different pathway. Upon reaching this trigger, a decision point is reached and there is an implementation window until the performance of the asset dives under the adaptation threshold. The length of this implementation window depends on the lead time for a new option. Different adaptation options require a different implementation time span, and therefore have different lead times. When delaying a change of pathway the options for choosing alternative pathways decrease, as can be seen in Figure 2.3. Before this happens, other triggers are reached where a different pathway is necessary to maintain the performance level of the asset above the adaptation threshold.

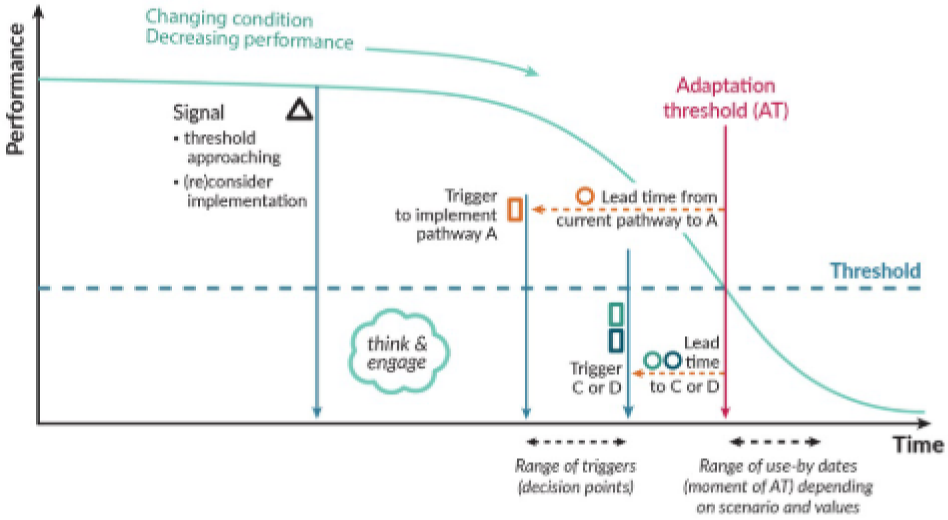


Figure 2.3: Adaptation Threshold and pathway performance, adapted from (Ministry for the Environment, 2017, p. 211)

Then, incrementally, a decision point is reached where either current management is continued or an alternative adaptation is implemented. This could be for example alteration of current approach such as raising stopbanks. After this there will be incremental continuation of current management where an alternative adaptation is required, or an alternative strategy. After this another strategy has to be implemented. It therefore provides a map for alternative routes (Pathways) for arriving at the same destination (Strategy). Currently there are few studies illustrating the applicability of DAPP for developing adaptation options for two water infrastructure in a practical setting and no studies were found using DAPP for two water infrastructure in a retreat setting. Discussing how it is used for creating two water infrastructure pathways for other adaptation strategies strategies will therefore provide a start for addressing the research question with regards to measures and service levels.

Manocha and Babovic (2017) applied a DAPP approach in Singapore to investigate storm water management infrastructure adaptation pathways. They preselected pathways based on a cost benefit analysis allowing for a better understanding of adaptation timing, and aiding ''Bridging the gap between the highly uncertain and long term climate change and short term decision making horizons of urban planning and development'' (Manocha and Babovic, 2017, p. 94). The study used a quantified approach to calculate ATP's for stormwater infrastructure. Triggers and signals for stormwater pathways are not included in the study. Babovic et al. (2018) reviewed the potential for addressing future uncertainty in drainage systems using DMDU methods. They found assessing drainage system pathways using DAPP too computationally intense due to the complexity of the hydrological models used, therefore simplified models were recommended (Babovic et al., 2018). Radhakrishnan et al. (2017) investigated applying a DAPP approach to fluvial flood protection in an urban setting in Can Tho, Vietnam. An extra component was added to the DAPP methodology to include a coping capacity assessment to determine community coping capabilities on different scales. No-regret actions included combining short term citizen initiatives with long term planning measures which could potentially delay AT's for pathways.

## 2.4 Urban Drainage Systems

Urban drainage systems handle wastewater and stormwater (Butler et al., 2018). In general these systems can be divided into a combined system where wastewater and stormwater are combined in the same sewers and a separate system. A combined system disposes of storm and sewer water, usually to a water treatment plant (WTP) in the proximity of the urbanized area. During periods of increased discharge due to stormwater, the flow is diverted into the natural water course, e.g. the estuary or river, using a combined sewer overflow (CSO). This causes pollution as both stormwater and untreated wastewater are diverted into the natural water course before reaching the WTP (Butler et al., 2018).

In separate systems the storm and wastewater pipe systems are separated, eliminating the need for a CSO (Butler et al., 2018) and therefore preventing wastewater pollutant spills in increased discharge scenarios. This does not remove pollution altogether as stormwater contains pollutants as well (Butler et al., 2018). An example of a separate drainage system can be seen in Figure 2.4.

Pumping stations are needed to pump water out of or along the system if this cannot be done by gravity. A gravity-based system is preferred to accommodate the necessary discharge, eliminating unnecessary maintenance. Since treatment facilities are usually not available in each natural sub-catchment, pumps are often necessary to overcome elevation difficulties (Butler et al., 2018).

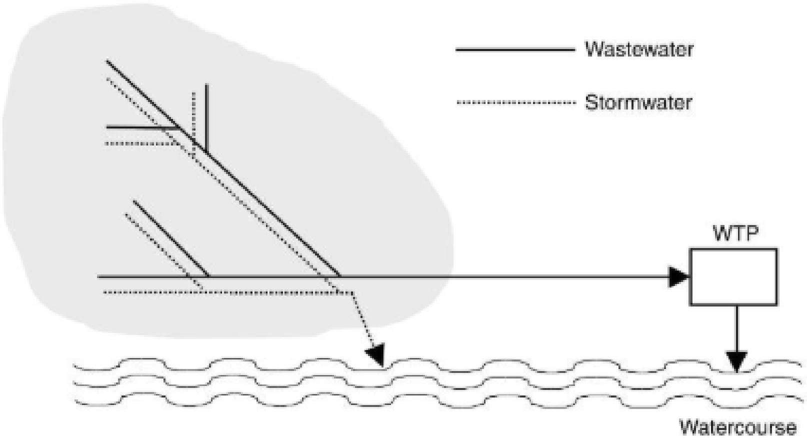


Figure 2.4: Conceptual overview of a Separate Drainage System, similar to the drainage system in the study area, adapted from Butler et al., 2018

### 2.4.1 Urban Drainage and Sea Level Rise Interaction

Most of the literature either investigates the spatial extend as a result of wave overtopping and the flooding of the pipes and nodes in the drainage system as a combined result (Gallien et al., 2014) or the effect of groundwater interaction with the drainage system in coastal areas (Archetti et al., 2011; Su et al., 2019). What we are looking for is the influence of sea level rise on the performance of current two water infrastructure drainage systems. These studies are mostly done as a case study. Gallien et al. (2014) found that a coastal drainage system actually reduces the spatial extend of flooding, on the condition that it is not running at capacity. It does not investigate the consequences on the urban drainage system performance or the consequences of saline water entering the system. It also stresses the importance of avoiding static inundation models in favour of hydrodynamic models.

Wdowinski et al. (2016) discussed the influence of flooding hazards due to SLR in Miami. A significant increase in flooding induced by rainfall was found due to SLR decreasing the discharge capacity (due to a decrease in the hydraulic gradient) of gravity-based drainage systems. This reduction in discharge capacity due to SLR was also found in (Bloetscher et al., 2011; Friedrich and Kretzinger, 2012; Almeida and Mostafavi, 2016). In order to adapt, Miami beach switched to a pump-based system (Wdowinski et al., 2016).

Increases in groundwater levels due to increased precipitation and snow melting were found to cause back water effects and reduce the discharge capacity of the drainage system when investigating climate change adaptation for Bucharest (Stancu et al., 2017). Investigations into flood risk for Shanghai concluded that decreases in drainage capacity caused by land subsidence and sea level rise will have the most significant contribution to future inundation risk in ShanghaiHu et al., 2019. This confirmed the observations from an extreme inundation event in 2015 where the high water level in the river prevented the drainage system to pump the excess in rainwater into the river.

Impacts from SLR include higher water tables and therefore a reduced soil storage capacity, in turn resulting in increased frequency and severity of flooding due to precipitation (Bloetscher et al., 2011; Almeida and Mostafavi, 2016). This compromises flow capacity of stormwater and coastal structures, and potentially pumping stations will have to be installed to reduce ponding (Bloetscher et al., 2011). Sue et al. (2019) investigates the relationship between infiltration in an aging urban sewer system and groundwater flooding in a coastal area. They concluded that when the pipes in the system are not repaired, there is an increased discharge of untreated sewage due to CSO overflow. Upon repair however, the water table rises resulting in groundwater floods, especially in coincidence with high tide, and this is expected to increase due to SLR. It was also found that increases in GWL result in sewage backup in septic tanks in conveyance pipes (Almeida and Mostafavi, 2016).

Sea level rise also results in increased inundation of WWTP's placed in the vicinity of the coastline. The increased salinity can cause damages in the WWTP, as it is not adjusted to this increased salinity (Friedrich and Kretzinger, 2012). Schoent et al. (2015) investigated the resilience of different wastewater system setups under a range of hazards, including SLR. It was concluded that although all systems were vulnerable to SLR, it was found that greywater reuse and a blackwater pressure sewer were the most robust due to less environmental contamination during extreme events (Schoen et al., 2015).

### 2.4.2 Water Sensitive Urban Design

Water sensitive urban design has been gaining currency with practitioners and implemented in some notable cases. Water sensitive urban design (WSUD) is: ''an integration of urban planning with management, protection and conservation of the urban water cycle, that ensures that urban water management is sensitive to natural hydrological and ecological processes'' (Wong, 2006, p. 214). Whereas it traditionally is associated with stormwater management, it now integrates management of the urban water cycle into urban design (Wong, 2006). For stormwater, some of the more common BMP's are detention ponds, wetlands, ponds, biofilters, swales, adsorption filters, infiltration basins, porous pavement, green roofs and settlers (Lerer et al., 2018). It is important to note that due to rise in the ground water levels as a result of SLR, SUD's that increase perviousness could result in increases in the local groundwater table (Joyce et al., 2017). It does offer a reduction in peak flow aiding traditional grey infrastructure in the system (Joyce et al., 2017).

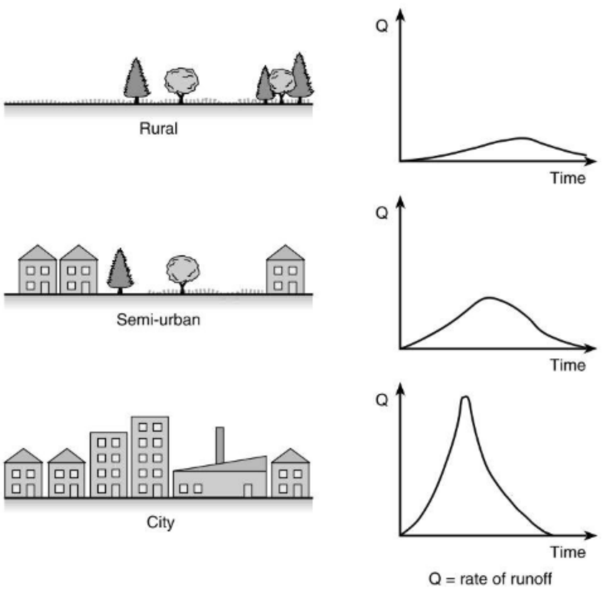


Figure 2.5: Different Runoff rates, adapted from Butler et al., 2018

Figure 2.5 shows differences in runoff rate Q for different environments. It can be seen that rural environments have a more consistent runoff rate whereas urban environments have a peak flow in runoff. This is undesirable, as sewers and pumps would have to be increased in capacity to deal with peak discharges for short times and are working under capacity for most of the operation time. This concept can also be applied to increases in hazards due to climate change. Increased rainfall, higher GWL levels and possible flooding of critical infrastructure will increase chances of encountering these peak discharges. The aim is therefore to look for ways to 'shave off' this peak discharge. This can either be done by 'delaying' part of the discharge to make sure that the runoff enters the system later (e.g. green roofs, swales), increasing storage capacity (retention basins, (sub) surface constructed wetland flows) or increasing capacity of the system (increase pipe and pump capacity).

## 2.5 Implications for Research

This research looks specifically into two water infrastructure retreat as a result of SLR, and seeks to frame this within a conceptual DAPP framework. It is expected that the ongoing increase in mean sea level (rather than episodic coastal flooding events), will have the most wide-ranging impacts on the drainage system. Several studies in the theoretical background discuss decrease in discharge capacity (Bloetscher et al., 2011; Friedrich and Kretzinger, 2012; Almeida and Mostafavi, 2016; Wdowinski et al., 2016) and groundwater table issues (Su et al., 2019; Bloetscher et al., 2011; Friedrich and Kretzinger, 2012; Almeida and Mostafavi, 2016; Joyce et al., 2017) in coastal environments as a result of SLR. The increase in the local groundwater table as a result of SLR is an important consideration for implementing adaptation options in the Petone area. These issues are also identified in a recent paper investigating climate change impacts on storm water and wastewater systems in New Zealand (Hughes et al., 2020 (In Press)). SLR was found to have severe impacts on both the storm and wastewater systems, only having low impacts on pressurized parts of the conveyance system. Pumping stations were still found to be severely affected (Hughes et al., 2020 (In Press)). The spatial extend of flooding in an urbanized coastal area is still a relevant topic to this research as SLR exacerbates these effects and more frequent inundation of the drainage system is to be expected.

Due to compounding hazards it is difficult to quantify adaptation threshold points like in Manocha and Babovic (2017). Babovic et al. (2018) suggests to use a simplified model to assess pathways. A simplified static inundation model is used and thresholds are determined by a mix of qualitative / quantitative measures of exposure to SLR. This does not take into account the vulnerability or performance of the system. Increased rainfall will further exacerbate the problems with the drainage system in the long term, therefore it is expected this will provide a conservative estimate. Including community coping capacity as in Radhakrishnan et al. (2017) would allow for precise determining of AT's for pathway options. In order to incorporate this the community would have to be engaged and involved in the pathway development. Due to time constraints this is beyond the scope for this study.

WSUD options could be included in pathways to mitigate the reduction in capacity while at the same time creating amenities for the area require extra space.Siekmann and Siekmann, 2015 describes WSUD's as intensified use of surface detention using technical infrastructure, and notes that implementation in urban areas is still rare. The paper suggests that disconnecting drained areas is a first step to prepare drainage systems to climate change. This could also indicate an opportunity for partial retreat. The paper also concludes that these measures are easier to upgrade then traditional sewer systems. This means they have a higher adaptive capacity, which would be an advantage considering the challenges the Petone area is facing.

The utilization of a more systematic retreat strategy that contributes to societal goals is suggested in Siders et al. (2019) and to plan long term retreat using a DAPP approach is expected to provide this. The retreat typology outline in Olufson (2019) provides an useful typology for approaching implementation of managed retreat, and sequencing options and actions. There is limited literature available on sequencing of two water infrastructure retreat while facilitating community retreat away from the coastline. A literature search of adaptation options for urban drainage (2.4.2) with managed retreat typology gives a start on this.

# 3 Methodology

This section outlines the overall research process. Methods and Data Collection discuss the various products, 'building blocks', produced during the research. The research scope discusses research boundaries. An overview of the research process is provided in Figure 3.1. The first phase of the research (1,2,3,4,5) consists of different inputs with mixed qualitative and quantitative data. This is then used to identify both system thresholds and adaptation option thresholds. These in turn are the input for a conceptual DAPP for two water infrastructure in the Petone/Alicetown area. By incorporating retreat in this approach, the output provides the basis to answer the research questions.

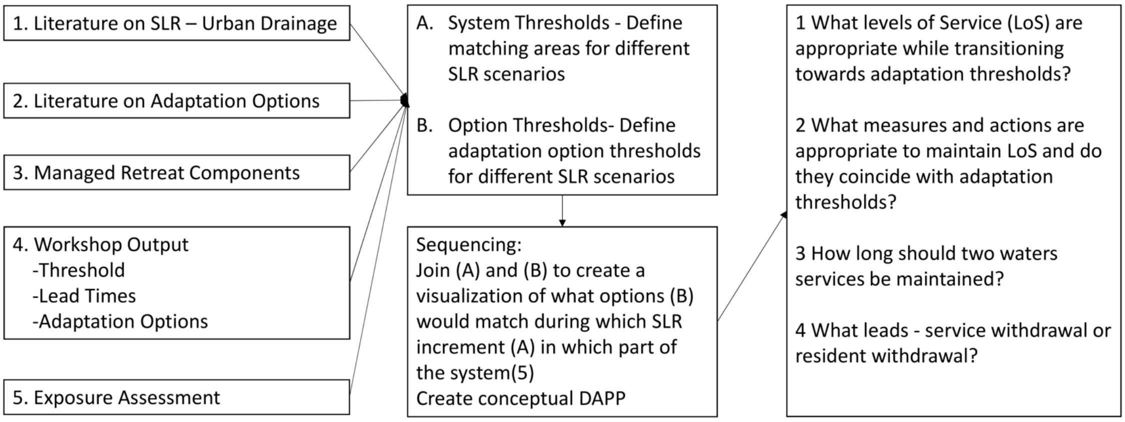


Figure 3.1: Research Process

## 3.1 Study Area

This section introduces the Petone and Alicetown drainage system (Detailed description provided in Appendix 1 and 2). The stormwater pumps are placed in the lower parts of the system in the inner area of Petone. Therefore it is possible to more efficiently get the excessive stormwater out during heavy Pluvial flooding. The Wastewater pumps are placed in the vicinity of the wastewater outlets. Since the systems are gravity-based, there is the need at the end of the system, e.g. near the outlet, (near the Hutt river or the coastline), to pump the discharge flow to the necessary hydraulic head towards the WWTP.

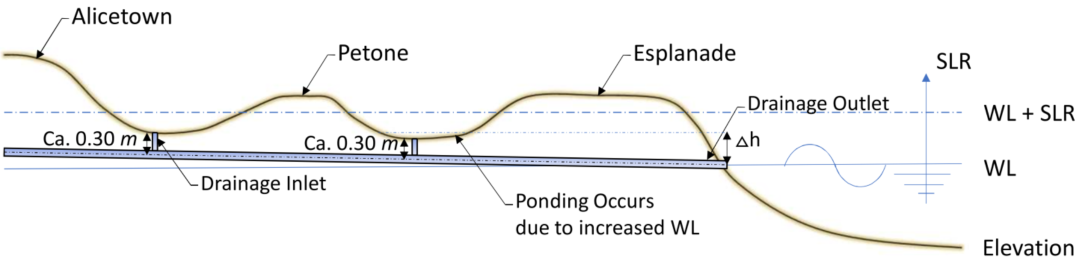


Figure 3.2: Conceptual Petone Cross Section illustrating SLR problems

An overview of the drainage system with the location of the storm water and wastewater pumps is provided in Figure 3.3. Discharge points of wastewater systems often are located at the lowest elevation points of populated areas (White et al., 2017). This means that the gravity-based two water infrastructure located in this area is especially vulnerable, and changes in water level as a result of SLR can therefore have a considerable impact in the hydraulic capacity.

Figure 3.2 illustrates this for specifically the Petone and Alicetown area. The left represents Alicetown, the middle Petone and the right the Esplanade at the coast. Even though not located in the direct vicinity of the coastline, in two sections the elevation drops considerably. This means that due to SLR the hydraulic gradient ($\Delta h/L$) will become smaller resulting in a reduced discharge capacity. Additionally, during periods of increased water levels the marine water can get into the pipe and cause ponding in the lower elevated areas, increasingly as SLR continues.

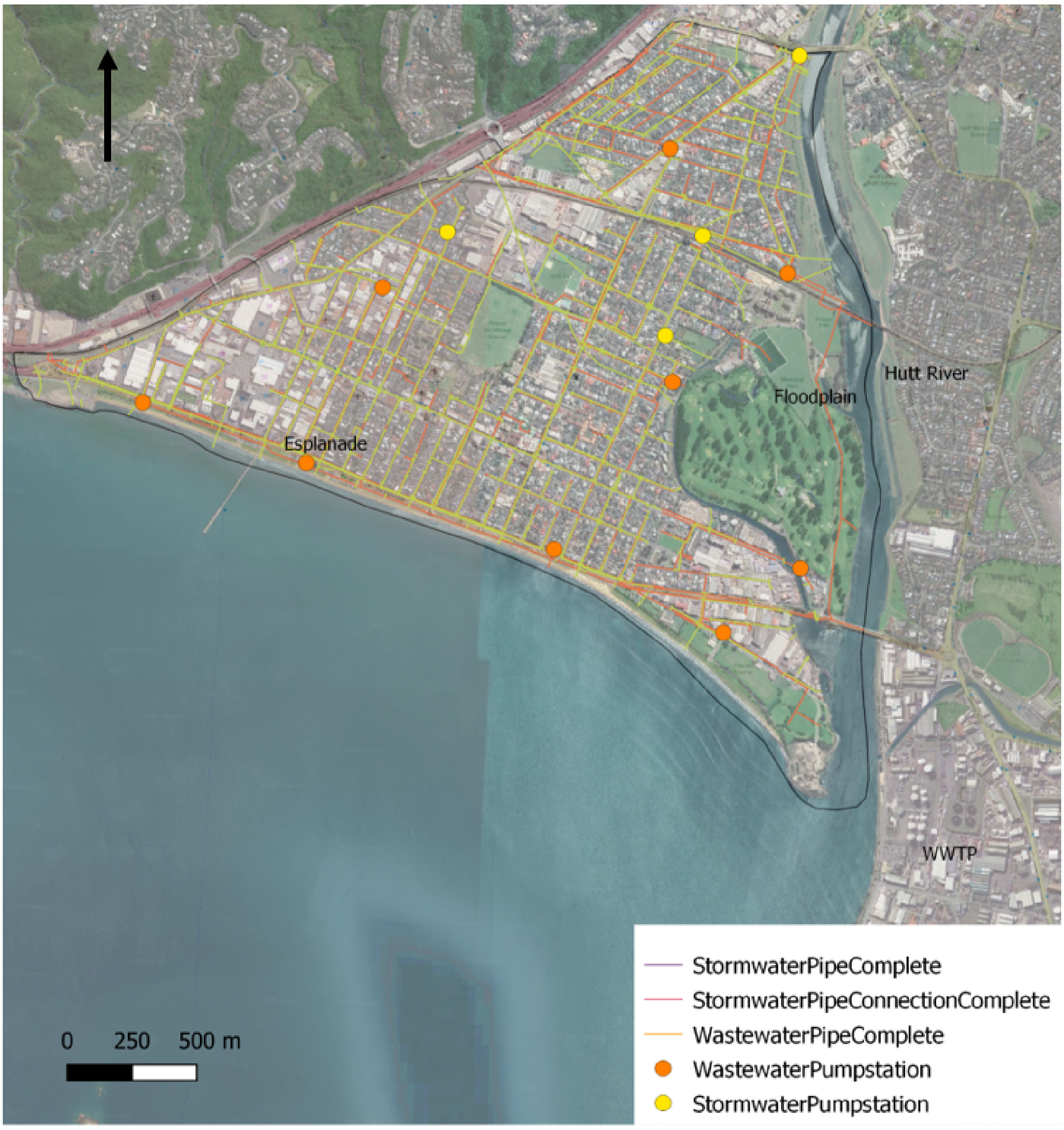


Figure 3.3: Research Area and Important Assets

## 3.2 Methods and Data Collection

This section discusses how the project was undertaken and the type of analyses and tools used to answer the main question. To have a better overview of the different components in the methodology, the components are outlined in Figure 3.4. The first paragraph discusses the exposure analysis. This includes hazard data, asset data and the tool used to identify exposure, RiskScape. The second section elaborates on the approach for the adaptation options. This includes a system analysis and the CIrcle tool to identify critical infrastructure cascades. It also sets out the approach for the workshop and identifying adaptation options. The last section discusses the approach leading up to the conceptual DAPP, which includes area selection, system adaptation thresholds and pathway adaptation thresholds.

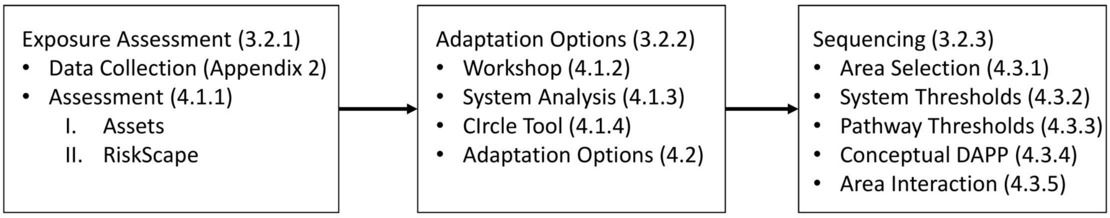


Figure 3.4: Methodology Components

### 3.2.1 Exposure Assessment

For the purpose of this research an analysis into exposure of the assets of the area was performed, where direct and indirect exposure of assets to SLR was investigated for two water assets in the area. It is difficult to assess the exact risk to the project area. Risk is conventionally assessed by considering the intersection of consequences and the likelihood of these arising from an event, or in this case gradual rise in sea level. Consequence here partially relates to exposure of assets and people . The difficulty with applying the conventional approach to assessing risk is that the likelihood component is difficult to quantify, because with ongoing sea level rise, uncertainty increases over time (Ministry for the Environment, 2017). Therefore the focus in this research is on the consequence, in the form of an exposure assessment of two water assets in the Petone area (but excluding a detailed analysis of the extent and type of disrepair, damage to asset types and the entire network with rising seas).

ISO 14090 defines exposure as ''Presence of people, livelihood, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social or cultural assets in places and settings that could be affected'' (Standard, 2019, p. 2). This provides the basis for starting up discussion with stakeholders in the area, giving an indication and prioritization of assets that are affected. This produces a combination of qualitative (Stakeholders) and quantitative (exposure assessment) input to prioritize asset exposure.

*''Exposure generally refers to the state and change in external stresses that a system is exposed to. In the context of climate change, these are normally specific climate and other biophysical variables (including their variability and frequency of extremes). The location of people and assets can also be regarded as exposure''*(Lawrence et al., 2011, p. 6)

The National Institute of Water and Atmospheric Research (NIWA) offered to help with setting up the correct functions for this analysis using their in-house developed tool Riskscape. RiskScape is a multi-risk modelling tool developed by NIWA and GNS Science, and also used to determine exposure to SLR in Paulik et al. (2020). It combines three important components as input, being a Hazard Module, a Vulnerability Module and an Asset Module (Schmidt et al., 2011). The unique aspect of this program is that it is designed to be a flexible tool that can adapt to different hazards and assets. Exposure of assets at risk over SLR (hazard) increments in the study area was investigated by the overlay of the hazard datasets and asset datasets to see the extent of exposure in relation to the corresponding scenarios. These exposed assets were then organised using a QGIS script (Appendix 2). To evaluate exposure for the two water assets using RiskScape, the following steps were used:

- Collect available data on SLR and Hazards, e.g. flooding
- Identify assets in the area, using asset data
- Combine and overlay the hazard with the asset data to determine the exposure
- Ground-truth with local experts

This type of exposure assessment was recently undertaken on a nation-wide scale (Local Government New Zealand, 2019b). Due to changes in the boundary conditions, like SLR, return periods will also change as the sea continues to rise. A SLR increase of 0.30 $m$ will change a 1 percent AEP into an event occurring at least once per year (White et al., 2017; Stephens, 2015). Wellington has the highest exceedance per increment in comparison to the other major cities in New Zealand (PCE, 2015).

**Data Collection**

A combination of several hazards is affecting the Petone area. Since most of the wastewater and storm water infrastructure is gravity-based this increases the vulnerability to sea level rise. Unfortunately no modelling of these systems is available at the moment, so it was not be possible to look into different scenarios for a sensitivity analysis. For marine flooding there is a predictive data layer for flooding scenarios under rising sea levels, which is provided by NIWA. The data used were 0.1 $m$ increments of SLR added to the present-day 1 percent AEP storm-tide and wave setup water level in Wellington Harbour Paulik et al., 2020. The storm event does not change, just the increment in the water levels. The dataset used as the coastal flooding hazard was developed for the Deep South Science Challenge (Paulik et al., 2020). The aim of the research was to map marine flooding extent for New Zealand nation wide for 1percent annual exceedance probability with SLR increments of 0.1 $m$, and enumerate a range of assets, including two water assets, that are at risk of coastal inundation (Paulik et al., 2020). Increases in groundwater level are a serious threat to the Petone area, especially since it is already dealing with relatively high groundwater levels.

Hazard and asset data were used for the exposure assessment. Hazard data layers were overlain with selected asset data layers that determined the exposure to the hazards. The overlays for increments in SLR are mapped for exposure up to +120 cm SLR. Asset data for two waters infrastructure was acquired from Wellington Water, which was used to investigate the exposure. A hazard map was also provided for pluvial flooding. It was decided not to use this hazard as it was not possible to calculate exposure using different increments and see compound hazard exposure for different scenarios. The marine hazard data is therefore more suitable for looking into asset exposure thresholds.

### 3.2.2 Adaptation Options

This section outlines the approach taken for the systems analysis, the CIrcle Tool and the workshop. The systems analysis utilizes ISO 14090 to identify important system components, relations and boundaries. These are used in the CIrcle tool to identify critical infrastructure cascades. The workshop provides expert input on the project. A more extensive investigation into literature was done in order to prepare the adaptation options. It made sure to both supplement the optioneering in the workshop as well as making sure no options were overlooked. It was clear that there are adverse effects on the two water system as a result of SLR, like water getting into the outlet pipes decreasing the drainage capacity, the effects of inundation, salt water intrusion and flooding problems. However the exact effect on a local area is seldom clear. It was not expected there are going to be any revolutionary new techniques available to implement this. Rather, existing adaptation options were used working in parallel with managed retreat depending on the threshold established and lead times associated.

**System Analysis**

In order to further investigate stakeholder interests and two water system interactions, a system analysis was performed during the research. ISO 14090 encourages systems thinking to understand the complex, nonlinear and interconnected system the project is set in (Standard, 2019). Mapping boundaries, sub systems and their interdependencies helps to identify priorities for adaptation. This has been previously used in a New Zealand specific study looking into cascading effects from a range of different hazards on the different infrastructure sub systems like a dike breach (Extreme event cascade), wastewater (SLR and coastal inundation cascade), stormwater (heavy rainfall cascade), transport systems (climate induced landslides), power and gas (storm event cascade) and water supply (drought cascade) (Lawrence, Blackett, et al., 2018). The result of these cascades on the infrastructure were used in conjunction with the CIrcle tool to identify cascading effects for a range of different districts like Christchurch and the Hauraki plains (Lawrence, Blackett, et al., 2018). This was used as a 'benchmark' making sure no major impacts or components within the system have been overlooked. For this research, these cascades were identified using a combination of assets identified in the exposure assessment and literature.

**CIrcle Tool**

The CIrcle tool – Critical Infrastructure: Relations and Consequences for Life and Environment – is a tool developed by Deltares to analyse and visualize cascading effects of infrastructure networks, to address awareness on critical infrastructure dealing with climate change related topics (Hounjet, 2014). It does so by dividing critical infrastructure into different categories, with the ability to add direct effects and establishing links, cascading effects, between the different categories. The drainage system, stormwater and wastewater pumps and stopbanks are selected for use in the tool. Impacts on main roads, citizens, hazardous materials and public health as they were affected by cascades and therefore relevant to this study. Direct impacts on these components and the full analysis can be found in Appendix 3. According to (Hounjet, 2014; Deltares, 2017, 2015) the most efficient approach is to discuss and analyse these critical infrastructure cascades with different interactions, with a group of experts in a workshop session using a GIS analysis. Due to time constraints with the workshop, and since the participants are largely unfamiliar with the tool, it was decided to apply the tool before the workshop and then discuss the outputs at the workshop. This enabled the workshop input to be added after the workshop. Direct impacts were added to each of the different sectors, based on the findings from the exposure assessment. Increments were added resulting in the thresholds for stormwater pumps, wastewater pumps and the drainage system. After the workshop, thresholds identified during the workshop were also added to the direct impacts for the different critical infrastructure cascades.

**Workshop**

In order to get some input on adaptation options and feedback on the project, a workshop was organized with a group of local experts from the agencies responsible and from different disciplines.. In order to prepare the participants for the workshop, a pre questionnaire containing the workshop objectives was send to the participants to familiarize themselves with the topic and consider the issues before the workshop. Furthermore interdependencies or cascading effects are discussed using the CIrcle tool from Deltares. The aim was to identify options and pathways for managed retreat of the infrastructure using an optioneering approach which systematically covered the following :

- Thresholds
- Lead times
- Currently Available options
- Innovative Solutions
- Timing of action – when to initiate options or pathways
- Conditions

Participants were from the Hutt City Council (HCC), Wellington Water (WW) and Greater Wellington Regional Council (GWRC). The participants have diverse backgrounds including strategic planning, engineering, infrastructure management, sustainability planning and drainage asset management to provide a range of knowledge and experience relevant to the area concerned. This aided the optioneering process and helped with the development of system thresholds and options from different perspectives.

### 3.2.3 Conceptual Dynamic Adaptive Pathway Planning

A set of parameters was developed to divide the Petone area into different sub parts, mainly based on the exposure assessment and the cross sections of the elevation profiles. Since the aim was to derive a conceptual DAPP of the Petone area and the project has time constraints, it was decided to outline conceptual areas, rather than giving them an exact spatial boundary. The important output were the parameters used to get to this outcome. System Thresholds were a combined output from the exposure assessment and the workshop. This means it is a mix of quantitative and qualitative efforts. The adaptation option thresholds summarized the findings from the high level adaptation options, and their associated AT's. Initially option thresholds were defined per conceptual sub area, each with their individual assessment. This was to tailor the high level option categories to area specific solutions in order to optimize the performance of the options in this area, as well as create options between them in different areas. The approach taken was to develop a number of adaptation options and combine them into adaptation portfolios.

## 3.3 Research Scope

This section discusses the research boundaries and the research scope. The physical boundary is the Petone area, around Petone and Alicetown. It is shown in Figure 3.3. The scope of the research is looking into managed retreat for two water infrastructure, namely the stormwater and wastewater system for the Petone and Alicetown area, as a response to SLR. Within the three water services potable water was shown to be less affected by SLR due to its sealed status in pipes and the location of the main supply line being in the elevated part of the study area so was not included for this reason.

Impacts from multiple hazard sources are affecting the Petone area. Due to the inability to quantify compound hazard impacts over SLR increments, the impacts of sea level rise on the two water infrastructure is utilized to investigate managed retreat. Components from other systems are excluded, e.g. two water infrastructure from the other side of the Lower Hutt River. Data included in the scope is asset data from Wellington Water and NIWA. This asset data was then be further divided in the Stormwater Nodes, Wastewater Nodes, Stormwater Pipes and Wastewater Pipes. Relevant attributes were selected for the exposure assessment.

The research questions are used to create context for a conceptual DAPP approach. It was not be possible to develop a realistic DAPP framework within the timeframe of the study. It was possible however to identify thresholds and lead times for a managed retreat pathway to assist an eventual full DAPP approach for the area.

# 4 Results

This chapter presents the research results and follows the structure of the research process outlined in section 3.1. Section 4.1. and 4.2. present the results for the conceptual DAPP input. The conceptual DAPP itself is presented in 4.3. including area selection, system thresholds, pathway thresholds and area interaction. The workflow can be seen in Figure 3.4 in Paragraph 3.2.

## 4.1 Vulnerability Assessment

This section includes the results from the Exposure Assessment including the workshop output, the system analysis and the identified critical infrastructure impacts and cascades using the CIrcle tool.

### 4.1.1 Exposure Assessment

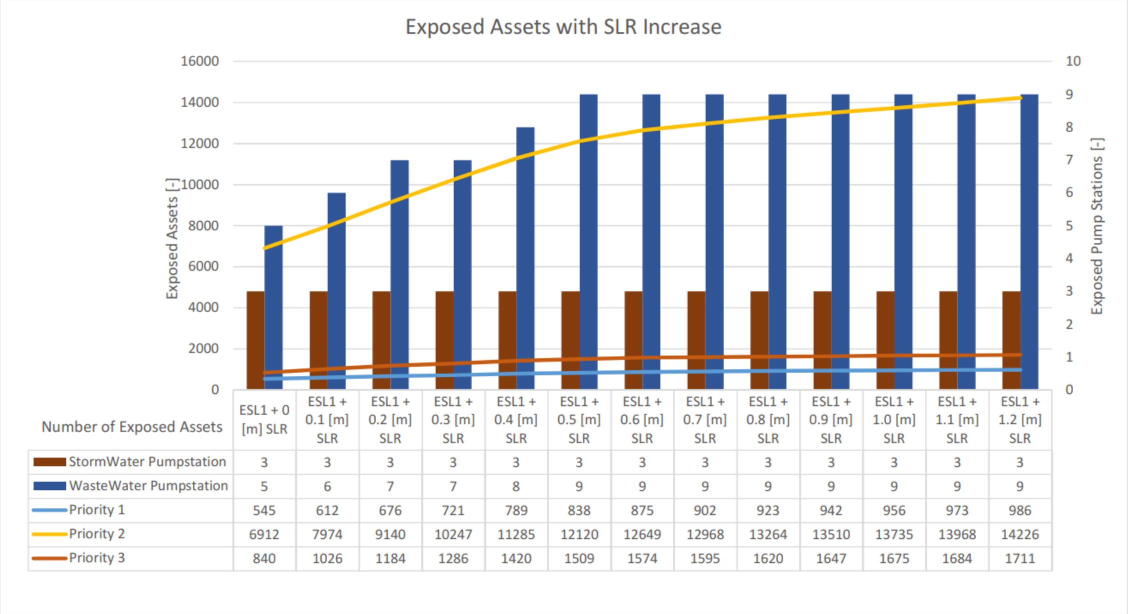
When looking into marine flood exposure for the area in (Paulik et al., 2020), it was seen that Lower Hutt (Petone and Seaview areas) experience an initial rapid increase of exposure to rising sea increments. Exposure was initiated using an inundation dataset with 0.10 $m$ increments and the 1 percent AEP event. It should be noted that these maps are based on a ‘bathtub’ approach, meaning that either natural barriers or protective structures are not taken into account.

The static coastal flood modelling highlights potential exposure to the range of water levels (1 percent AEP present-day + increments of SLR) used. Both direct overtopping flow of seawater and indirect, with the latter including seawater ingress to the network, rising groundwater, and residual risk (e.g. possible breach of coastal foreshore berm or the coastal end of river stopbanks/dikes).

After identifying the hazard exposure extend over SLR on the two water infrastructures with Riskscape the exposure output from RiskScape, was sorted using a Qgis script (Appendix 2). The exposed assets per SLR are divided into three priorities. Priority 1 assets are critical assets with high replacement costs like pumping stations and pipes that discharge into the marine and fluvial water bodies. Priority 2 assets are assets not critical to the system unless if large numbers are threatened, for example sumps and manholes. Priority 3 assets are not critical elements regardless of the number affected.

**Asset Exposure**

Figure 4.1 shows the number of exposed asset per SLR increment. The left y-axis displays the total amount of assets, the right y-axis displays the amount of Pumping stations exposed. The bar charts represent the pumping stations, the line charts represent the total number of assets with different priorities. The aim is to identify system thresholds based on SLR increments, as opposed to time- based thresholds. The asset exposure over SLR increments is the quantitative component which is combined with stakeholder input at the workshop.



| Number of Exposed Assets | ESL1 + 0 [m] SLR | ESL1 + 0.1 [m] SLR | ESL1 + 0.2 [m] SLR | ESL1 + 0.3 [m] SLR | ESL1 + 0.4 [m] SLR | ESL1 + 0.5 [m] SLR | ESL1 + 0.6 [m] SLR | ESL1 + 0.7 [m] SLR | ESL1 + 0.8 [m] SLR | ESL1 + 0.9 [m] SLR | ESL1 + 1.0 [m] SLR | ESL1 + 1.1 [m] SLR | ESL1 + 1.2 [m] SLR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StormWater Pumpstation | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| WasteWater Pumpstation | 5 | 6 | 7 | 7 | 8 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Priority 1 | 545 | 612 | 676 | 721 | 789 | 838 | 875 | 902 | 923 | 942 | 956 | 973 | 986 |
| Priority 2 | 6912 | 7974 | 9140 | 10247 | 11285 | 12120 | 12649 | 12968 | 13264 | 13510 | 13735 | 13968 | 14226 |
| Priority 3 | 840 | 1026 | 1184 | 1286 | 1420 | 1509 | 1574 | 1595 | 1620 | 1647 | 1675 | 1684 | 1711 |

Figure 4.1: Asset Exposure over SLR increments

Figure 4.1 shows a steep increase in the exposure of priority 2 assets in the area until around +0.50 $m$, +0.60 $m$, after which the increase in exposed assets per SLR increment starts to flatten out. A similar curve can be observed for priority 1 and priority 3 assets, albeit in smaller numbers. Three out of four storm water pumping stations are, using this static hazard approach, all immediately inundated at a current 1percent AEP event. Since the location of these are inland from the coast, this might be a conservative estimation. Wastewater pumping stations are incrementally exposed until around +0.50 $m$ SLR combined with the present day 1percent AEP storm tide level. Since they are key to running the system now and adapting it to future challenges, a conservative estimation would still be valid. How representative this static hazard exposure is, was verified at the workshop and will be discussed in section 4.1.2.

**Exposure Intensification**

It can be seen in Figure 4.2 that during a current 1percent AEP event, there is a high density of assets exposed in the west lower side of the Petone area, between the two wastewater pumping stations. The reason for higher occurrence around the pumping stations is due to the increased number of asset components in and around the pumping station. Other increased density areas are due to a high occurrence of exposed wastewater assets.

The output for a current 1percent AEP event can be seen in Figure 4.2. The algorithm used to produce this 'heatmap' is a Kernel Density Estimation. It interpolates between different points, and provides a value based on the occurrence of points in the proximity of an area. Although this produces non-quantifiable values, it is very effective in pinpointing a high occurrence of points, or in this case, assets. Given the high level nature of this assessment and the considerable number of datapoints in the asset datasets, this is a good representation of where asset exposure happens at different SLR increments.

Comparing this to a 1percent AEP event +0.50 $m$, it becomes clear that throughout the different thresholds, intensification of asset exposure occurs in these areas. This is an important observation, as it provides an indication of where to focus a closer examination of assets located in that area for potential compartmentalizing or replacement. Furthermore, it becomes clear that intensification of hazard exposure occurs in the slightly elevated area behind the Esplanade, where the main wastewater pipes and wastewater pumping stations are located.

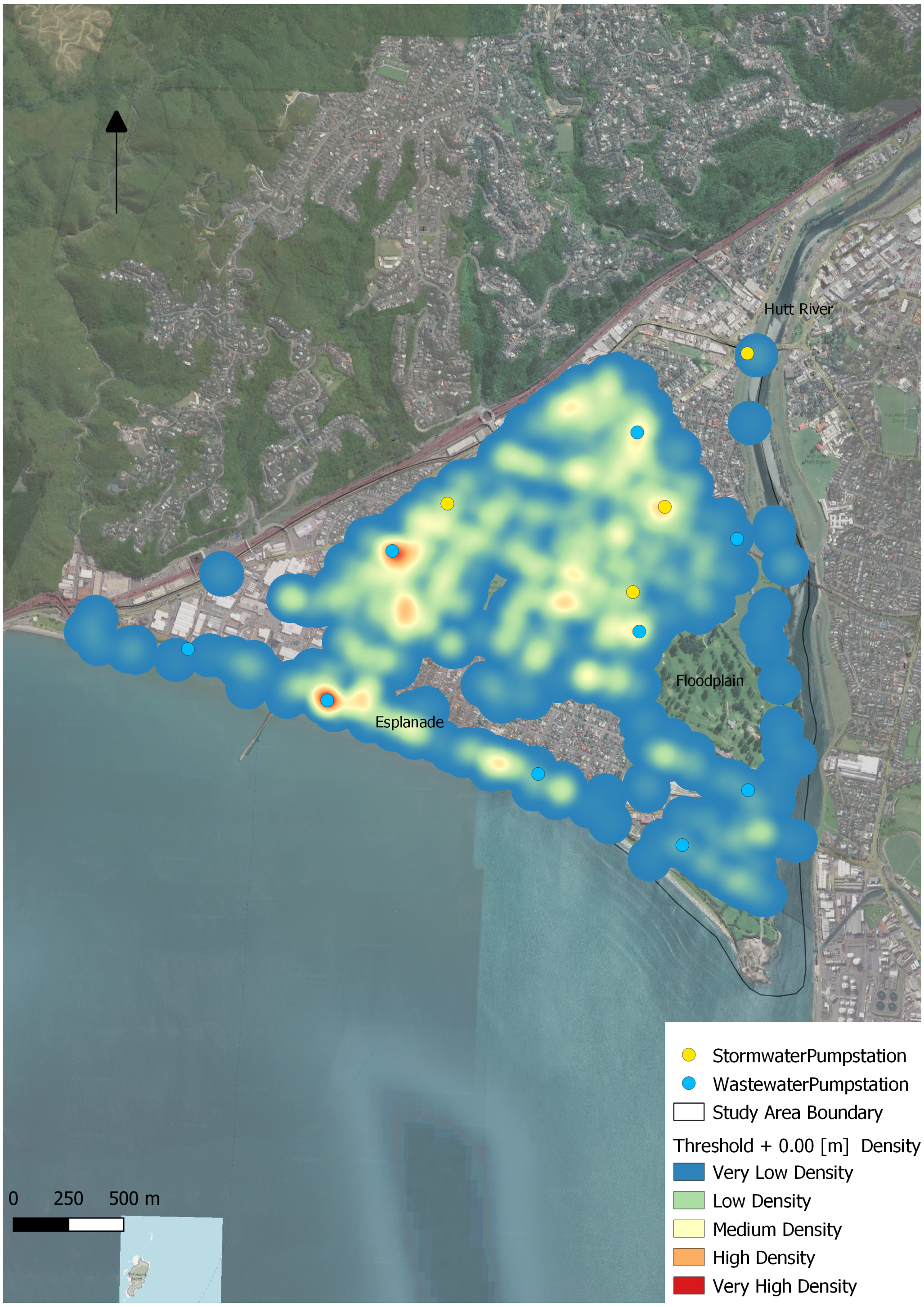


Figure 4.2: Location of Asset Exposure Intensification over SLR increments

**Retreat Opportunities**
For looking into any coincidence of affected assets and SLR increments, replacement values are calculated based on average lifespan of assets, provided by Wellington Water. The output shows a significant number of replacements were due in the mid 1990's through to the mid 2000's. There are lower numbers due in the next three decades with peaks starting after the 2060's. This can be found in Appendix 2.

It also shows a coincidence of pipes that are expected to need replacement based on estimated lifetime of materials where intensification occurs over SLR increments. Actual replacement however occurs based on scheduled inspection and when performance is compromised, rather than on the life expectancy of the pipes. This also expected for intensification of exposed assets behind the Esplanade. This gives a good indication of when to expect replacements to occur in the coming decades.

The location of asbestos pipes was also investigated. There is coincidence with the area mentioned in the previous section, but the asbestos pipes are located mainly along the Esplanade. This is the main Petone wastewater collection sewer discharging towards the WWTP. There is no date that these assets have to be removed from the ground by Wellington Water (noting that no new asbestos pipes are being used and that the existing ones are unlikely to be harmful when buried underground, rather they can become a hazard during replacement, e.g. cutting of the pipe). Should they be replaced at some point in the future they would provide an opportunity to consider retreat or redesign of the system.

### 4.1.2 Workshop Output

The Petone/Alicetown drainage system thresholds with regards to SLR was discussed at the workshop and an optioneering exercise was conducted. The optioneering exercise aimed to identify suitable adaptation options and to validate the work performed to that point in the project timeline. The workshop outputs are presented in this order.

The system thresholds identified during the workshop are the possible future scenarios where:

- +0.30 [m] of SLR until regular ponding due to increases in GWL is expected
- +0.30 [m] of SLR until hydraulic capacity is critically reduced
- Regular Wastewater Overflows
- Affordability as economic damages increase
- Cannot fix the system anymore
- No longer a contained system
- Regular overflows to property or watercourses
- Property owners can't afford to upgrade their own part of the system
- Property owners are not able to get insurance for their property
- GW at the surface most of the time, ponding

These thresholds were combined with the thresholds identified based on the exposure assessment. Since there was limited time for discussion during the workshop, it was not possible to discuss thresholds for adaptation options (pathways) in detail, therefore thresholds for the two water system were mainly discussed. It was proposed at the workshop that when identifying adaptation options there may be parallel options that can reduce the risk in the interim leading up to full retreat thus giving time for adjustments to be made that enable implementation of managed retreat less complex.

During the optioneering phase, possible pathways were discussed. This started out with more conventional techniques, such as increasing pumping station capacity. After this some more contemporary options were discussed, like creating water storage in lower areas. For the optioneering output, the most important adaptations discussed can be divided in the following main categories:

- Pumping Stations
- Increase Capacity
- Decentralize / Local Infiltration / Reuse
- Pressurize / Vacuum the system
- Create Storage in lower areas / overcome high tide
- Increased Imperviousness

Increasing infiltration through pervious surfaces, as discussed in the theoretical background, a great approach to infiltrate stormwater more locally, therefore reducing peak discharges in the drainage system. Examples of this are porous asphalt or bioswales. Both in the literature and in the workshop it was suggested that implementation of these measures locally, results in an increase in groundwater levels in lower elevated areas, and therefore increases the groundwater table. Therefore this would not be a good solution in the lower lying parts of Petone, but could be considered for implementation in more elevated areas, alleviating the discharge towards the lower lying areas in the Petone area. It also became clear that more effort until now has gone into thinking about stormwater adaptation then wastewater adaptation. This is why during the optioneering there are limited adaptation options for wastewater. For the purpose of this research however this is still a valid level as we were not looking into component level solutions. Pathways were representing the level of detail needed for establishing a conceptual DAPP.

As stated in the project plan and exposure assessment (Appendix 1 and 2), a static bathtub approach modelling map was used to identify exposed areas over SLR increments. This involved two main characteristics, the spatial extent of the flooding and the assets affected over different SLR increments. During the workshop these characteristics were discussed with the intent of verifying it with experts who have been working with more in depth models of the area. It was concluded that both the extent and exposure over SLR increments are considered a valid representation on which to continue the study. This validation was based on current static assumptions and dynamic models that are still being developed for the Petone area.

### 4.1.3 System Analysis

ISO 14090 outlines the components for setting up a systems concept (Standard, 2019). The System Boundary is a geographic or conceptual boundary used to demarcate the system that is being investigated. As can be seen in Figure 4.3, the decision was made to distinguish between a system and a sub system. The outer system boundary consists of the complete Petone and Alicetown infrastructure. Geographically, this would be the circumference described in Figure 4.3. The storm and wastewater system is defined as a subsystem within the Petone infrastructure. This allows for the possibility of mapping the system components and interdependencies of the sub system, and their connections to the larger system in more detail (Standard, 2019). Based on the system and sub system boundary demarcation the components in these systems are now described according to the ISO 14090 (Standard, 2019).

Standard (2019) describe organization as a comprehensive system component. This will from now on be referred to as a system component. Since the system boundary is described as infrastructure in the Petone/Alicetown area, critical infrastructure will be included in the system. The two water infrastructures were chosen as the system components, with a sub system for both Stormwater and Wastewater. Other components included are potable water, and more generic Petone infrastructure. This includes roads, electricity and gas utilities. External factors that have been implemented in this case are external stressors driven by climate change, and will be referred to as external stressors from now on. The rationale used was to include hazards that were driven by climate change, but would compound to area specific system interventions (Impacts). This resulted in external stressors influencing the infrastructure being sea level rise (a), increased rainfall and therefore pluvial / fluvial discharge (b), increased periods of drought (c) and earthquakes (d). These in turn result in systematic interventions for the Petone/Alicetown infrastructure. Earthquakes were included for completeness, but are not included in the research solution space.

Systematic Interventions were new inputs changing the total output of the systems, as a result of the external factors described above. For the Petone/Alicetown infrastructure system these include Flooding (Marine Flooding (1), Pluvial Flooding (2), Fluvial Flooding (3)), Groundwater level increases (4) and liquefaction due to earthquakes (5). Liquefaction due to earthquakes was left out of considerations in line with the established boundary conditions of the study. These main four hazards lead in turn to a range of systematic interventions in the sub system specifically for storm water and waste water. These include drainage problems such as the inability to overcome peak discharges, salt water intrusion and inundation. These direct impacts were added to the CIrcle tool in Figure 4.3, where cascading effects as a result of these sub system interventions were investigated.

Discussions with key stakeholders and actors were important to get an overview of key influences on the different organizations within the system. The relation between the stakeholders and the system components can be seen in Figure 4.3. Relationships between the different stakeholders and systematic interventions was visualized by showing the connections between the different components in the system. For example, how the system components and key actors are connected, and how they are affected by systematic interventions and their link outside of the sub system. The output from this, especially the systematic interventions, was used as the input for identifying cascades and interdependencies within the two water subsystem using the CIrcle tool.

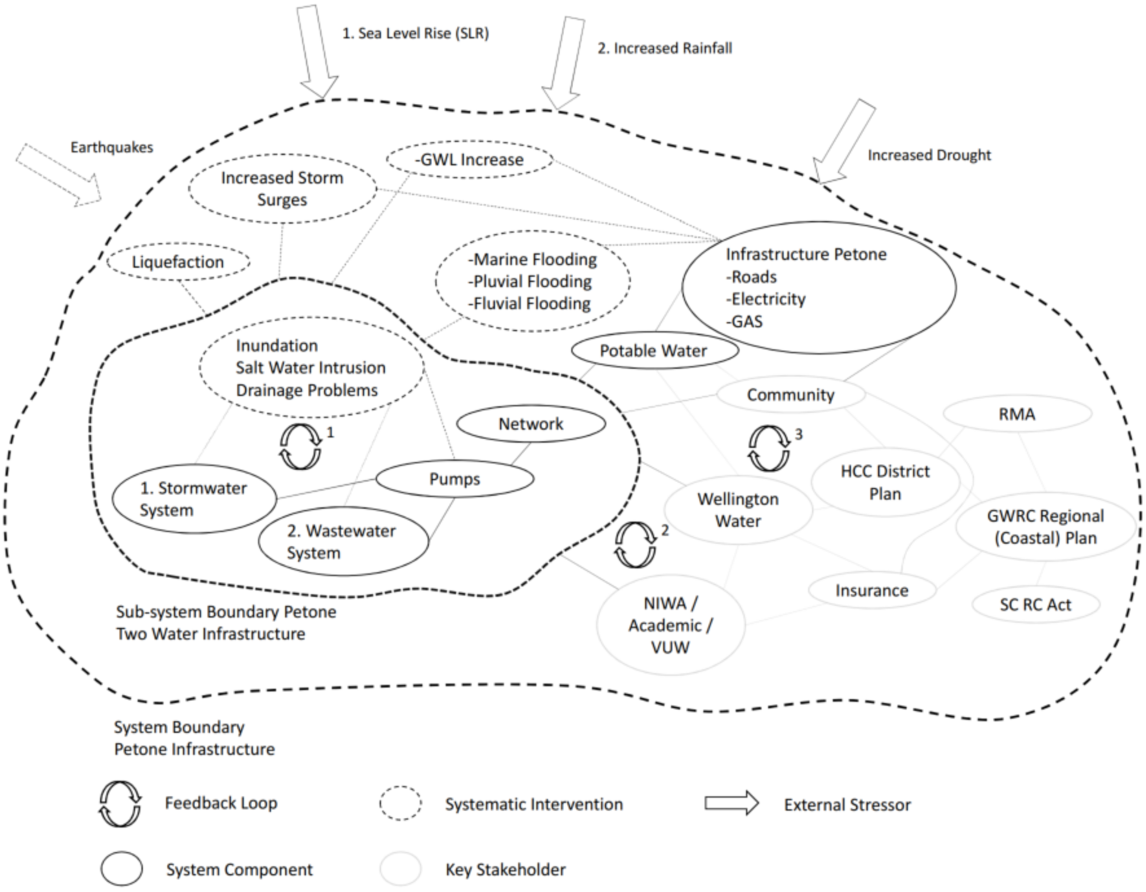


Figure 4.3: System Outline

In addition to this, the contribution and involvement of different governmental instruments, like the New Zealand Resource Management Act (1991) and the Local Government Act (2002), were also included. For instance the latter Act requires councils to develop 10-year Long-Term Plans and 30-year Infrastructure Management Plans and regularly update them engaging with the communities they service. The RMA governs land use planning in New Zealand which provides for 10-year plans on regional and local levels which influence exposure to natural hazards and the effects of climate change.

Feedback loops are related to the involved stakeholders. Feedback loop 1 is caused due to impacts driven by SLR, which are inundation, salt water intrusion and drainage problems. This is going to put increasing stress on the storm water and wastewater system (sub-system two water). Feedback loop 2 is related to increasing knowledge, improved models, new guidance and area assessment due to research and knowledge sharing by the relevant stakeholders, like Wellington Water and NIWA. The recent paper by Paulik et al. (2020) is a good example as it aids the decision making process for stakeholders. Feedback loop 3 contains new guidance (Ministry for the Environment, 2017) (e.g. existing development of services to accommodate for SLR as required by Wellington Water through their Regional Standard for Water Services) and plans like the upcoming 30 year infrastructure plan. Others include Asset maintenance and Asset upgrades.

### 4.1.4 CIrcle Tool

The input for the CIrcle tool was the comprehensive system components, outlined in section 4.1.3. These are critical infrastructure components. Table 4.1 and Figure 4.4 show the output from the Circle tool after including suggestions made during the workshop discussion. Only the critical infrastructure defined in the project scope, the two water infrastructure was included for direct impacts as a result of SLR. Cascades to other critical infrastructure were included. A mix of qualitative and quantitative system thresholds were added to the direct impacts based on exposure assessment and workshop output. This aided the development of Pathways for the conceptual DAPP. Figure 4.4 shows the setup of the circle tool. Each of the coloured elements in the Circle represent one of the different types of critical infrastructure used, which can be found in 4.1. The coloured connection lines represent indirect consequences in this sector, or in other words cascading effects.

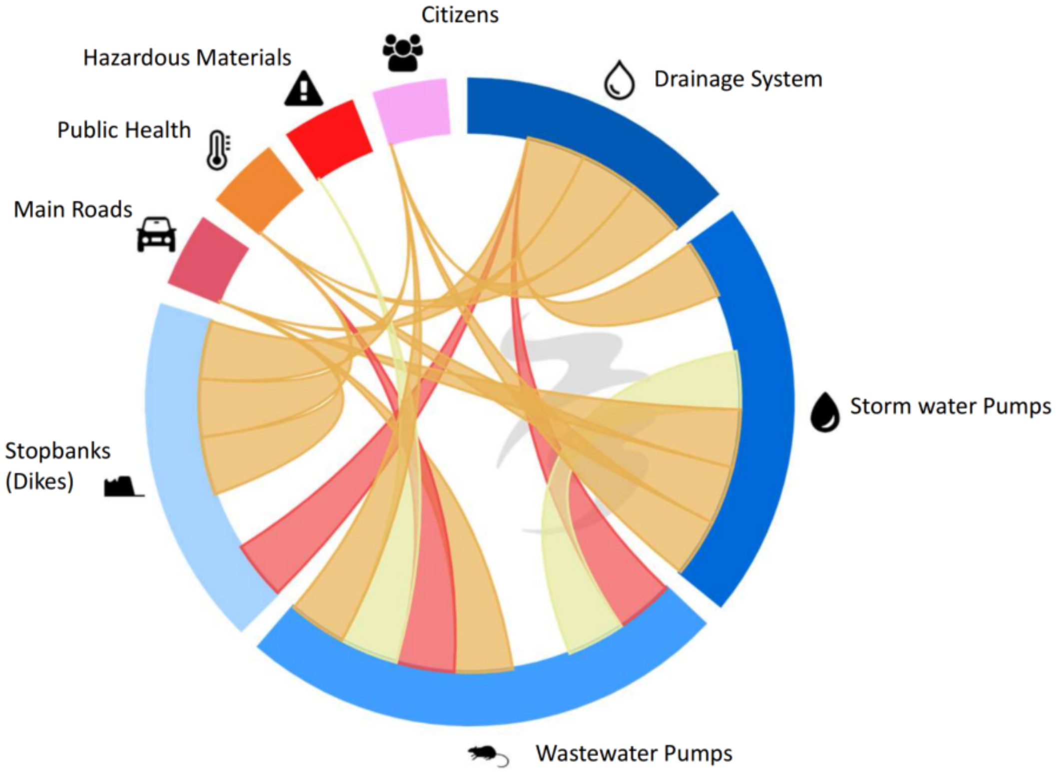


Figure 4.4: CIrcle Tool Critical Infrastructure Interdependencies

Direct impacts on the storm water pumps and wastewater pumps were found to have cascades towards citizens, public health, main roads and the the general drainage system. Due to the inability to dispose of the excessive storm water and wastewater, the system will be put under increasing stress as the sea rises and under more intense rainfall events. Excess water containing pollutants will overflow inundating roads, resulting in consequences for traffic or potentially more long term damage to the road infrastructure. These pollutant spills, occurring either from storm water, wastewater or simultaneously, also have health implications. This could range from injuries, for example as a result of inundated recreational spaces or roads, negative consequences for water quality or bad odor due to pollutant spills. When inundation starts to occur more frequently, this causes increased costs for citizens to maintain their property. This also could result in an inability to get insurance for certain areas.

Based on the output generated in 4.1, system thresholds were established for use in the conceptual DAPP. This is part A) outlined in the research progress in Figure 3.1. The first threshold is identified as +0.30 $m$, where the gravity-based system ceases to work and regular ponding is expected. The second threshold is established at +0.50 $m$, where all wastewater pumps, 3/4 stormwater pumps and a considerable part of the two water system is exposed. The third established threshold is +0.80 $m$ where the rate of exposure considerably decreases over SLR increments as most of the system is already exposed. For a visual overview see Figure 4.1.

Table 4.1: Critical Infrastructure Direct impacts and Cascades

| Direct Impact | Cascades |
|---|---|
| Water - Non Critical Components | |
| From the exposure assessment:<br>Priority 1 - 0.80 $m$ Wastewater Outlets<br>Priority 2 - 0.50 $m$ Manholes / Sumps<br>Priority 3 - 0.80 $m$ Low Priority<br><br>From the workshop:<br>Groundwater Threshold - 0.30 $m$<br>Reduced Hydraulic Capacity - 0.30 $m$ | To Citizens<br>- Overflow due to reduced capacity<br>- Inability to get Insurance<br>To Public Health<br>- Overflow due to reduced capacity<br>To Main Roads<br>- Overflow due to reduced capacity |
| StormWater Pumps | |
| Stormwater Pumps Immediately affected:<br>0.00 $m$ 3/4 Stormwater Pumps Affected | To Water<br>-Increased stress on the system<br>To Main Roads<br>- Road overflow / inundation<br>To Wastewater Pumps<br>- Stormwater Overflow<br>To Public Health<br>- Stormwater Inundation<br>To Citizens<br>- Inability to get Insurance<br>- Increased Costs<br>- Stormwater Overflow |
| Wastewater Pumps | |
| Wastewater Pumps affected over SLR:<br>0.00 $m$ 5/9 Wastewater Pumps Affected<br>0.10 $m$ 6/9 Wastewater Pumps Affected<br>0.20 $m$ 7/9 Wastewater Pumps Affected<br>0.40 $m$ 8/9 Wastewater Pumps Affected<br>0.50 $m$ 9/9 Wastewater Pumps Affected | To Water<br>- Increased stress on the system<br>To Stormwater Pumps<br>- Wastewater pollutants infiltration<br>- Increased stress on Pumps<br>To Main Roads<br>- Inundation with pollutants<br>To Citizens<br>- Inability to get Insurance<br>- Increased Costs<br>- Wastewater Overflow<br>To Public Health<br>-Wastewater overflow, health implications |

## 4.2 Adaptation Options

This section presents the condensed list of adaptation options considered for the DAPP pathways. The complete list of options can be found in Appendix 3. These were discussed according to the policy categories outlined in IPCC (2019). Pro's and Con's are also summarized to aid the decision making process.

### 4.2.1 No Response

No response is the current strategy utilized in the area. This does not mean that the system is not maintained, it is being maintained continuously, rather it is not proactively prepared for future increased stresses on the system from SLR and climate change. Problems are being treated as they arise. The advantage of using this approach is that no big investment has to be made in the short term, with costs remaining consistent. The disadvantage is that, due to changing stresses on the system these disruptive interventions will not only become increasingly frequent, but once the current system has reached its threshold, major investments will be necessary to continue achieving the required levels of service and disruption to communities will result, an overview can be found in Table 4.3

Table 4.2: No Response Strategy

| No Response | Specific Options | Pro's | Con's |
|---|---|---|---|
| Repair Pipe | Close off leaks upon emergence | Short Term non Expensive | Long Term complete replacement costs |

### 4.2.2 Protect

Lowering the groundwater level around critical infrastructure would be mainly applicable for the pumping stations that will be affected by SLR. This would delay the water reaching the pumping station causing damage to corrosive parts in the pumping station. The advantage of this option is that initially current pumping stations in place can remain functional. Planting vegetation to locally lower GWL would be an inexpensive short term no regret option to implement. Sea levels however will rise gradually and this option will see a decline in performance and gradual increase in costs to keep the increased water away from the asset components, eventually facing complete replacement costs.

Preventing undesirable inflow is already being done in the Petone area, mostly for pipes. The method uses valves to prevent inflow in the system during high tide. As SLR increases, structural measures to protect the system from inflow will be required. The advantage is that it can be applied to the current drainage system. However, permanent closure of the outlets ceases the functioning of the drainage system. Therefore the system will not function anymore resulting in the threshold failure condition of this adaptation option. The last two options for protect as an adaptation, dry and wet proofing critical infrastructure assets, fall in a similar category. While wet-proofing allows non-essential parts of the asset to be flooded, dry-proofing completely separates the asset from the water. This could also be an opportunity to incorporate robustness into this option by implementing it as a dry-proofing solution, and when different parts of the infrastructure start to flood, use it as a threshold to move to a different adaptation option. Depending on the type of implementation, this approach could be adjusted to be effective for a long time. Once the threshold is reached however, the whole system has to be replaced.

Table 4.3: Protect Strategy

| Protect | Pro's | Con's |
|---|---|---|
| Lower GWL around assets | Relatively Inexpensive | Limited mitigative capacity |
| Dry - Proof | Long term beneficial, especially together with increased pumping capacity | When waterproofing capacity is exceeded, expensive to replace |
| Wet - Proof | Long term beneficial, less expensive then entire waterproofing | When waterproofing capacity is exceeded expensive to replace |
| Prevent Inflow | Effective Short Term, | Once the threshold is exceeded, it cannot be upgraded, whole system needs to be replaced |

### 4.2.3 Accommodate

Raising the system and sewer outlets would be a way to make sure that the water does not get in the pipes anymore at current water levels. Over the course of different SLR increments this will be a recurring situation and the system will have to be raised again on reaching the next threshold condition. Considering its design and lifetime limitations, the SLR will keep increasing the problem until it starts to occur again. The biggest issue however is the implementation. As most of the drainage system is designed to be a gravity-based, raising the outlets will significantly reduce hydraulic capacity. This means that the system in place now only allows for a limited increase in outlet levels before having to switch to a pressurized system to overcome this hydraulic loss.

To overcome this it is also possible to replace the pipes and nodes. With regards to the loss in hydraulic capacity, the sewer connections in the system could be raised, so that the hydraulic gradient is restored. This is also only possible to a limited extent. With regards to the increased discharges in the system, it is possible to increase the pipe diameters by replacing the pipes. Pressurizing the system is also a way to overcome the initial stages of SLR. Increased corrosion and vulnerability of the pumping stations, and the need for increasing pumping station capacity over SLR increments, will reduce the lifetime of this option under SLR. The major disadvantage is that it is not possible to do this for part of the system, the whole system has to be adjusted.

Pumping stations are going to be under increasing stress as a result of SLR. Increasingly pressurized systems and increased discharges mean pumping capacity has to be increased. Increased GWL due to SLR means that there is a risk of pumping stations flooding, especially since they are partly located underground. Raising the pumping stations would be a way of accommodating this. Failure conditions of this option is when the ongoing SLR leads to flooding of the pump station components.

Table 4.4: Accommodate Strategy

| Accommodate | Pro's | Con's |
|---|---|---|
| Raise Sewer and Outlets | Prolongs usage of gravity-based system | Can only be raised a limited amount, relatively expensive for small SLR extention |
| Increase capacity pipes and nodes | Prolongs usage of gravity-based system and increased discharge capacity | Becomes obsolete when the system is replaced |
| Pressurize Sewer | Prolongs usage of drainage system | System becomes less adaptable |
| Increase Pump Capacity | Effective | Expensive to implement, when failure condition is met, non - upgradable |
| Raise Pump Stations | Effective and will prolong the lifetime of the drainage system | Very expensive |
| Decentralize System | Long term effective / adaptable / upgradable | Initially expensive, more 'invasive' for community, unusual practice |

### 4.2.4 Nature Based Adaptation

Nature based options are mainly derived from WSUD approaches, as explained in the theoretical background. Nature based adaptation options are designed to enable the drainage system to adapt without structural interventions. The two examples would be to either delay entrance to the drainage system in an extreme event by temporarily storing or facilitating local infiltration until the system has normalized again and is not working at full capacity anymore after an extreme event.

However, many of these options require extra space. Since the Petone area is a relatively densely developed area it might prove difficult to implement these options on a large enough scale in order for it to be effective in mitigating SLR impacts. Implementing the WSUD options requiring a larger spatial extent in later retreat stages, when there is space available in retreated areas, would allow for implementation of these options. Storage of excessive discharge is considered effective and can be integrated in many urban community facilities. Failure conditions would be dependent on the hazard. When considering SLR increments, this will increase the GWL, leading to inundation of the storage facility. This will start with ponding, but will increasingly fill up the storage facility until the system is unable to handle the discharge and the storage facility can overflow.

On site treatment, applicable to both storm and wastewater, is a way of decentralizing the drainage system. For wastewater this is more limited because storm water can be more effectively treated and reused as grey water. This decentralized approach reduces the need for all peak discharges to flow to the outlets / treatment facilities in the system, mitigating the negative impacts of the reduced hydraulic capacity due to SLR. This can be done with the help of biofilters, either reintroducing the treated storm water as greywater or reduce the load on the WWTP by using natural solutions to pre filter the wastewater before releasing it towards the WWTP.

Increasing perviousness to aid local infiltration is also a double-edged sword. On the one hand it decreases stress on the system during an extreme event. As stated in the theoretical background however, this increase in perviousness works both ways and might have the opposite effect in coastal areas, like Petone, where the perviousness allows for the groundwater table to rise further. It is therefore important that it is implemented in lesser effected areas in the upper part of the drainage system to mitigate and reduce discharge to the lower parts of the drainage system. The system failure conditions are when SLR causes the water levels to also reach these areas, and the increase in groundwater table is accelerated due to this increased perviousness.

Delay of discharge can be addressed with increased nature based solutions like green roofs, rain gardens and revegetation. These are relatively easy to implement short term and quite robust. Especially when implementing these in higher parts of the Petone area thus reducing stress on the lower parts of the system. Failure conditions would be when the discharge capacity is exceeded.

Table 4.5: Nature Based Strategy

| Nature Based | Pro's | Con's |
|---|---|---|
| Biofilters (on site treatment) | Re use, decrease stress on treatment plant | Reusage of treated water not always possible |
| Local Infiltration | Can be integrated into surroundings, ecosystem benefits | When GWL becomes too high, ponding occurs |
| Discharge Storage | Handles discharge, ecosystem benefits, community benefits, adaptability | Spatial requirements |
| Discharge Delay | Delays discharge, short term no regret, ecosystem benefits | Some options might require space or integration into public facilities and spaces |

## 4.3 Sequencing Adaptation Pathways

This section presents the results from the exposure assessment, workshop, systems cascades and adaptation options into a conceptual DAPP. The first part focuses on establishing parametrization for sub area selection. The second part focuses on the system thresholds as an output from the workshop and exposure assessment. The third part summarizes the findings from the high level adaptation options, their associated ATP's and the transition to adaptation portfolios. The last part combines them into a conceptual DAPP for visualization between different areas, retreat phases and interaction between different implementation methods for each area.

### 4.3.1 Area Selection

Retreat will eventually be necessary at different SLR increments for the entire study area. The sequence of retreat can however be different for different sub areas within the study area. This is because of the different elevations in relation to SLR and opportunities to make interventions for different areas based on different adaptation thresholds. This also includes other areas that can help implement retreat in the whole study area. Since retreat in this context is a spatial shift in retreat phasing, there is a need to divide the project area into smaller sub areas, each with their unique retreat strategy.

Three areas were identified using cross sections of the area from a DEM file (1) and asset exposure information with respect to exposure intensification over SLR increments (2). The interrelations between the areas were explored using the parameters set out in Table 4.6. The first row in table 4.6 defines the Area strategy. Eventually all areas will retreat, therefore the strategy noted here is the first strategy in the sequence. Asset exposure and intensification, elevation classification (DEM), pumping station exposure, coastline proximity and area opportunities come from the exposure assessment.

It is the coincidence and parallel implementation between the area specific solutions that enable the spatial retreat of services in a managed way. Consequently an holistic perspective is used by examining the implementation of area specific solutions for all areas and their inter-relationships.

Table 4.6: Area Selection Parameters

| Parameters | Area 1 | Area 2 | Area 3 |
|---|---|---|---|
| Adaptation Strategy | Retreat | Protect/Retreat | Accommodate/Retreat |
| Land Use | Residential | Industry / Residential | Industry / Residential |
| Asset Exposure | Intensification | Intensification | Low Intensification |
| Pump Exposure | Medium | High | Low |
| Elevation | Low | Medium | Medium / High |
| Coastline Proximity | Medium | Close | Far |
| Opportunities | Old Pipes | | |

### Area 1

Retreat is the strategy identified as the initial sequence for this area. The area has a high asset exposure over all SLR increments. It is the highest exposure level in the study area. A high concentration of assets can be correlated to either a high density of residential development, or an industrial area. In terms of pumping stations, there are both stormwater and wastewater pumping stations affected. The area also has a low elevation sump, in combination with a medium coastline proximity and therefore will be particularly vulnerable to the SLR threshold of +0.30 [m].

Opportunities for Managed Retreat through the spatial relationships that can facilitate Managed Retreat are also present in the area. The first opportunity is that the area has a high number of expected pipe replacements due. By not replacing the pipes and thus continuing use of the current system until retreat begins creates an opportunity.

The second advantage is that, since the system won't be used anymore, even with considerably reduced hydraulic capacity, this can create useful redundancy in the system. By rerouting stormwater through the old drains creates an increase in capacity in the other areas. It also creates the opportunity to repurpose this area with the aim of creating extra drainage capacity, as well as providing community and ecosystem benefits in the form of public spaces.

### Area 2

The first strategy in the retreat sequence for this area is Protect. Due to the close proximity of the area to the coastline, retreat might be expected to be the first action. It also has a high asset exposure like Area 1. The elevation of Area 2 however is higher and therefore not located in the lower part of the study area, despite coastline proximity, and Area 2 is critical for the pressurized wastewater system in the lower Petone part. The area already has been artificially reinforced with a seawall and dune planting in front of the sea wall. To allow for this part to retreat, the storm water system would have to be isolated or completely re-routed.

Pipes in the area are not expected to require replacement soon, therefore opportunities in other parts of the system may facilitate retreat. The advantage of doing this is that the current system can remain in place, since it is a critical pressurized part that will become increasingly affected. For that to happen, adaptive capacity will need to be created in other parts of the system like Area 1, until retreat is initiated in this area.

### Area 3

The first strategy for the area is Accommodation. There is a low exposure of assets affected for SLR increments and for critical infrastructure like pumping stations. The area is located the furthest from the coastline in the study area and has a relatively high elevation in relation to the other areas. Initiation of retreat phasing will therefore be at high SLR increments. This means that this part of the two-water system in its current form will be utilized for the longest duration of time. Accommodating the system and in the process also capitalize on opportunities arising for this replacement are important components of this strategy.

Opportunities with this strategy is the creation of mitigative capacity for the lower parts of the Petone drainage system. This means that it can minimise disruption during retreat and maximize the effectiveness of retreat in the low 'sump' parts of the Petone area, thus creating a reduction in discharge towards the other areas. Furthermore, the area will need to adapt to increased stresses on the system. From the system analysis these include increased rainfall intensities and increased groundwater levels resulting in increased pluvial flooding, increased saltwater intrusion, reduced hydraulic capacity and inundation.

### 4.3.2 System Adaptation Thresholds

System adaptation thresholds emerge from both the exposure assessment and expert input during the stakeholder workshop which comprised a mix of quantitative and qualitative threshold indicators. Thresholds denote when the current system performance is unacceptable and/or unsustainable. For example x cm of SLR (quantitative) and community tolerability of impact (qualitative).

From the exposure assessment and workshop, the quantitative thresholds identified are 0.30 $m$, 0.50 $m$ and 0.80 $m$ of SLR increments for different assets in different areas. This allows for generating expected pathway scenario-based lifetime and failure conditions. The 0.30 $m$ threshold is associated with the gravity-based system and regular ponding due to increases in GWL. The 0.40 $m$ and 0.50 $m$ thresholds are associated with the wastewater pumps becoming increasingly exposed, all of them by the time 0.50 $m$ is reached and the major increase in the number of manholes and sumps exposed. At 0.80 $m$, the number of assets affected over different SLR increments tails off. This means that the biggest stresses on the system occur in the first 0.80 $m$ of SLR increments. The qualitative thresholds are related to observed unacceptable performance from a community and a service provider perspective. The thresholds comprise physical consequences including increasing wastewater overflows, regular ponding due to increased GWL and regular overflows to properties or watercourses.

### 4.3.3 Adaptation Option Thresholds

Option (Pathway) thresholds are determined per adaptation option based on their failure conditions. Initially this was done for each of the options, which can be found in Appendix 3. During the research it became clear that a lot of the options would have to be implemented together. Therefore the list of options is simplified into pathway portfolios of actions that would be taken together to achieve the objectives, which can be seen together with portfolio failure conditions in Figure 4.5. Failure conditions are based on the type of option and the system thresholds. Initially, pathway thresholds were defined per conceptual area 1,2,3, each with their AT. This was to tailor the high-level option categories to area specific option sequences and to optimize the performance of the options in the area.

By calculating the performance of pathways over a range of SLR increments per Sub Area and visualize this with a graph, enables identification of possible levels of service across the different SLR increments, depending on the adaptation options chosen. It was decided not to continue with this approach for this study as it would require consideration of an area specific option for each high level category, in each sub area. Dividing up a number of areas would simply be too time consuming because of the detail generated.

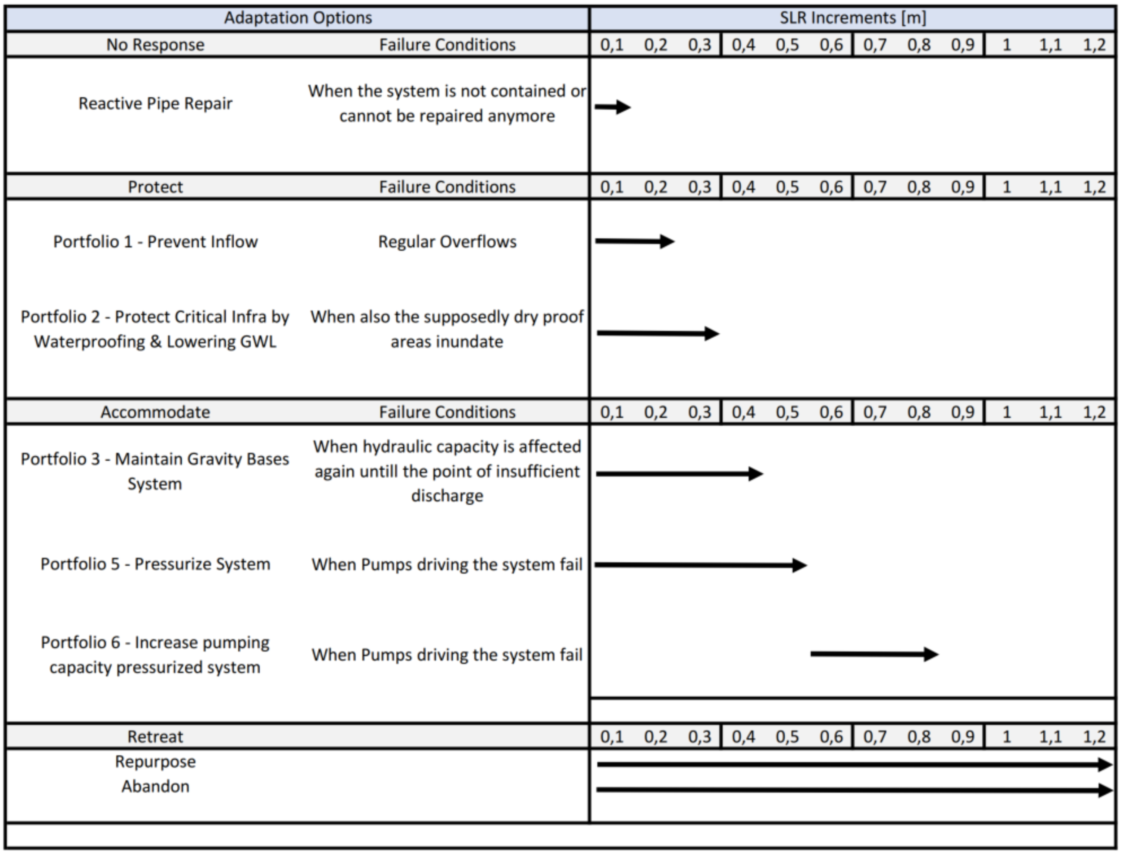


Figure 4.5: Failure Conditions Adaptation Portfolios

**Planning Signals**

During development of two water adaptation portfolios planning options were added to the portfolios, in preparation of retreat. Land use planning changes are not consequently related to infrastructure adaptation options, which is different for each area, but in which retreat phase these adaptation options (pathways) are based. A good example is upgrades to water services and facilities by Wellington Water, through their Regional Standard for Water Services, need to accommodate SLR as recommended by the Ministry for the Environment (2017) guidance. This is serving as a signal of future sea level rise impacts. Table 25 and Table 26 in Ministry for the Environment (2017) are used to illustrate possible planning changes alongside two water retreat, signalling retreat phases identified in Olufson (2019). These are discussed per retreat phase.

Community Engagement (1) – Conditional Rules

Development in the area allowed under new specifications, like the current development of services to accommodate SLR as required by Wellington Water. This is an attempt of 'specifying minimum floor levels' in Table 26 Ministry for the Environment, 2017 through their Regional Standard for Water Services, and suitable for areas where increases in GWL are a problem, like the project area. The intention is that new development is more robust and able to be in service until retreat is initiated. Regional Policy statement and Plan can be updated to prepare for retreat. 'Collaborative planning' and 'Asset Management Planning' from Table 25 Ministry for the Environment, 2017 can be used to start stakeholder and community inclusion in the planning process.

Planning and Preparing (2) – Plan changes, rules
Development in the retreat area limited. Planning methods used for this area can be 'Specifying types of construction and building design and use' from Table 26 Ministry for the Environment, 2017 and planning process on a smaller scale, like 'District Plans' following the signalling based on the Regional Policy statement in the previous retreat phase.

Enabling Investment (3) – Closed Zoning
Development in the retreat area is restricted, to prepare the area for retreat. Planning methods could be 'Excluding particular activities from identified areas' from Table 26 Ministry for the Environment, 2017 to prohibit further development.

Active Retreat (4) – Relocation
Active relocation, the retreat area is being prepared for a new function. 'Community futures' from Table 25 Ministry for the Environment, 2017 to discuss and plan repurposing of the retreat area to meet the community needs.

Repurpose (5) – Re Zoning
The area redeveloped according to the new repurpose / zoning strategy and a new 'Zoning' established to support the repurposing. An example could be a lake developed as a park for amenity and recreational purpose. The planning process used can be 'Precinct, area or structure plans' from Table 25 Ministry for the Environment, 2017 to integrate into the district plan.

**Adaptation Portfolio**
The adaptation portfolios outlined in Figure 4.5 are discussed in this section by area. This combines the option pathways into portfolios, the failure conditions and planning signals. The adaptation options within the portfolios are discussed in section 4.2.

**Area 1**
Portfolio 1 – Prevent Inflow
Adaptation pathways in this portfolio include implementing a non return valve and closing off parts of the system during extreme events. Failure condition occurs when the water is continuously above a level that does not allow to discharge the excess water without pumps, which occurs at +0.20 m. In Area 1 Portfolio 1 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2) and Enabling Investment (3). Associated Planning Conditions with this Portfolio are therefore Conditional Rules, Plan changes and no development.

Portfolio 2 – Protect Critical Infrastructure
Adaptation pathways in this portfolio include dry / wet proofing critical infrastructure like pumping stations and lowering GWL locally around pumping stations with using e.g. vegetation. Failure conditions occur when the gravity-based system ceases to function at +0.30 m. In Area 1 Portfolio 2 is related to the retreat phases until Repurposing, at which point the area will be re zoned. This means the area will be anticipated to have a different planning purpose. Active Retreat (4) has a planning condition of closed zoning, meaning the active part of managed retreat has begun with people moving away, houses moved to other available land for example.

**Area 2**

Portfolio 3 – Maintain Gravity-Based System
Adaptation pathways in this portfolio include raising nodes and pipes, increasing capacity nodes and pipes and increasing local infiltration and filtering. Failure Conditions occur at the threshold of +0.40 m. In Area 2 Portfolio 3 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2) and Enabling Investment (3). Associated Planning Conditions with this Portfolio are therefore Conditional Rules, Plan changes and no more development.

Portfolio 4 – Pressurize the Drainage System
Adaptation pathways in this portfolio include pressurizing sewers, increasing local infiltration and filtering and adapting pumping stations. Failure conditions occur when the pumps driving the system fail at the threshold of +0.50 m. In Area 2 Portfolio 4 is related to the retreat phases until Repurposing, at which point the area will be re zoned. Active Retreat (4) has a planning condition of closed zoning, meaning the active part of managed retreat has begun with people moving away, houses moved to other available land for example.

**Area 3**

Portfolio 3 – Maintain Gravity-Based System
Adaptation pathways in this portfolio include raising nodes and pipes, increasing capacity nodes and pipes and increasing local infiltration and filtering. Failure Conditions occur at the threshold of +0.40 m. In Area 3 Portfolio 3 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2). Associated Planning Conditions with this Portfolio are therefore Conditional Rules and Plan changes.

Portfolio 4 – Pressurize the Drainage System
Adaptation pathways in this portfolio include pressurizing sewers, increasing local infiltration and filtering and adapting pumping stations. Failure conditions occur when the pumps driving the system fail at the threshold of +0.50 m. In Area 3 Portfolio 4 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2). Associated Planning Conditions with this Portfolio are therefore Conditional Rules and Plan changes.

Portfolio 5 – Replacing and / or Raising Pumping Stations
Adaptation pathways in this portfolio include replacing pumps for increased capacity, raising the operating height of the pumps. Failure conditions occur when the pumps driving the system fail at the threshold of +0.80 m. In Area 3 Portfolio 5 is related to the retreat phases until Repurposing, at which point the area will be re zoned. Enabling Investment (3), Active Retreat (4) has a planning condition of closed zoning, meaning the active part of managed retreat has begun with people moving away, houses moved to other available land for example.

### 4.3.4 Conceptual DAPP

After the options were developed they were grouped in terms of costs and time needed for the implementation based on the lifetime and adaptive capacity of the options. This was done using the managed retreat components identified in Olufson (2019) in order to group the different phases displayed in Figure 4.5. This provides an accompanying ‘road map’ where each pathway indicates which component of MR is being initiated, and what the actions should be associated with this stage of the retreat. The components are set out in section 2.2.2.

To illustrate changes in retreat phasing, phases are implemented using a DAPP approach. Signals and Triggers are also implemented using each of the DAPP’s for the different areas. These are DAPP pathways signals and triggers for retreat strategies in the different areas. This is why some pathways can have multiple signals on one pathway sequence. The trigger is the point where active retreat is initiated, signals indicate a change in retreat phase. Signals are included qualitatively as a result of the workshop. Triggers are linked to the mix of quantitative and qualitative AT’s established for the study area. All available pathways for each area were not developed for this study as it was beyond the level of detail able to be undertaken within the time limitations of this study.

Failure conditions were determined by portfolio, rather than by portfolio per area. Some loss of detail has occurred here as different portfolios with pathway options have different failure conditions within different areas. This is also noted in section 4.4.3. For example, Portfolio 5 would not be applicable in area 1 as the pump inundation at low SLR would stop the pumps working as they would start to pump salt water into the system. Increasing the pump capacity would not address this. By iterating and determining the strategy for each of the areas and accompanying it with possible portfolios (preselecting) the conceptual DAPP could be developed and used illustratively within the timeframe of the study. Another component not included in detail in the pathways is costing. Preliminary considerations were made during development of the portfolios but not enough to quantifiably weigh them in relation to other portfolios. How to improve on this and its relevance is outlined in Chapter 5 Discussion.

### Area 1

Area 1 has a retreat objective. These pathways are mainly feasible short to medium term because of the low elevation of this area. The focus is therefore on protecting the current system until the point of retreat. Post retreat repurposing options are considered for this area. Due to the low elevation, this area would be suitable for creating extra flood detention, also with nature based options, in the two water system. This way the area is repurposed both providing community amenity by creating ecosystem and recreational benefits and having a positive effect on the discharge capabilities for the two areas. All portfolio options are outlined and a conceptual pathway outline is presented in Figure 4.6. Threshold for this area is a SLR of +0.30 $m$ as this is when the current gravity-based system ceases to function. The retreat trigger is placed at +0.25 $m$ since this is when regular ponding and an inability to overcome the influence of the tide for discharging is expected.

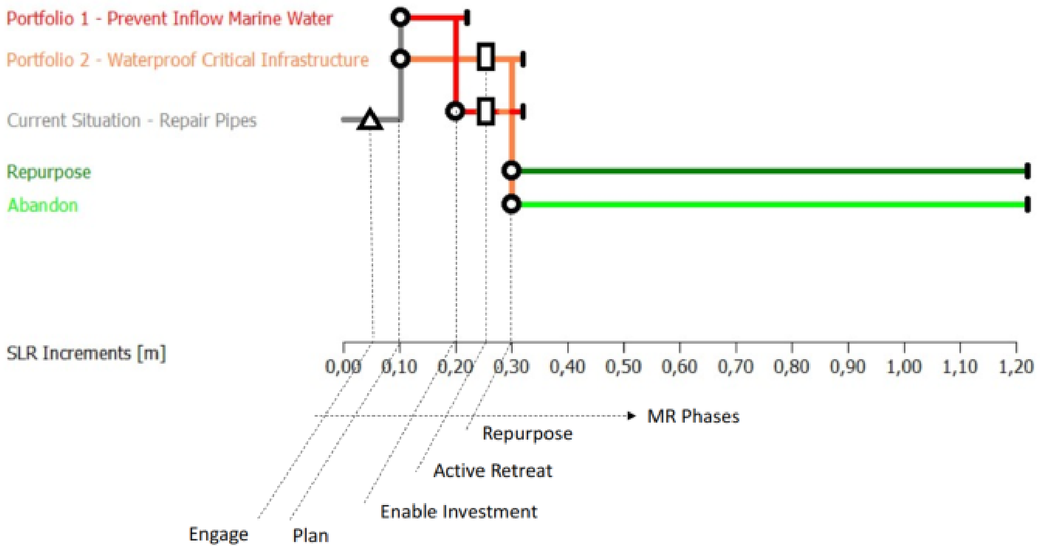


Figure 4.6: Conceptual DAPP Area 1

### Area 2

Area 2 has a retreat objective, but at higher SLR increments than Area 1. This means that pathways should function above the ATP of area 1, which for area 2 is +0.50 $m$. This results in pathway portfolios that are more focused towards accommodating the existing infrastructure to longer term changes. This could be raising the level of the sewerage system and increasing capacity of the pipes and nodes, in conjunction with nature-based solutions like promoting local infiltration, or switching to a pressurized system. The conceptual DAPP is outlined in Figure 4.7. There are two approaches illustrated for this area. The first is to maintain the gravity-based system as long as possible. Although costs are not quantified in this conceptual DAPP, raising the whole system is extremely expensive, causes major disruption for the community and is limited by the burial depth of the pipes. Before the retreat trigger there would have to be a change to the pressurized pathway portfolio. This is also an expensive option but would be able to maintain service until the retreat trigger for Area 2. Due to the proximity to the coastline, repurposing options could be a natural buffer or recreational zone in between the coast and retreated Area 1.

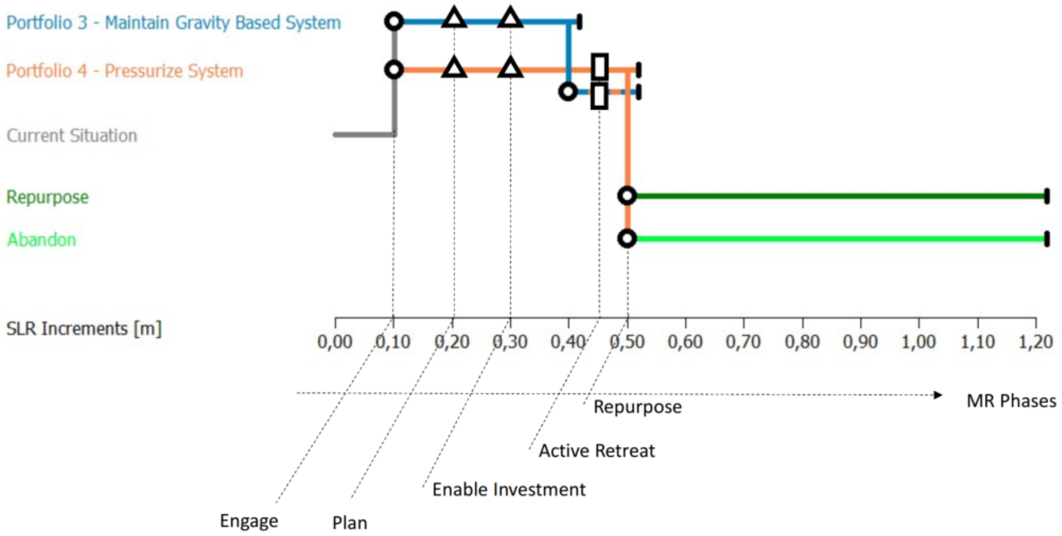


Figure 4.7: Conceptual DAPP Area 2

**Area 3**
Area 3 has the highest ATP for retreat, +0.80 $m$. Therefore, more long-term options, like combining longer term accommodation options, increased pumping station capacity with a pressurized system, are considered. The conceptual DAPP is outlined in Figure 4.8. Area 3 has initially a similar portfolio choice as Area 2, where a decision is made between accommodating the gravity-based system or switching to a pressurized system. The lifetime of the pressurized system can be extended by initiating the portfolio to increase pump capacity and / or heighten pump elevation. The retreat trigger for this area is pump failure due to a combination of pump inundation and increasingly more saltwater being pumped through the system due to increases in GWL.

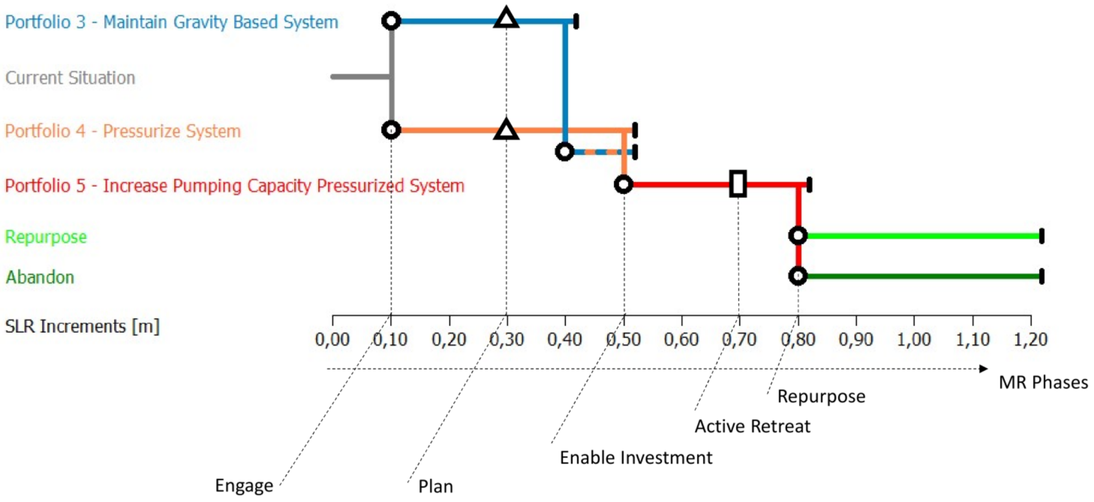


Figure 4.8: Conceptual DAPP Area 3

### 4.3.5 Area Interaction

The parallel implementation of pathway portfolios in each area and the interaction between the portfolios when implemented provides an opportunity to optimize the use of the different options across the whole study area. The possibility of having a visual overview between the different portfolios and pathways in each of the three areas enables the system to be adjusted using a range of different adaptation strategies to achieve the retreat. For example, implementation strategies in the higher elevated part of the study area allow for reduction in discharge in lower parts. This results in lower requirements for adaptation or buys extra time before a pathway in another area has to be changed. This increased flexibility to influence one area by implementing other adaptation options in different areas is crucial of being able to buy more time across the Petone system while the planning and costing of the adaptations are developed and the engineering design undertaken for the retreat over time.

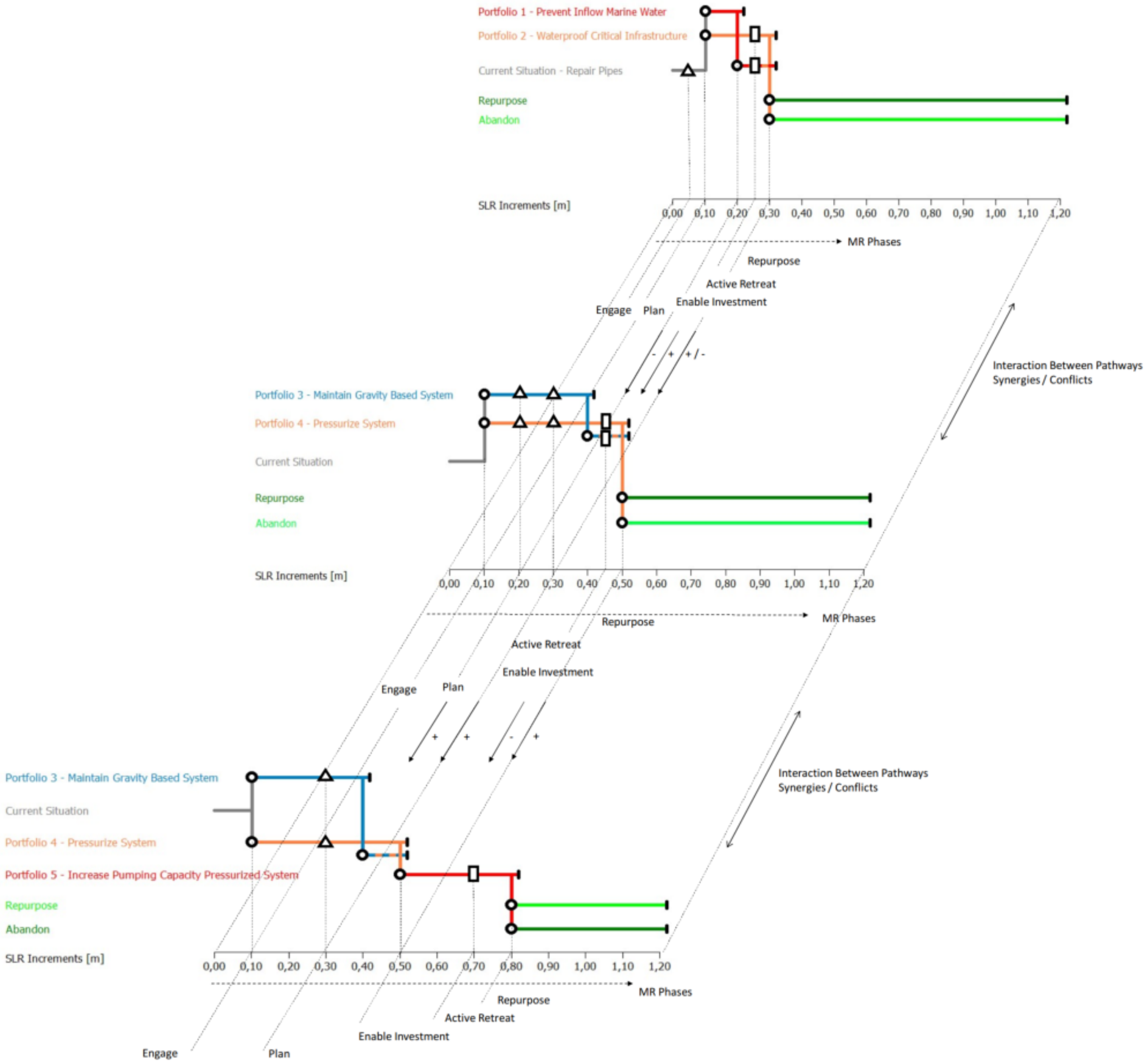


Figure 4.9: Conceptual DAPP

Implementation of an interactive conceptual DAPP assessment for the Petone area is shown in Figure 4.9. All areas will retreat eventually, but sequencing will be different. The synergies and conflict between pathways in different areas are marked with the arrows showing Synergies (+) and Conflicts (-). These are outlined in Table 4.7. Figure 4.9 shows a conceptual way of indicating the interaction between different pathways in different areas providing an overall dynamic strategy for the area. It first starts with a DAPP for each of the sub areas across the study area. These pathways are selected from the portfolio pathways in Table 4.5, based on the sub area strategy and pathway failure conditions. The thresholds identified for the Petone area are added to the x axis, indicating the need for pathway changes for the current drainage system. For the areas targeted for managed retreat, retreat phases are indicated also along the x axis of the DAPP. Aligning these pathways for each of the areas allows for the visualization of interaction between different areas. Table 4.7 shows Synergies and Conflicts between pathway portfolios throughout different retreat phases in each sub area.

This approached also allows for illustrating positive and negative feedback between different options and pathway strategies, depending on the phase of the retreat. For example, initial stages of retreat could create redundancy in the system by leaving the pipes in the ground, but not have the extra discharge from residential / commercial use. This offers a positive effect on the rest of the Petone drainage system. Over time the capacity of this system will decrease. The assumption is that it will not be upgraded indefinitely because there will be a retreat when conditions meet the trigger point, and there is no benefit from doing so. During repurposing however, retention space could be created to allow for increased water storage capacity that could have amenity and recreational value for the remaining and wider community in the Hutt valley. This again has a positive effect on the pathways implemented for the other areas.

Table 4.7: Pathway Conflicts and Synergies

| MR Phase | Synergy (+) | Conflict (-) |
|---|---|---|
| Area 1 | | |
| Engagement / Consultation | | |
| Planning / Preparing | | |
| Enabling Investment | | Area 2 |
| Active Retreat | | Area 2 |
| Repurpose | Area 2 | Area 2 |
| Area 2 | | |
| Engagement / Consultation | | |
| Planning / Preparing | Area 3 | |
| Enabling Investment | Area 3 | |
| Active Retreat | | Area 3 |
| Repurpose | Area 3 | Area 3 |
| Area 3 | | |
| Engagement / Consultation | Area 2 | |
| Planning / Preparing | Area 2 | |
| Enabling Investment | | |
| Active Retreat | | |
| Repurpose | | |

# 5 Discussion

The study produced a number of findings contributing to answering the research questions. These findings are integrated into a methodology or ’routine’ that could be used to approach managed retreat in a systematic way by using a DAPP approach and specific options and pathways for the study area. The central research findings are presented in Table 5.1, where they are linked to the relevant result section and research question. In order to answer the main question, a systematic approach was used in each of the sub areas to create a portfolio of adaptation options. This was used to set up a conceptual DAPP for the area that illustrates the interactions between sub areas that provides opportunities to buy time during which planning and preparatory work could be undertaken to stage and underpin the active retreat. The DAPP assessment of options and pathways thus acts as a framework for implementing a retreat strategy over time in a manner that aims to cause the least disruption to the community and the available investment streams.

Table 5.1: Central Research Findings

| Results | Section | Research Findings |
|---|---|---|
| Service Levels and Duration | | (Research Question 1,2) |
| System Thresholds | 4.4.2 | Duration of service depends on when a trigger is reached initiating retreat to avoid an AT |
| Adaptation Thresholds | 4.4.3 | AT’s have consequences for relevant stakeholders and are key to minimizing disruption |
| Adaptation Portfolios | | (Research Question 1,2,3) |
| Pathway Portfolios | 4.3 / 4.4.3 | Portfolios contain two water adaptation measures which can be used to maintain L.o.s. until active retreat is initiated<br>Repurposing the area using WSUD measures creates amenity for the community and buys time until active retreat starts for adjacent areas |
| Planning and Land use | 4.4.3 | Signalling planning changes warns people and creates certainty about the future |
| Withdrawal Sequence | | (Research Question 4) |
| Pathway Interactions | 4.4.5 | Visualization of pathway interactions allows for identification of synergies and conflicts arising from retreat |
| Retreat Routine | 4.4 | DAPP provides a way to systematically frame individual retreat strategies and deal with emerging uncertainties<br>The methodology used in this study provides an example of a retreat ’routine’ |

To reiterate, the main and sub questions of the research are as following:

*How could the retreat of two water infrastructure (Stormwater and Wastewater) in the Petone and Alicetown Area be managed alongside a community retreat from the coast, considering and defining;*

- 1) What levels of Service (LoS) are appropriate while transitioning towards adaptation thresholds?
- 2) How long should two waters services be maintained?
- 3) What measures and actions are appropriate to maintain L.o.S and do they coincide with adaptation thresholds?
- 4) What leads - service withdrawal or residential withdrawal?

**Levels of Service and Maintaining two water Services**

The duration of service, or how long two water services can be maintained, depends on the retreat phase within the overall retreat strategy of the retreat area. Active retreat must be initiated before the portfolio Adaptation Threshold (AT) is reached, which can be aided by using signals like planning provisions to warn, and condition-based triggers to decide on options and pathways ahead of the threshold. This provides a conceptual DAPP that can set out portfolio conditions using SLR increments for the different portfolios, thus enabling the portfolios to be implemented. The duration and L.o.s depends on the area strategy that is set while developing the retreat sequencing. Failure conditions are determined for the pathway portfolios indicating when service stops, before switching to an alternative portfolio.

AT's have consequences for the infrastructure operator in charge of maintaining the system and providing the service, Wellington Water. Not switching to alternative portfolios before an AT is reached, could result in steep cost increases as economic damage increases, an inability to adapt the current system and the system being no longer a contained system. There are also consequences for property owners, when they can't afford to upgrade their own connections to the system, when property owners are not able to get insurance or when surface water or contamination becomes increasingly disruptive. It is therefore important to not only monitor pathway performance but also implement timely signals and triggers that indicate/warn that an AT is approaching, to minimize economic and community disruption. Not implementing signals and triggers would result in a reduced ability to switch portfolios before reaching an AT and preclude the possibility to signal these upcoming changes to the community.

AT's are not necessarily technical or quantitative. From the workshop it became clear that considerations for retreat were also related to the coping capacity of the community. This again stresses the importance of stakeholder and community engagement. When the coping capacity of the community is lower than the technical threshold, for example there are more regular periodic overflows but the system is able to cope, it could potentially accelerate AT's for retreat. There is also the possibility that the coping capacity of the community could extent the duration of pathways (Radhakrishnan et al., 2017). Including this extra coping capacity without communicating could bring damage claims from the community as they have to cope with more frequent inundation.

**Measures (Adaptation options / Pathways)**

Adaptation options (pathways) were selected from both the literature and through expert input from stakeholders, responsible agencies and academics. To investigate this research question a set of pathway portfolios was developed based on a literature review and expert input during the workshop. The system and exposure analysis helped identify adaptation options. Ideally a unique set of pathway portfolios would be developed for the different retreat sub areas. The reason for this is that adaptation pathways are going to perform differently in the sub areas and therefore would give a more accurate indication of AT's and improve the ability to quantify pathway performance. In this study, sub areas defined by a list of parameters were used, rather than having geographic boundaries representing Petone/ Alicetown.

WSUD detention and/or retention options were found to have larger spatial requirements (Section 2.5). Since the study area is urbanised and relatively densely developed these spatial constraints limit the possibility for implementing WSUD measures as two water adaptation. Upon finishing the active retreat phase the area could be repurposed. During this phase there is an opportunity to create amenity for both the community and the two water system depending on the pathway implemented. A water retention space in the form of a natural water body or a park could create recreational benefits, ecosystem benefits and create extra storage capacity for the stormwater drainage system, extending the initiation of the active retreat phase in adjacent areas.

The proposed approach of implementing area dependent retreat strategies essentially 'buys time' for residents and authorities. For residents to retreat and for authorities to stage their budget more gradually over time. This could however potentially create unrealistic expectations for residents in areas that are retreated at a larger AT, as they perceive the extra time alleviates the pressure the move and creates a false sense of security. Likewise, there is also a reputational risk for Wellington Water and the council involved if they claim that service can be provided until a certain SLR increment, and then due to sudden disruption, this turns out to be unfeasible. At the time of this study multiple service failures occurred in Wellington over the last three months.

Signalling planning and land use changes for the community and relevant stakeholders (Section 4.1.3.) can enable changes in retreat phases and service levels to be anticipated. Section 4.3.3 provides a range of planning options based on the retreat phase of an area. Currently there is a requirement for upgrades to water services and facilities by Wellington Water, through their Regional Standard for Water Services, with the aim to accommodate SLR as recommended by the Ministry for the Environment (2017) guidance. However such signals could create a legacy effect for managing the drainage system because the dwellings are accommodated at a higher threshold than the infrastructure servicing it. This could create disruption where part of the community potentially wants to extend the service in the accommodated area, creating conflicts for the retreat strategy in adjacent areas and limiting repurposing possibilities by forcing expensive maintenance of services as drainage conditions become worse.

**Withdrawal Sequence**

The retreat typology used from Olufson (2019) is based on a signalling approach for managed retreat where the community starts to withdraw in a planned proactive retreat scenario. Alternatively, the council could start to withdraw services. There are cases in New Zealand where councils have signalled that service levels for infrastructure will not be provided anymore[1]. Following the typology outlined in Olufson (2019), compensation could initiate house relocation or removal before a service level change is used as a signal. In a post disaster scenario, where service levels are compromised as a result of the extreme event, community retreat happens as a reactive response (Hino et al., 2017). If there is a decision to lead with infrastructure retreat, part of the community might choose to stay and accept the reduction in L.o.s. In the Petone/Alicetown case, this could hinder the repurposing of the retreated sub area, therefore preclude creating recreational or ecological amenity for the community using repurposing options and cause disruption in retreat of adjacent sub areas. This would accelerate the AT's SLR increment for retreat in these areas.

All the results in Table 5.1 contributed to the development of a routine applicable for staging managed retreat. It is the coincidence and parallel implementation between the area specific strategies that enable retreat of services spatially in a managed way. Planning signals are also added to the pathways, to help initiate plan changes necessary to facilitate community retreat. The planning signals are not consequently related to different portfolios of options for each area. Rather, in which retreat phase the portfolios are based. When used in the routine, identified pathway conflicts require another iteration that is necessary to either redefine pathways or create measures mitigating the effects of these conflicts.

The 'routine' developed consists of the following elements:

- Identify Relevant Hazards
- Exposure Analysis of Area Assets to the selected Hazards
- System Analysis and Cascades
- Adaptation options to the hazard by combining options suggested in literature and expert consultation
- Based on the Asset Exposure, System Cascades and Adaptation Options divide the study area into different sub areas
- Define an Area Strategy determining at which hazard increment is retreat necessary, then work backwards using pathway AT's
- Establish a Conceptual DAPP for each of the areas
- Identify Synergies and Conflicts between pathways
- Investigate Conflicts and Capitalize on Pathway Synergies especially for repurposing

Alongside this routine it is important to involve relevant stakeholders to validate and contribute to the steps taken. A decision tree could aid this engagement process. Local expert knowledge combined with community input would minimize chances of critical aspects being overlooked.

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[1] D and C Gallagher v Tasman District Council W245/2014

### Methodological Considerations

The combination of quantitative output from the exposure assessment and input through local knowledge from the experts managing the system and responsible for delivery of services to their communities, is the basis of the methodology used. A suite of GIS overlays specifying the areal extent of present-day storm-tide levels with SLR increments, was used to verify exposure. This means that there was some loss of detail as static inundation maps have a tendency to overestimate flooding extent. Increases in system stress due to external stressors as a result of climate change (Section 4.1.3) are going to increased discharges and reduce system coping capacity. An argument can therefore be made that the exposure assessment is actually a conservative estimate when taking into account compounding hazards that will emerge as climate changes impact on the area more frequently and with greater intensity. These compounding hazards could for example be higher water levels due to SLR in combination with increased precipitation exacerbating flooding impacts due to an increase in discharge but a decrease in discharge capacity. This means that AT's could potentially emerge at lower SLR increments, accelerating further retreat phases. This highlights the importance of implementing DAPP signals and trigger points and monitoring pathway performance.

Portfolio costs were not quantified in the research. High level estimates were included in the option pro's and con's. However, with input from experts it was possible to determine cost implications for the options. Quantifying costs and pathway performance over hazard increments, as undertaken by Manocha and Babovic (2017), it is possible to convert the conceptual retreat areas to a geographic location for modelling purposes. This would enable pathway costs and benefits to be determined quantitatively. Combining the suggested quantification of pathway service levels with costs, in combination with stakeholder/expert input, would enable another level of detail to inform the decision making process. It also would allow for visualisation of costs over the lifetime of the assets. Showing the differences in costs between a reactive, or current, approach and a proactive long term retreat approach, potentially could enable the relevant stakeholders to consider a change in strategy allowing for more gradual budgeting of the retreat of two water infrastructure.

The L.o.s throughout the portfolio lifetime were not quantified in this research. Visualizing pathway performance over SLR increments alongside portfolio duration in Figure 4.5 would help determine pathway changes and provide the possibility to signal upcoming changes in service levels to the community. Quantifying the transient nature of the L.o.s in different parts of the drainage network would require detailed hydro-systems modelling incorporating tolerances of residents and business owners, which is beyond the scope of this thesis. The process of developing the portfolios for each pathway in this study is a mix of qualitative input and quantitative exposure assessment, which in practice would benefit from more detailed spatial information on the withdrawal of L.o.s over time. Therefore to further develop L.o.s. for the area assessing system performance by performing a hydrologic analysis would allow more insight into the performance of the drainage system over SLR increments, and how portfolio actions affect the drainage system from a hydraulic point of view. There is also a need in reality to connect and engage with residents and stakeholders (e.g. businesses) about L.o.s thresholds. How they perceive the decrease in L.o.s, the rate at which this happens and the extent of disruption that is tolerable to the community. These are important factors in determining the AT's. It therefore is not just a technical decision to set the thresholds. Without intervention, flooding due to rising seas will diminish the L.o.s over time until an agreed adaptation threshold is reached.

### Implications and Implementation Barriers

There are a number of practical barriers to implementing retreat in the Petone and Alicetown area. During implementation of the portfolios developed it would be important that all the actions within the portfolio are implemented. Due to the complexity of the drainage system a varied set of actions is needed to achieve a goal. Stress testing different portfolios under different scenarios with the use of a hydrodynamic model (see methodological considerations) would help to convey clearly the implications of using a certain set of actions within a portfolio to the relevant stakeholders. Current portfolios address criticalities identified in the exposure assessment, until AT's are reached. For areas with a higher retreat threshold, the set of portfolio actions becomes more transformative.

As identified in the System analysis and CIrcle tool application (4.1.4.), there is a range of hazards affecting the Petone and Alicetown area. These can be divided in three tiers, increasing and ongoing hazards like SLR, compounding hazards like more frequently induced weather events and rising water levels, and episodic compounding hazards like earthquakes coinciding with an extreme weather event. Occurrences of compounding hazards could cause disruptive damage to the system resulting and unexpectedly pushing the system towards or exceeding an AT. These need further investigation, as they potentially change the long term systematic retreat to an ad hoc post-disaster retreat. Cascades for other critical infrastructure identified using the CIrcle tool (4.1.4.) could be integrated into the long term infrastructure planning and the effects of retreat considered. A major road link, the Esplanade, runs along the southern boundary of the study area. Retreat is going to impact this infrastructure. There is two water infrastructure located underneath the road, service levels might be reduced as hazard exposure increases and road usage could change due to driver behaviour, changing their routes and thus creating consequences elsewhere.

The availability of funding and its budgeting over time is closely related to cautious engagement with managed retreat as a politically viable option. This is despite the regional example of making room for the river in Hutt City and purchase of properties for the purpose of a managed retreat to make room for the river. Addressing the planning implications of managed retreat provides a bridge with the community using illustrative pathways and decision points to moderate a wider council and community engagement as set out in the coastal hazards and climate change guidance (Ministry for the Environment, 2017). A two waters strategy based on the approach taken in this study could provide the basis for addressing what, how and when retreat becomes a viable option. Managed Retreat as outlined in this research could address these uncertainties as options are implemented, with the aim of eventual retreat in a sub area and introducing costs more gradually over time when planned strategically.

The role compensation plays in addressing the inequity of signaling restrictive land use planning (e.g. closed zoning to further development) is an important consideration (For example; residents may have recently invested in accommodating their property in anticipation of SLR). Timely discussions around compensation and limiting development in vulnerable areas is therefore important for fitting retreat in a long term threshold based approach (Siders et al., 2019). The proposed repurposing of areas and the amenities created in the area could help overcome the social feasibility barrier, as retreat becomes part of a broader development project for the community (Hino et al., 2017). Recent infrastructure failures in two water infrastructures in the Wellington region could create an opening for managed retreat to be considered as part of the long term infrastructure planning and investment. In the end this is a socio-political issue, what has been developed in this study is a way to inform and improve the decision making process for relevant stakeholders, authorities and the community.

# 6 Conclusion

This section concludes the study and provides recommendations for future work. Retreat sequencing was found to be possible by allowing for different retreat strategies in different sub areas. This integrated strategy could minimize community disruption, allows for gradual budget adjustments over time and buys time until retreat for adjacent sub areas.

It was found that by using a systematic approach combining adaptation pathways, retreat phases and signalling land use changes long-term planning over potentially different pathway portfolios, could minimize disruption, signal land use changes and allow for gradual budget adjustments. Therefore it is an overall spatial strategy that is achieved by implementing a range of pathway portfolios in an integrated way containing two water adaptation options. Retreat phases and signalling planning changes support the different portfolios.

A combination of quantitative input with expert consultation used system adaptation thresholds of +0.30 $m$, +0.50 $m$ and +0.80 $m$. Pathway portfolios were developed until the extend of having a portfolio of actions, planning and land use implications and failure conditions. This was useful for determining pathway / portfolio changes. The result of no specific retreat pathways was an emerging need to (1) Separate the retreat phasing from the pathways and (2) Visualize the effects between these pathways.

The development of the 'routine' essentially addressed the main research question, providing a structured approach for managed retreat of two water infrastructure. At the time of this study no literature was found on approaches to two water infrastructure retreat as a result to SLR. By using a DAPP approach to frame retreat in different areas it was found to be a suitable approach to address uncertainties arising from SLR when implementing a two water retreat strategy. It was found this was possible using a combination of and area specific retreat strategy (1), area specific pathways (2), area specific retreat phases (3), signal land use changes (4) and identify pathway conflicts and synergies. This systematic approach and 'routine' that emerged potentially provides coastal communities facing similar hazards, a framework of how to approach two water infrastructure retreat.

For the Petone and Alicetown area, there lies a decision to be made collectively by the Wellington Water, stakeholders and the community. Either continue on the current pathway of reactive maintenance and accept major economic damages and community disruption eventually leading to a sudden decline in L.o.s. with ad hoc and improvised solutions, or start embracing a proactive approach where the inconvenient truth is that adaptation due to SLR is necessary. Using a DAPP provides a window of opportunity to get out of response mode, to a more anticipatory mode that starts to plan for retreat, making sure compensations are handled with equity, planning of land use changes is signalled to minimize disruption and amenity is created by repurposing the retreated areas.

**Future Work**
Several recommendations for future work emerged throughout the research process. The first is the implementation of DAPP signals and triggers into the routine in conjunction with planning/land use measures and retreat signals and triggers. During the research only AT's for pathways were considered. Implementing DAPP signals and triggers by developing pathway/portfolio lead times will enable a more detailed pathways assessment to be undertaken.

Quantification of service duration and L.o.s. using a hydrologic analysis would enable a more detailed assessment of the conditions under which pathways have to be changed to maintain service levels for the community. It therefore also provides a better basis for discussion with the relevant stakeholders. Involving the community and relevant stakeholders to investigate what they perceive as disruption and what their expectations are in terms of L.o.s. would aid future decision making and produce a better consensus on the establishment of AT's.

Costing of the adaptation portfolios would aid the decision making process in two ways. The first is the need to assess the costs and benefits of the different pathway options. The second is the visualization of budget development over the lifetime of the pathways. This allows for better understanding of budget increases and how it can be allocated gradually over the lifetime of the investment.

Finally, there is the matter of how a managed retreat strategy can be communicated with the community, and their involvement in the managed retreat process. As stated in the introduction, two water infrastructure adaptation, and specifically retreat is not exclusively a technical issue, it has equity, financial and political implications that are non-trivial for the community. It is therefore necessary to connect and engage with residents and other stakeholders (e.g. businesses). Efforts have been made in this study to consider community-relevant issues by including planning and land use implications into the retreat routine, however this is still one step away from the community. Their involvement is key to gain support and the momentum needed to systematically start implementing these changes over a long term planning horizon.

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# A Appendix 1

# Appendix 1

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## Project Plan

# Contents

# 1. Introduction

Recent investigations in New Zealand seek to document how climate change is likely to affect coastal communities, e.g., by means of sea level rise (SLR) and enhanced risks of storm surges. Increased damage costs and coastal squeeze stresses communities to adapt and accelerates incentives for working towards long term but flexible solutions that can be changed over the lifetime of the investment. Sea level rise has been indicated as one of the key factors affecting coastal communities (Local Government New Zealand, 2016; Ministry for the Environment, 2017). Negative consequences include more frequent inundation, increased erosion and increases in groundwater levels, saltwater intrusion, liquefaction and drainage problems. This study aims to look into managed retreat of two water infrastructure, namely wastewater and stormwater, and identify retreat sequencing, asset interdependencies and adaptation thresholds using a conceptual dynamic adaptive pathways planning (DAPP) framework. The project is funded from the Resilience Science Challenge with MBIE-funded Resilience Science Challenge Coastal Sub-theme Adapting to New Zealand's Dynamic Coastal Hazards.

## 1.1. Background

Several scenarios for SLR have been adopted from the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2013) by the coastal hazards guidance for local government (Ministry for the Environment, 2017), which aims to assist local government in preparing for climate change.

It can be seen in Figure 1 that even in moderate emission scenarios, significant rise in sea level in reference to preceding measurements is projected for New Zealand. It is also expected this process will continue well into the next century (IPCC, 2019; Ministry for the Environment, 2017; IPCC, 2013). Preceding the publication of (IPCC, 2019), projections were available up until 2100.

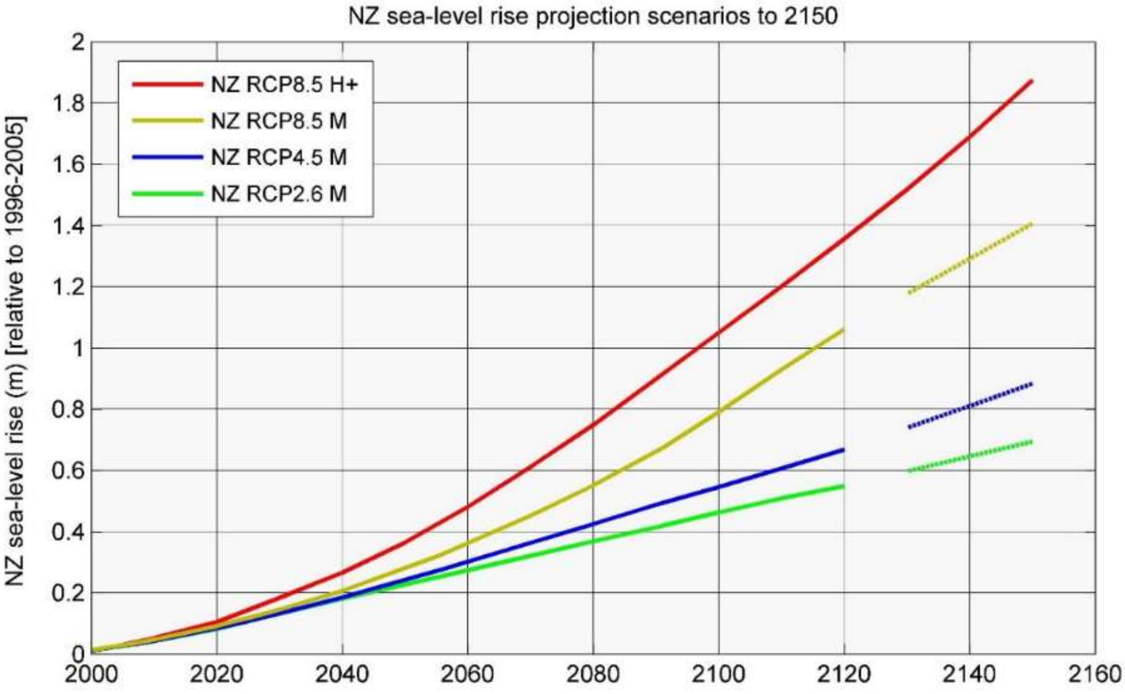


*Figure 1: New Zealand Sea Level Rise (SLR) projections untill 2150* (Ministry for the Environment, 2017)

For the New Zealand projections these have been extrapolated until approximately 2120, as can be seen in Figure 1. Offsets have been applied to adapt the projections to New Zealand specific scenarios by 2100, 0.05 m for RCP 8.5 and 0.02-0.03m for RCP 2.6 and RCP 4.5 scenarios, linearly applied (Ministry for the Environment, 2017). The following representative concentration pathways (RCP's) are described as:

- Scenario RCP 2.6. – Peak and Decline in global emissions would have to occur within the next decade, zero-net or negative emissions by the end of this century
- Scenario RCP 4.5. – Moderate emission-mitigation Pathways peaking around 2050 before declining
- Scenario RCP 8.5. – Continuing high emission baseline scenario with no effective global emissions reduction, emissions stabilising after 2100, medium trajectory
- Scenario RCP 8.5. H+ – Also continuing high emission baseline scenario with no effective global emissions reduction, 83rd percentile projections taking into account polar ice sheet instabilities

Infrastructure exposure to Climate Change in New Zealand was investigated by the Local Government New Zealand in (Local Government New Zealand, 2019a, 2019b), where it became clear that three waters (waste water, water supply and storm water) infrastructure have the greatest exposure, and Wellington is among the cities with the highest replacement costs. In (Local Government New Zealand, 2019b), it was found that the replacement value of three waters infrastructure exceeds the value of exposed roads &buildings.

## 1.2. Adaptation

Climate Change impacts for New Zealand as a result of SLR threaten coastal infrastructure, communities and low-lying ecosystems (Rouse et al., 2017). Adaptation options in response to SLR can be found in Figure 2, where the five most commonly used management approaches are shown.

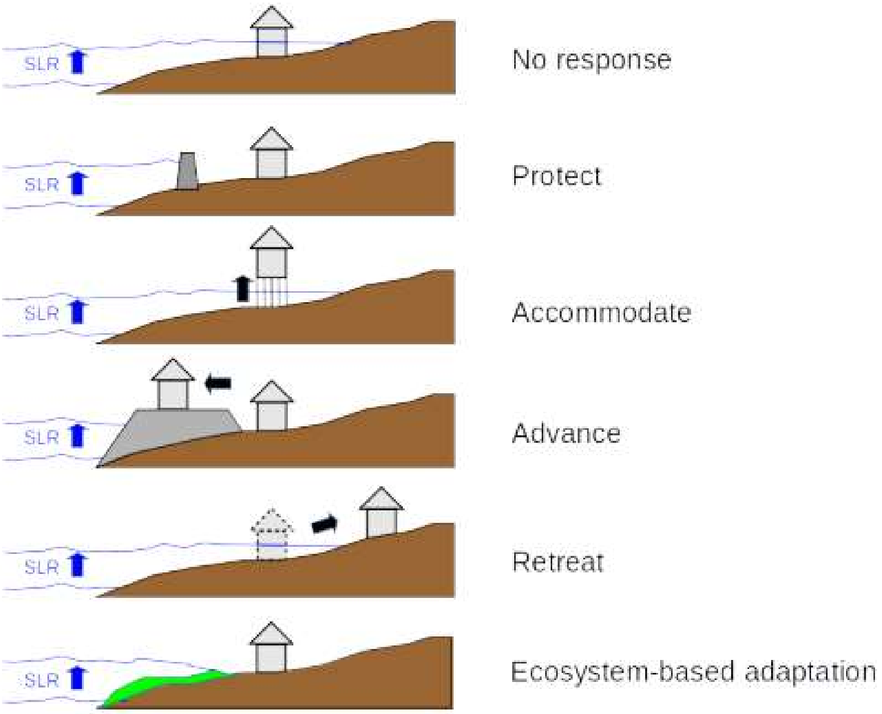


*Figure 2: Adaptation Options, adapted from* (IPCC, 2019)

(Rouse et al., 2017) outlines the advantages and disadvantages that arise from each of the three most commonly considered adaptation policies:

- Do nothing, advantage is that it would result in low cost and effort for the present generation. Disadvantages include that there is no future certainty for any of the actors, projected impacts would occur with consequences for people, property and infrastructure, ignores risks for future generations
- Protect, advantage is that hard engineering provide immediate protection for high value infrastructure, soft engineering aligns with natural processes and allows for cyclic erosion. Disadvantage is that this approach is expensive, assumptions might lead to a mis perspective of the risk, direct coastal squeeze and physical impacts on adjoining beaches
- Accommodate, advantage is that it works more with natural geomorphic processes, allowing for periodic erosion or inundation, retrofitting will give immediately remove current risk. Disadvantage is moderate costs depending on retrofitting, based on static risk assumptions, requires change in expectations of use/service levels, requires careful communications
- Retreat, advantage is that it allows for a dynamic risk, it allows ecosystem resilience to be maintained and seeks to avoid risk. Disadvantage is that is potentially expensive for councils due to relocation of infrastructure, compensation costs and likely community resistance, it also needs a long term timeframe to be implemented without major community disruption.

Advance in a coastal engineering context is commonly achieved by land reclamation. Since the foreshore is a highly dynamic zone, advancing methods intervening here are inclined to have an increased maintenance frequency. Ecosystem based disaster risk reduction seeks to work with natural processes, e.g. coastal ecosystems, rather than work against them resulting in a higher adaptive capacity and lower costs on a life cycle basis then traditional engineering solutions when applied in an appropriate setting (de Vriend, van Koningsveld, Aarninkhof, de Vries, & Baptist, 2015; Lange, Pirzer, Dünow, & Schelchen, 2016).

A good example of a project that fits in both Advancing and Ecosystem based disaster risk reduction is the sand engine project in the Netherlands. In this project a large beach nourishment is applied where natural processes will distribute the sediment along the coastline. A recent status review concluded that although there was a positive impact on coastal protection, the lessons learnt have not translated into a daily nourishment practice (Brière, Janssen, Oost, Taal, & Tonnon, 2018). This demonstrates the disadvantage of ecosystem based adaptation, where methods are still experimental, difficult to quantify and therefore not yet commonly integrated into shoreline / hydraulic protection guidelines. Advances in research with the aid of numerical modelling will start to push these solutions to a more common approach to adaptation.

In order to aid this climate change adaptation process the Coastal Hazards and Climate Change Guidance (Ministry for the Environment, 2017) adopts a decision cycle aimed at guiding communities in a more uniform way using a 10 step decision cycle (Ministry for the Environment, 2017). Dynamic adaptive planning pathways is embedded in this decision cycle. The aim of DAPP is to adapt and transition current static and time bound planning to decision making that enables gradual adjustments (Lawrence, Bell, Blackett, Stephens, & Allan, 2018). This is required due to a combination of deep geophysical and socio-economic uncertainties. Accordingly, involvement of stakeholders is critically required; for example as facilitated using a simulation game (Lawrence & Haasnoot, 2017).

It is a Decision Making under Deep Uncertainty (DMDU) approach, where the planning is dynamic and based on future developments, as it explores alternative strategies. (Babovic, Mijic, & Madani, 2018) focusses on urban drainage systems, and acknowledges that the main drivers for DMDU are Climate

Change and Changes in human settlement patterns, due to a shift in global wealth. In this context deep uncertainty arises due to high uncertainty of future conditions while at the same time implementing infrastructure with long design lives. The paper proposes the following factors have to be addressed:

- Knightian Uncertainty
- Multiple valid Potential Futures
- Consider decisions with path dependence in mind

Policy actions have an uncertain design life and might fail sooner or later to be effective as boundary conditions change. This could be for example reaching an Adaptation Tipping Point (ATP) (Haasnoot, Warren, & Kwakkel, 2019), which from now on will be referred to as Adaptation Threshold Point.

*'' DAPP explores alternative sequences of decisions (adaptation pathways) for multiple futures and illuminates the path dependency of alternative strategies. It opens the decision space and helps to overcome policy paralysis due to deep uncertainty. There are different routes that can achieve the objectives under changing conditions (like 'different roads leading to Rome').''* (Haasnoot et al., 2019)

In (Manocha & Babovic, 2017) a DAPP approach was applied in a Singapore case study to investigate adaptation pathways for stormwater management infrastructure. It was found that it allowed for a better understanding of adaptation timing, and that it helps ''*Bridging the gap between the highly uncertain and long term climate change and short term decision making horizons of urban planning and development*''.

Adaptation thresholds are defined as the conditions under which a policy will fail to deliver on objectives. (Haasnoot et al., 2019). ATP's are defined the when boundary conditions are exceeded, and new actions are needed to ensure acceptable service levels. This can be technical, environmental, societal or economic standards (Haasnoot et al., 2019; Manocha & Babovic, 2017). In (Babovic et al., 2018), this adaptation threshold is found by modelling the system and placing it under increasingly large stress. Adaptation thresholds can also be identified through moderation processes using scenarios with different conditions representing the stress similar to sensitivity testing.

## 1.3. Managed Retreat

For some coastal communities "managed retreat" has been identified as a potential adaptation pathway, especially in coastal settings for considering sea level rise impacts. This means retreating these communities away from the coastline over time and in the process also abandoning existing (water) infrastructure. In such cases, an evidence-based dynamic / staged approach towards decision-making and implementation is key.

Implementation barriers to managed retreat are becoming increasingly identified literature. (Gibbs, 2016) recognized that although there is a lot of studies that take managed realignment into account, there is a lack of implementation of these studies and little on-the-ground experience. It also acknowledges a previous study, where *''Evidence of climate change impacts is rapidly increasing but there is unfortunately little change to the speed of adaptation by governments and individuals''*(Mills et al., 2016). This applies in particular to those that address the increasing sea level rise that will be ongoing for centuries.

Hanna, C., White, I., Glavovic, 2018 identified several key implementation barriers for managed retreat in New Zealand. It concluded that implementation of managed retreat was difficult due to a lack of national policy guidance, legislative mechanisms and implementation support. In addition to this funding was found to be uncertain and voluntary retreat the only tool currently able incentivise managed retreat. When combined with withdrawal of service, it also was perceived to be mandatory (Hanna, C., White, I., Glavovic, 2018). Hanna, C., White, I., Glavovic, 2017 identifies three District Councils implementing cases of managed retreat as a response to a range of hazards. These include a relocation of council assets due to coastal erosion risk, voluntary retreat as result to damaging debris flow and a flood risk reduction project.

Siders, Hino, & Mach, 2019 concluded that managed retreat is often ad hoc and focused on risk reduction, treated isolated from broader societal goals. It reasons that without guiding policies, ad hoc managed retreat fails and misses opportunities to contribute to societal goals. It therefore recommends a strategic retreat, aimed at contributing to these societal goals. Identified barriers making managed retreat difficult to implement in practice included profitable, short term economic gains in coastal development, imperfect risk perceptions, subsidized insurance rates and disaster recovery costs, misaligned incentives between residents, local officials and national governments and a preference for the status quo. (Hino, Field, & Mach, 2017) concluded that managed retreat is favoured for longer timeframes, approx. >25 yrs. It agrees with (Rouse et al., 2017) on traditional protection projects, where it states that building levees result in high maintenance costs, environmental damage and increases development in hazardous areas. In short, the following four categories are identified

- Post Disaster, there is mutual agreement as risk is perceived to be not tolerable, there is high political will and there is a high cost benefit
- Greater Good, Risk is perceived tolerable therefore resident opposition must be overcome, there is high political will and high cost benefit
- Hunkered Down, mandatory resettlement, risk is perceived to be tolerable, there is low political will and there is a low cost benefit
- Migration Risk is perceived intolerable however there is low political will and low cost benefit, e.g. remote settlements where there is an emphasis on self-reliance

## 1.4. Problem Statement

This study will focus on the Petone area, located in Lower Hutt in the Wellington region, which can be seen in Figure 3. The area was historically developed in the early settlement part of the late 19th and early 20th centuries to the point where the flood plain is largely urbanized, also shown in Figure 3. Earthquakes in the area are frequent and there is a major fault line running through the west boundary of the Petone area (GWRC, 1996). Compared to its adjacent areas, there is also an increased risk of liquefaction, ground shaking and tsunami inundation hazard (GWRC, 1996).

Flooding has been an issue historically in the area, where ten major floods have happened between 1855 and 2000, and more recently the 2004 Hutt river floods (Lawrence, Quade, & Becker, 2014). Recent adaptation initiatives have been leaning towards structural protection measures like levees and stop banks, creating a legacy problem where citizens are having an unrealistic perception of flood risk and an expectancy that the government will continuously provide protection against floods. Wellington, 2019 identifies the Petone area as the most vulnerable geographic unit together with the Seaview area, a reclamation area located next to Petone, for the Hutt City Council despite the presence of one of New Zealand's largest flood protection schemes (Lawrence et al., 2014). NIWA, 2019 a, 2019 b show that Wellington is among the cities with the highest pipeline exposure for all three waters infrastructure in New Zealand. This increases vulnerability to SLR, as many of the waste and stormwater systems are gravity based, which will result in the runoff capacity of these systems being affected.

This raises the issue of how local government can maintain levels of service for the 3 waters as the impacts of climate change worsen over at least 100 years to reflect the plausible futures during the lifetime of the asset. Local government has a mandate to address the effects of climate change, for the delivery of services and for the wellbeing of communities. This broadly includes planning and avoiding and mitigating adverse effects of hazards, flood risk reduction, and delivery of water services. To date the approach taken by the local government is to address impacts of flooding on the 3 waters infrastructure as they emerge. This strategy may appear to suffice in the short term but may compound the impacts in the long term as the effects of sea level rise become more apparent. A strategy that can be developed to anticipate those impacts can be explored along a number of pathways before the adaptation threshold materializes. Adaptation options to be explored include managed retreat and how it might be designed and implemented. In this context my research question is as following:

How could the retreat of two water infrastructure (stormwater, wastewater and roading) in the Petone Area be managed alongside a community retreat from the coast, considering and defining;

- What levels of Service (LoS) are appropriate while transitioning towards adaptation thresholds?
- What measures and actions are appropriate to maintain LoS and do they coincide with adaptation thresholds?
- How long should two waters services be maintained?
- What leads - service withdrawal or house withdrawal?
- How can the vulnerable be identified and their needs addressed?

- What water infrastructure is present in the study area?
- What are the physical characteristics of the study area?
- Preceding (vulnerability) assessment of the study area?

# 2. Study Area

As stated in the problem statement the study area for this project will be the Petone area, and is located in Lower Hutt, Wellington. As can be seen in Figure 3, the area is located in between a river mouth and the Wellington harbour area. What becomes apparent when looking at the project area is how the urbanized area of Petone is trapped between incline at the west road, the floodplain and the vicinity of the coastline. The area is characterized by being located in a river valley where the 54km long Hutt river meets the Wellington Harbour area. The width of the estuary is 4.5 km wide at this point ( Lawrence, Tegg, Reisinger, 2011). The esplanade, a major road link, runs along the coastline with some vegetated dunes present. There is also a tidal interaction with the Hutt river.

Figure 3: Petone Area with points of interest

## 2.1. Area Characteristics

When looking into marine flood exposure for the area in (Paulik, Stephens, et al., 2019), it was seen that Lower Hutt, meaning Petone and Seaview areas, experienced an initial rapid increase of exposure, which can be seen in figure 4. Exposure was initiated with an inundation dataset using 0.10 m increments in addition to an extreme storm event. Exposed elements gathered until now include nodes and pipes. After a meeting at NIWA it became clear that these were just polygons without any metadata information attached to them. Wellington water will be able to provide this information. (Paulik, Craig, et al., 2019; Paulik, Stephens, et al., 2019). It should be noted that these maps are based on a 'bathtub' approach, meaning that either natural barriers or protective structures are not taken into account.

*Figure 4: Current Extreme Event Flood Inundation Scenario*

When looking at the inundation scenario in Figure 4, it is the area more inland located in extension of the flood plain that is most susceptible to inundation at the moment, the low elevation of this area can be seen in Figure 7. When adding the SLR +100cm scenario in Figure 5, it can be seen that the majority of the Petone area will be inundated, indicating the vulnerability of the area. This is only valid in a worst case scenario though where the effectiveness of the flood protection scheme is compromised.

*Figure 5: Extreme Event Flood Inundation Scenario +100cm SLR*

Discharge points of wastewater systems often are located at the lowest elevation points of populated areas (White et al., 2017), small changes can overwhelm the capacity of these systems. It also operates gravity based, meaning that groundwater coming up due to climate change will influence the runoff capacity of these systems. This means that the two water infrastructure located in this area is especially vulnerable. (White et al., 2017) stresses the importance of thinking ahead as it is stated that the discharge points of wastewater systems often are located at the lowest elevation points of populated areas, and that even small changes can overwhelm the capacity of these systems. It also operates gravity based, meaning that groundwater coming up due to climate change will influence the runoff capacity of these systems. (Hendy et al., 2018) focusses on climate change driven drought in New Zealand where, as well as in (White et al., 2017), it was argued that drought is going to make a significant impact on the wastewater system as it relies on stormwater to flush the system.

## 2.2. Site Visit

A site visit was conducted aimed at having a clearer approach to answer the three questions related to the characteristics of the study area, which would be the infrastructure present in the area, physical characteristics of the area and preceding assessments or vulnerability assessments in the area. Pictures from the site visit will be included also, as well as some information on past projects and documents that are relevant.

Figure 6 was taken at the esplanade, the road connecting both ends of the valley and located right at the coastline. It can be seen from the picture that, along with sparse vegetation and a minimal levee the Petone area is separated from the sea. It also becomes clear that it is quite a significant road judging from the size and traffic usage.

*Figure 6: View from the coastal road 'The Esplanade', separating Petone and the Beach Zone*

Figure 7 was take at Wakefield street, with Cuba street crossing over the bridge. Along the road there is a steep incline towards the adjacent street in the distance, indicating it is a lower lying area. This area is also among the first to be inundated in Figure 4.

*Figure 7: Wakefield st with Cuba street intersecting this area is already part of the inundation zone in Figure 4*

# 3. Methodology

This chapter will discuss how the project will be outlined, the type of analyses used and what tools will be used to answer the main questions. The first paragraph will discuss the scope of the project, where also the project process will be elaborated. The second paragraph will discuss the Exposure analysis, the last paragraph will elaborate on the DAPP sequencing, identifying adaptation thresholds and stakeholder involvement.

## 3.1. Scope

Scope of the research will be looking into managed retreat for two water infrastructure, namely the stormwater and wastewater. The project looks into stormwater and wastewater affected for the Petone area. Within the three water services potable water is unlikely to be as majorly affected by SLR. These potable water systems are not gravity based but are pressurized, and problems are expected to occur with the actual source of the water, which is located in the upper catchment area. This is why it is only stormwater and wastewater infrastructure will be considered. Components considered as infrastructure can be viewed as connecting components, like pipelines, and key objects like pumping stations in the area.

Impacts from multiple hazard sources are affecting the Petone area, however the primary focus of the research is to use the impacts of sea level rise on the two water infrastructure to investigate managed retreat. Other hazards could be considered depending on the timeframe, like pluvial exposure in a separate exposure assessment. The physical scope will be the Petone area, with its boundary around Petone and Alicetown. It is shown in Figure 3. Components from other systems are excluded, e.g. two water infrastructure from the other side of the Lower Hutt River. Data that will be included in the scope will be asset data from Wellington Water and NIWA. This asset data can then be further divided in the Stormwater Nodes, Wastewater Nodes, Stormwater Pipes and Wastewater Pipes. Relevant attributes will be selected for the exposure assessment.

The research questions will be used to create context for a conceptual DAPP approach. It will not be possible to develop a realistic Dapp framework within the timeframe of the study. It will be possible however to identify thresholds and timeframes for a managed retreat pathway leading up to aiding a full DAPP approach for the area.

## 3.2. Exposure Assessment

For the purpose of this research an analysis into exposure of the assets and inhabitants of the area will be done, where both the exposure from natural hazards will be investigated for both assets in the area, being housing and infrastructure, and citizens. First there will be a little bit of background on different levels of assessment. It is important to illustrate the need to investigate this pathway, both to initiate the research as well as to stakeholders. It is difficult to assess the exact risk to the project area. In a practical setting risk is assessed by likelihood X consequence (Ministry for the Environment, 2017). Consequence here relates to exposure of assets or people. The difficulty with applying this rhetoric is that the likelihood component is difficult to quantify, with ongoing sea level rise uncertainty increases over time (Ministry for the Environment, 2017). Therefore the focus will be on the consequence, in the form of an exposure assessment of assets and people in the Petone area.

(Standard, 2019), defines exposure as *''Presence of people, livelihood, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social or cultural assets in places and settings that could be affected''*.

This means that this analysis will provide the basis for starting up talks with stakeholders in the area, giving an indication and prioritization of assets that are affected. (Ministry for the Environment, 2017) outlines three levels of assessment.

- First pass risk screening using available data
- Second pass risk assessment takes a standard risk based approach using national data, regional and local information.
- Third pass enables further investigation of short-listed risks and enables prioritisation and testing of strategies in conjunction with the vulnerability assessments

The more extensive vulnerability assessment has the function to overlay hazards, values and objectives information, difference between top down and bottom up assessments. The three main steps involved in the vulnerability assessment are a sensitivity analysis for the systems associated with the planning area, evaluation of the adaptive capacity for the system, assessment of how vulnerable the system is to the effects of climate change (Ministry for the Environment, 2017).

The vulnerability assessment is either bottom up or top down. ''Top down assessments use climate change scenarios for a *range of drivers over different planning timeframes* to generate climate change exposure maps, indexed to a vulnerability scale. Bottom up vulnerability assessments develop tables or maps that assess *human and community* coping capacity and distributional impacts'' (Ministry for the Environment, 2017). For this research, a top down assessment would be the most relevant.

When transferring this into assessing risk, consequences will be quantified by overlaying hazard exposure. (Ministry for the Environment, 2017) describes the function of such a risk assessment to overlay hazards, values and objectives information with asset fragility, sensitivity and adaptive capacity information, with the aim to

- Aggregate information for assessing impacts and adaptive capacity
- Input for a comparative ranking process or prioritizing exposed areas
- Input for identifying adaptation thresholds, triggers or for activating decision points

*''Exposure generally refers to the state and change in external stresses that a system is exposed to. In the context of climate change, these are normally specific climate and other biophysical variables (including their variability and frequency of extremes). The location of people and assets can also be regarded as exposure''*(Judy Lawrence, Simon Tegg, Andy Reisinger, 2011)

For the exposure analysis, one percent annual exceedance probability (AEP) data is available for pluvial flooding + climate change increments, and marine flooding + climate change increments. In this case the incoming data will be a combination of combining the available hazard layers, and use riskscape to evaluate the consequences. For the vulnerability identification, which is what is aimed with the exposure assessment, (*LGNZ*, 2019) proposes the following identification steps:

1. Collect available data on SLR and Hazards, e.g. flooding
2. Identify assets in the area, using asset data
3. Combine the datasets to identify hazard extents
4. Ground-truth within and across teams

### Hazard Data Collection (1)

A combination of several hazards was identified for the Petone area, three water related hazards,, Marine Flooding and high groundwater levels. Since most of the wastewater and stormwater infrastructure is actually gravity based, which increases the vulnerability to sea level rise. Unfortunately no modelling of these systems is available at the moment, so it will not be possible to look into different scenarios for example. However there are some calculations and measurements available, also in the form of maps.

For Marine Flooding there is a predictive data layer for flooding scenarios under rising sea levels, which can be provided by NIWA. The data used will be a certain increment in water height with an additional extreme storm event. The storm event does not change, just the increment in the water levels.

Increases in groundwater level is a serious threat to the Petone area, especially since it is already dealing with relatively high groundwater levels. Some more research into the actual implications of this increase will be necessary to accurately estimate the magnitude of the threat.

### Asset Identification (2)

For this part Wellington Water will play a vital role, since they are in the position to provide data on their infrastructure. NIWA has provided a map already with water infrastructure, and also has access to datasets on population from their Riskscape database. This asset data will provide an important part to start describing what water infrastructure is present in the area.

### Combine Datasets (3) and Ground Truth, discuss with experts from WW and NIWA (4)

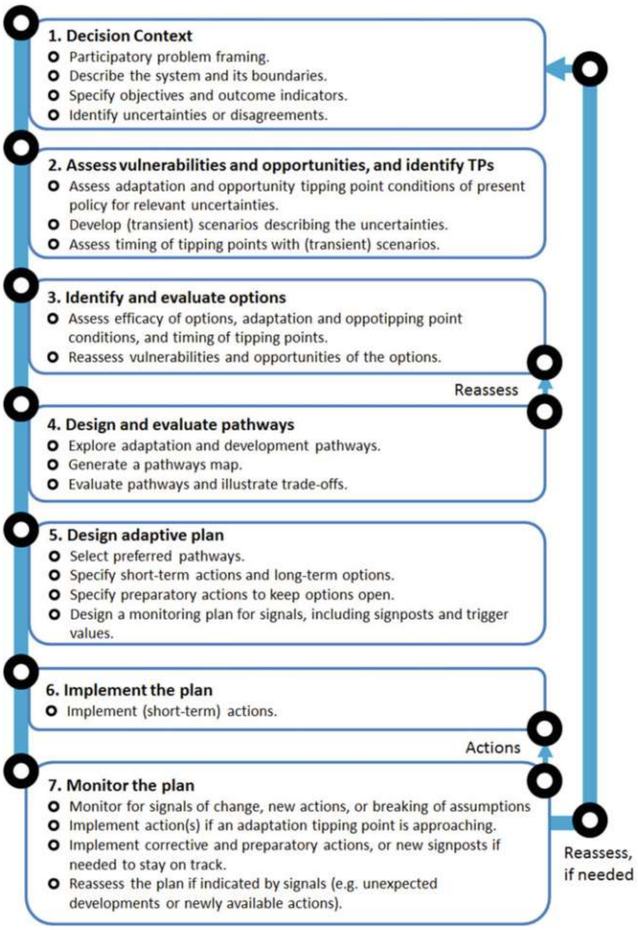
Looking into consequences for assets at risk will be the aim of this analysis. The first thing to do would be to overlay the hazard datasets and asset datasets to see the extent of exposure in relation to the corresponding scenarios. Since finding the correct functions to accurately assess this might be tricky in QGIS, NIWA has offered to help with setting up this analysis using their in-house developed tool Riskscape. This multi risk modelling tool combines three important components as input, being a Hazard Module, a Vulnerability Module and an Asset Module (Schmidt et al., 2011). The unique aspect of this program is that it is designed to be a flexible tool that can adapt to different hazards and assets.

The outcome of the exposure analysis will provide a good starting basis to understand what is at risk and where the weak points are in the system and for engaging stakeholders and start exploring possibilities for retreat sequencing.

## 3.3. Retreat Sequencing

Building upon the exposure analysis for the area, interdependencies and thresholds can now be investigated to start addressing the main question. For this the Dynamic Adaptive Planning Pathways (DAPP), elaborated on in the introduction, will be used to start investigating the sequencing of the retreat, and what areas to focus on. This means also identifying plausible pathways.

These options will follow from the exposure analysis that should start to give a good discussion starter for engagement of different stakeholders in Wellington. Based on the preceding exposure analysis, and in collaboration with relevant stakeholders, it will be possible to start identifying short and long term options, both maintenance actions and more structural changes in short term to longer term that maintain flexibility for future adaptation.



**1. Decision Context**
- Participatory problem framing.
- Describe the system and its boundaries.
- Specify objectives and outcome indicators.
- Identify uncertainties or disagreements.

**2. Assess vulnerabilities and opportunities, and identify TPs**
- Assess adaptation and opportunity tipping point conditions of present policy for relevant uncertainties.
- Develop (transient) scenarios describing the uncertainties.
- Assess timing of tipping points with (transient) scenarios.

**3. Identify and evaluate options**
- Assess efficacy of options, adaptation and oppotipping point conditions, and timing of tipping points.
- Reassess vulnerabilities and opportunities of the options.

**4. Design and evaluate pathways**
- Explore adaptation and development pathways.
- Generate a pathways map.
- Evaluate pathways and illustrate trade-offs.

**5. Design adaptive plan**
- Select preferred pathways.
- Specify short-term actions and long-term options.
- Specify preparatory actions to keep options open.
- Design a monitoring plan for signals, including signposts and trigger values.

**6. Implement the plan**
- Implement (short-term) actions.

**7. Monitor the plan**
- Monitor for signals of change, new actions, or breaking of assumptions
- Implement action(s) if an adaptation tipping point is approaching.
- Implement corrective and preparatory actions, or new signposts if needed to stay on track.
- Reassess the plan if indicated by signals (e.g. unexpected developments or newly available actions).

*Figure 8:DAPP process, adapted from (Haasnoot et al., 2019)*

Due to the duration of the project, there is not enough time to develop a real life DAPP approach for the Petone area. Rather, a conceptual DAPP will be developed to indicate how it could be done. The process can be seen in Figure 8. In short the DAPP process follows the following steps (Haasnoot et al., 2019):

- Framing
- Analysis
- Actions
- Evaluation of actions and options
- Development of adaptation pathways
- Selection of preferred possible pathways
- Specify and implement
- Monitor and review

### Identifying Thresholds

Identifying adaptation thresholds will be critical in determining how to transition infrastructural assets from the present scenario to some point in the future where a threshold is reached and make sure these assets are ready before this threshold is surpassed. The different increments used in the datasets can be used to identified initial thresholds, using the exposure analysis. The output from the exposure analysis can then be a starting point for discussing coincidence of maintenance/replacement schedules of assets and pathway changes.

ISO 14090 defines the threshold analysis as *''a point beyond which a system is deemed to be no longer effective (economically, socially, technologically or environmentally). The aim of thresholds analysis is to identify such points, determine the current proximity to these thresholds, and develop an adaptation plan that will reduce the likelihood of crossing these thresholds.''* (Standard, 2019) In order to identify these it proposes the following steps:

- Characterize the system
- Research possible climate changes
- Identify Thresholds
- Assess Resilience
- Identify suitable indicators

Characterizing the system could be done with the aid of the systems concept outlined in Figure 9. This would provide valuable input to both the exposure analysis and identifying interdependencies for which I will use the CIrcle tool, which enables such interdependencies to be characterised (see section Identifying Interdependencies).

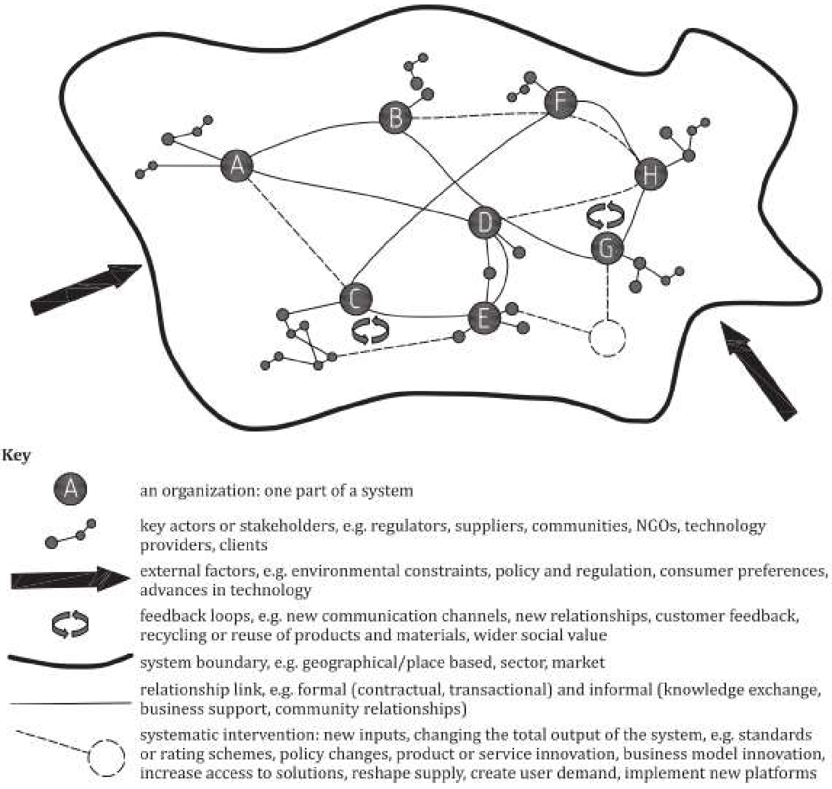


**Figure A.1 — Systems concept showing a general systems concept with interventions highlighted**

*Figure 9: Systems Concept, adapted from* (Standard, 2019)

### Identifying Interdependencies

Building on the concept, once system boundaries and links identified using the system in Figure 9, for identifying interdependencies and potential cascading effects the Circle (Critical Infrastructures: Relations and Consequences for Life and Environment) tool from Deltares will be used. A cascading effect is a result of, in this case effects of climate change, on the system which sets of a chain of events. Mapping these interdependencies between different infrastructure assets is crucial for identifying adaptation thresholds and pathways. An example of linking these different infrastructure assets with the CIrcle tool can be found in Figure 10. The tool is developed with the aim to have input from different experts, where identifying these relations help developing the DAPP for step 2 and the iterative process between step 3 and 4 in Figure 8. Licensing options and possibilities still have to be looked into.

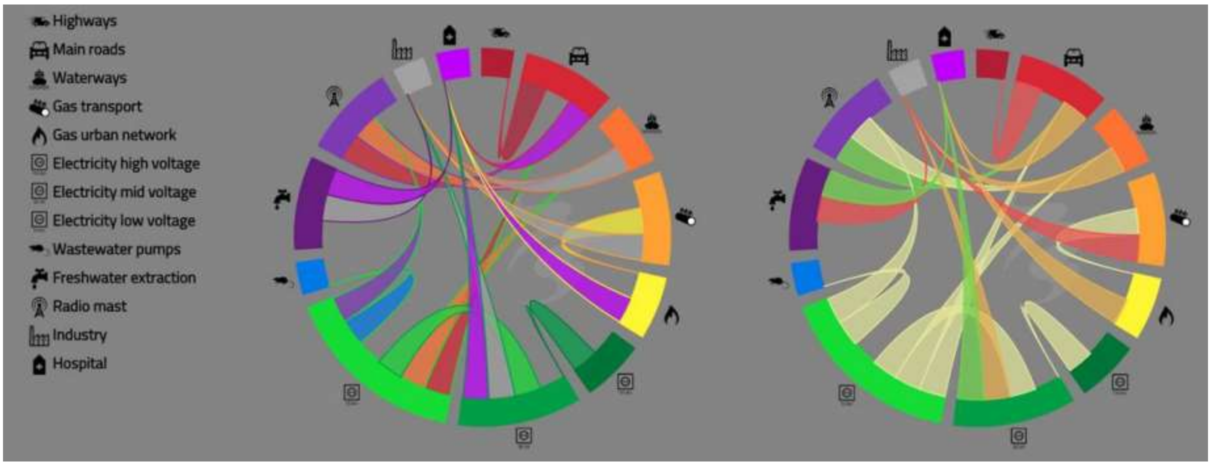


*Figure 10: Interdependencies from the CIrcle Tool, adapted from* (Deltares, 2017)

### Workshop

In order to aid the CIrcle tool process, a workshop will be held on the 27th of November. The aim is to gather expert input from various backgrounds on the topic. Input for the meeting will be results from the exposure analysis, interdependencies between different infrastructure assets and background on the study area which in conjunction with the Circle tool will be used for identifying adaptation thresholds and pathways.

### Process

The process for the project can be seen in Figure 11. The first part focusses on investigating the area and possible consequences, conducting a exposure analysis, evaluating asset information and gathering information on the area and literature. The second phase will be more focussed on collaboration with stakeholders, whereas the last phase will work towards establishing a conceptual DAPP for retreat of two water infrastructure in the Petone area.

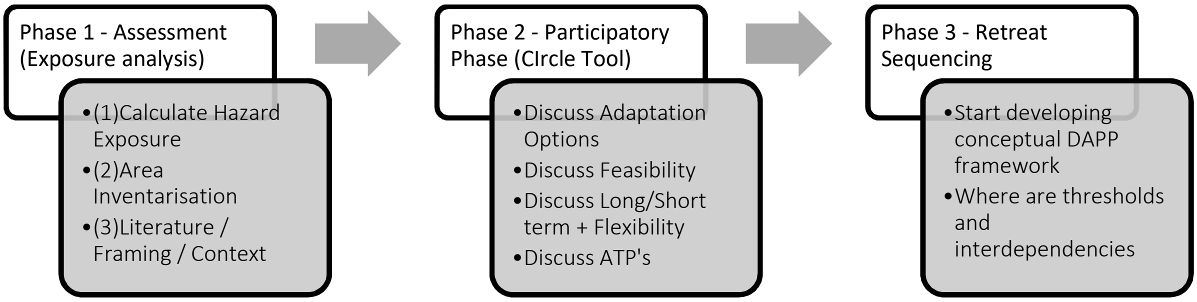


*Figure 11: Project Process*

# 4. Data Collection

Data collection will be necessary in order to reach an evidence based product, mainly to characterise the study area, and perform an exposure assessment, which then can be used to start finding answers to the 'How' in the problem statement. Focus is on the two water infrastructure data. Water infrastructure data, in specific asset data, will be acquired from Wellington Water and should give a first indication of assets located in the area. It should also give an overview of maintenance intervals and or material properties.

Hazard data will come from both Wellington Water and NIWA. The dataset from NIWA is related to modelled sea level rise, already seen in Figure 4 and Figure 5. It provides +10cm incremental projections until a level of +300cm, and what impacts this would have on the Petone area. Groundwater predictions are necessary, as this is expected to largely impact the assets in the area. An overview of the data that is expected is shown in Table 1.

*Table 1: Data*

| Source / Responsible | Data | Product |
|---|---|---|
| General Information about the Area | | |
| Wellington Water / GWRC Open Data | Topographic / Elevation Data | Area Assessment / Exposure Assessment |
| NIWA / GWRC Open Data | District Boundaries | Area Assessment |
| GWRC Open Data | Roads, Physical Location and usage | Area Assessment / Exposure Assessment |
| GWRC Open Data | Water Level Records | Area Assessment |
| | | |
| Hazard Data | | |
| NIWA | Incrementally Increasing Flood Map | Exposure Assessment / Retreat Sequencing |
| Wellington Water / GWRC Open Data | Three Water Information | Exposure Assessment / Retreat Sequencing |
| GWRC Open Data | Groundwater Predictions | Exposure Assessment / Retreat Sequencing |
| | | |
| Asset Data | | |
| Wellington Water | Three Water Assets | Exposure Assessment / Retreat Sequencing |
| Wellington Water | Service Levels | Exposure Assessment / Retreat Sequencing |
| Wellington Water | Legacy Problems Old Pipes | Exposure Assessment / Retreat Sequencing |
| Wellington Water | Earlier Model Results / Return Periods | Exposure Assessment / Retreat Sequencing |
| Wellington Water | Lifespan / Maintenance | Exposure Assessment / Retreat Sequencing |
| NIWA | Population | Exposure Assessment |

# 5. Deliverables

It is envisioned that in the first stages of the project, mainly two sections of the project are developing now, first one being related to the area and managed retreat literature, second one related to the study area and corresponding exposure assessment. This should in turn start to give an answer to the following questions

- What water infrastructure is present in the study area? (1)
- What are the physical characteristics of the study area? (2)
- Preceding (vulnerability) assessment of the study area (3)

Then it becomes important to use this knowledge and insights into the area, and start to discuss it with different stakeholders on what kind of other uncertainties or problems could arise, and what could be a good way of sequencing these steps. This means that a pretty in depth outline of what is to be achieved should be done at this point. This would in turn aim to discuss the following

- What levels of Service (LoS) are appropriate while transitioning towards adaptation thresholds? (4)
- What measures and actions are appropriate to maintain LoS and do they coincide with adaptation thresholds? (5)
- How long should water services be maintained? (6)
- What leads - service withdrawal or house withdrawal? (7)
- How can the vulnerable be identified and their needs addressed? (8)

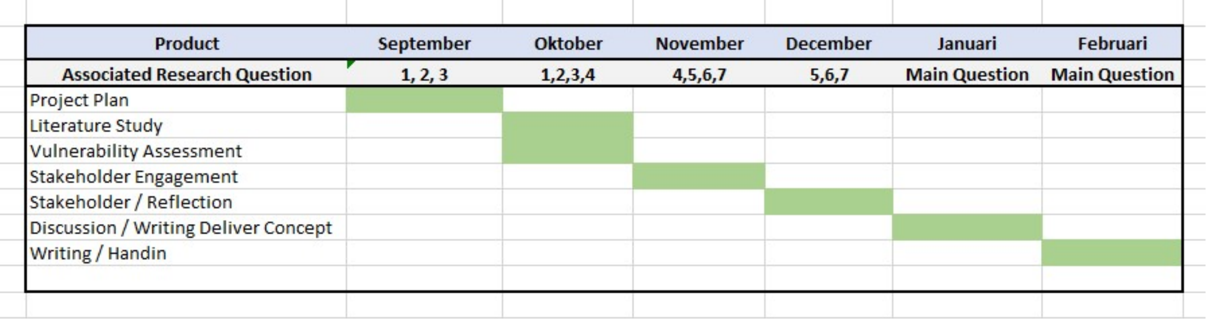
Ultimately leading to how to sequence this and tie this into a DAPP approach, with regards to identified return periods and maintenance/replacement timeframes. In the end it should start to point towards an answer of the how, ''How could the retreat of water infrastructure (stormwater, waste water and water supply, roading) be managed alongside a community retreat from the coast'', already having answered the what, why, and where. Question that remains is the when.

*Table 2: Preliminary Milestones*

| Month | Activity | Comments | Products/Milestones | Meetings |
|---|---|---|---|---|
| September | Literature study, methodology, define what infrastructure will be taken into account | -Base on pre identified vulnerabilities<br>-Define methodology | Project plan + notes on findings from the literature study + methodology | |
| October | -Finish Literature<br>-Finish Area / Vulnerability Assessment | -Input from pillar 3<br>-Prepare stakeholder meetings | Status report + Exposure/area assessment + Literature | (1) Discuss Phase 1 Fig 11, 29th Oktober? |
| November | Assessment, start qualitative data collection | -Engage stakeholders in the study area, e.g. Wellington | Rough outline of the thesis, what is going to be included in the end product? | (2)Discuss Stakeholder Progress, |
| December | Start writing, start identifying level of service | -Discuss implementation<br>-Discuss Sequencing | Start a discussion on results / reflections | (3)Agree on definitive |

| | | | | |
|---|---|---|---|---|
| | | | on stakeholder meetings | scope to continue |
| January | Writing | -Discuss feasibility | Discussion/writing, deliver concept | (5) Discuss Draft |
| February | Finish Study | | Writing/hand-in | |

*Table 3: Preliminary Planning (revise in template)*



| Product | September | Oktober | November | December | Januari | Februari |
|---|---|---|---|---|---|---|
| **Associated Research Question** | **1, 2, 3** | **1,2,3,4** | **4,5,6,7** | **5,6,7** | **Main Question** | **Main Question** |
| Project Plan | 🟩 | | | | | |
| Literature Study | | 🟩 | | | | |
| Vulnerability Assessment | | 🟩 | | | | |
| Stakeholder Engagement | | | 🟩 | | | |
| Stakeholder / Reflection | | | | 🟩 | | |
| Discussion / Writing Deliver Concept | | | | | 🟩 | |
| Writing / Handin | | | | | | 🟩 |

# 6. Organisation

This is a collaborative project between Victoria University Wellington and DTU. This chapter will include some information on the participating organizations / professors. Meetings between the universities will be aligned with the deliverables (see Table 2) to discuss each next phase and reflect on the progress made. After the project is submitted it will be defended and presented via skype as part of DTU requirements for completion of the project.

**Victoria University**

Since the research takes place in New Zealand, the main guidance will come from the New Zealand research team, consisting of Dr Judy Lawrence from VUW and Dr Rob Bell from NIWA as the direct supervisors for the research.

**DTU**

Dr Martin Drews will be the supervisor in Denmark and will make sure the research complies with DTU standard for a thesis.

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# B Appendix 2

# Appendix 2

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## Exposure Assessment

# Contents

# 1. Introduction

Sea level rise has been indicated as one of the key factors affecting New Zealands coastal communities (Local Government New Zealand, 2016; Ministry for the Environment, 2017). Negative consequences include more frequent inundation, increased erosion and increases in groundwater levels, saltwater intrusion, liquefaction and drainage problems. Research into New Zealand exposure on natural hazards, namely Marine, Fluvial and Pluvial flood exposure (Paulik, 2019 (a); Paulik, 2019 (b)) shows that Wellington is among the cities with the highest pipeline exposure for all three waters infrastructure. (Wellington, 2019) also identifies the Petone area the most vulnerable geographic unit together with the Seaview area for the Hutt City Council, a reclamation area located next to Petone, despite the presence of one of New Zealand's largest flood protection schemes (Lawrence, Quade, & Becker, 2014).

This study will focus on investigating managed retreat of two water infrastructure for the Petone area, as a potential adaptation pathway. This means retreating two water infrastructure away from the vulnerable areas over time. An evidence-based staged approach towards decision-making and implementation will be key. Additional qualitative data from the study area, supporting the planning perspective will be acquired through stakeholder interviews. The principal research question is as follows:

How could the retreat of two water infrastructure (stormwater, wastewater and roading) in the Petone Area be managed alongside a community retreat from the coast, considering and defining;

- What levels of Service (LoS) are appropriate while transitioning towards adaptation thresholds?
- What measures and actions are appropriate to maintain LoS and do they coincide with adaptation thresholds?
- How long should two water services be maintained?
- What leads - service withdrawal or resident withdrawal?

For the purpose of this research an analysis into exposure of the assets and inhabitants of the area is done, where both the exposure from natural hazards are investigated for assets in the study area. It is important to illustrate the need to investigate retreat, both to initiate the research as well as to stakeholders. This exposure study focuses on services and infrastructure and where people live. It is important to start identifying which elements are exposed (both presently and in the future), and their spatial extent. Some background on the hazard data will also be provided. Chapter 1 will focus on background on the hazard data used, and Chapter 2 will discuss the assets and their definitions. Standard (2019) defines exposure as *''Presence of people, livelihood, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social or cultural assets in places and settings that could be affected''*. LGNZ (2019) proposes the following identification steps for an exposure assessment:

1. Collect available data on SLR and Hazards, e.g. flooding
2. Identify assets in the area, using asset data
3. Combine the datasets to identify hazard extents
4. Ground-truth within and across teams

## 1.1. Background

In this chapter the background for both Pluvial and Marine Flooding will be investigated, as these were provided by Wellington Water and the National Institute of Water and Atmospheric Research (NIWA). It is not possible to run multiple extreme hazard events at the same time, since the interaction between the different hazard occurrences is both unknown and extremely complicated to model (Schmidt et al., 2011). Accordingly, hazard scenarios have to be treated as separate assessments. Since this coincidence cannot be calculated accurately, after discussing this at NIWA and during the workshop it was decided to only use the Marine Flooding arising from sea-level rise (SLR) as the hazard to focus on for this study. Background on the Pluvial flooding data is still provided.

### Hazard Data types and Applied RiskScape Scenarios

Hazard and asset data are used for the exposure assessment. Hazard data will be overlain with selected asset data that will be assessed to determine the exposure to the hazards as a components of risk. This section discusses the hazard data sets. Different SLR increment scenarios will be investigated in RiskScape, using Marine flooding maps. A detailed background for RiskScape and its functions can be found in Chapter 3. This is available for a present day scenario of 1% AEP and then increases with 10cm SLR increments. The RiskScape scenarios for these marine flooding maps are based on the New Zealand SLR projection scenarios (Figure 1). The scenarios will be run through until + 120 cm SLR. This corresponds with a NZRCP8.5 H+ scenario just under approximately 90 years, until 2110.

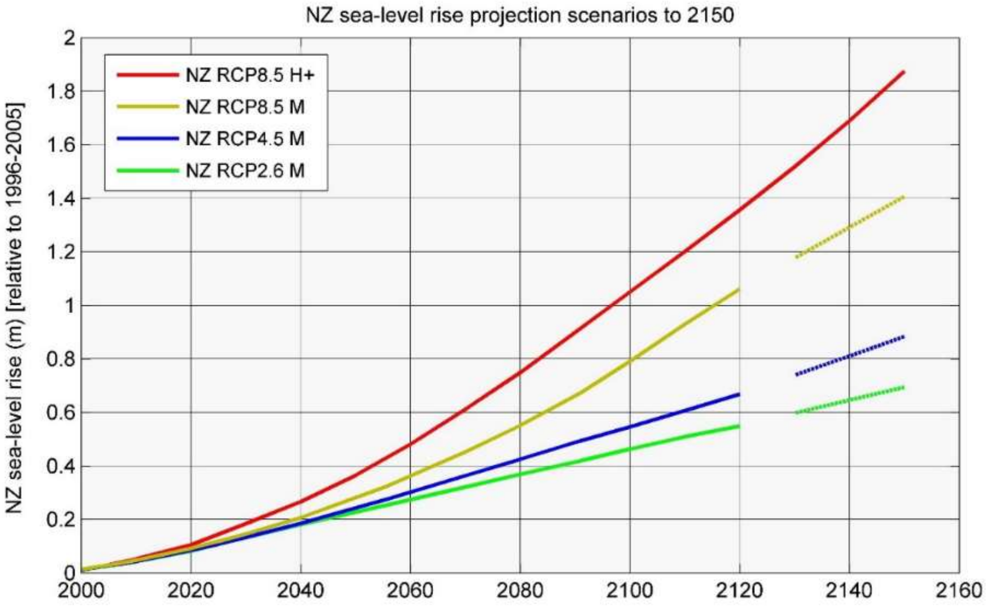


*Figure 1: New Zealand Sea Level Rise (SLR) projections untill 2150* (Ministry for the Environment, 2017)

A hazard map was also provided for Pluvial flooding. For this hazard data, a 20% increase in rainfall was added and then the 1% AEP was calculated. Temperature changes will contribute significantly to changes in the rainfall regimes, increasing precipitation and storm intensities (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018). In the end it was decided not to use this hazard as it was not possible to calculate exposure using different increments and see hazard exposure for different scenarios. The Marine hazard data was therefore more suitable for evaluating asset exposure thresholds.

## One percent annual exceedance Background

(Faber, 2012) gives some background on return periods for extreme events. Since both datasets used here are based on an annual exceedance probability of 1%, or in other words an annual exceedance probability of 0.01. The return period for planning or design period *T* is given as following:

$$T_R = \mathrm{n} * \mathrm{T} = \frac{1}{\left(1 - F_{X,T}^{max}(\mathrm{x})\right)} \quad T$$

In which $F_{X,T}^{max}(\mathrm{x})$ is the cumulative distribution function (CDF) of the extreme events (Faber, 2012). Since the annual exceedance probability is 1%, the return period is calculated as follows:

$$T_R = \frac{1}{(1-(1-0.01))} = \frac{1}{(0.01)} = 100\ years$$

The following conditions apply for using this method for the planning or design period and return period, the process must be an ergodic random process X(t) and extremes within the design period T must be independent (Faber, 2012). The cumulative distribution function (CDF) for the reference period n*T can therefore be described as:

$$F_{X,nT}(\mathrm{x}) = (F_{X,T}(\mathrm{x}))^n$$

This means the occurrence probability after a planning timeframe of 100 years is:

$$P = 1 - (F_{X,T}(\mathrm{x}))^n = 1 - (1-0.01)^{100} = 0.634$$

This is however assuming stationary conditions with regards to boundary conditions, and therefore the return period. Due to changes in the boundary conditions, like SLR, return periods will also change as the sea continues to rise. According to (Stephens, 2015; White et al., 2017), a SLR increase of 0.30 m will change a 1%AEP into an event occurring at least once per year in the case of the Wellington region. This means flooding predictions are likely to underestimate the impact of SLR increases. An overview of how SLR affects exceedance of 1 / 100 years extreme high water levels for different cities in New Zealand can be found in Table 1, adapted from (NZ, 2015). The Wellington region has the highest exceedance per increment in comparison to the other major cities in New Zealand, because of its low tide range.

*Table 1: The changing Return Period for the exceedance of the present-day 1% AEP High Water Level (HWL) in major New Zealand cities.*

| SLR increment [m] | Auckland | Wellington | Christchurch | Dunedin |
|---|---|---|---|---|
| 0 | Every 100 years | Every 100 years | Every 100 years | Every 100 years |
| 0.20 | Every 12 years | Every 4 years | Every 5 years | Every 9 years |
| 0.40 | Every 2 years | Every 2 months | Every 3 months | Every 9 months |
| 0.60 | Every 2 months | 3 times a week | Twice a week | Once a month |

## 1.2. Marine Flooding Hazard Data

As stated in the project proposal, the dataset used as the coastal flooding hazard is the one developed for the Deep South Challenge, published in (Paulik et al., 2019). The aim of that research was to map marine flooding for New Zealand nation wide for 1% annual exceedance probability with SLR increments of 0.1 m, and enumerate elements that were at risk of coastal inundation (Paulik et al., 2019). During this process, elements at risk were mapped by intersecting the digital elevation model (DEM)(derived from aerial LiDAR surveys) with the present-day 1% AEP extreme sea level and successive 0.1 m increments of SLR. However, these elements were, for three waters infrastructure, just defined as nodes and pipes. Due to inconsistent attribute information it was not possible to individually map these on a nationwide scale. For this research, the same exposure of assets will be initially be used in this research, however it will be done on the Petone scale.

In order to define areas potentially exposed to direct or indirect flooding, a baseline must be established. This is done by defining the land-sea boundary (Paulik et al., 2019). The land sea boundary is defined by the MHWS10 level, which is the water level that is only exceed by 10% of all high tides (Paulik et al., 2019). This includes geographic tidal variations.

Another complicating factor is that homogeneous boundary conditions cannot be applied on a nation-wide scale. Different areas have a different set of underlying components that defines an extreme AEP event. Due to sheltered conditions the Wellington Harbour, and therefore the Petone area, was categorized as an estuary with a tidal gauge. Included in this scenario are the 1% AEP storm tide levels, MSL offsets and MHWS-10 from the tidal gauge at Queens Wharf in Wellington. This means no wave setup was added for this scenario.

**Bathtub Approach**

The marine hazard data is modelled using a static method, or bathtub approach. The bathtub approach only considers the intersection of two vertical levels, being the water level and the digital elevation model (DEM). This may not be a realistic representation of reality, as bathtub flood modelling has a tendency to overestimate flooding exposure for a couple of reasons (Paulik et al., 2019). The first is duration of an extreme event, this is not an instant transition towards a fully extended hazard. In order to inundate larger areas, flow needs time to make its way through narrow connections with the sea, e.g. channels and culverts (Paulik et al., 2019).

An alternative approach would be the use of a dynamic inundation model, using a numerical hydrodynamic model (Ministry for the Environment, 2017), where the (over)flow from sea to land is numerically resolved (DHI, 2017). As setting up and calibrating a model like this is time intensive and requires detailed input data, the bathtub model was considered sufficient for the exposure assessment.

**LiDAR and DEM**

For different parts of the coast different sources for elevation data were used. Satellite DEM data is available for the entire coastline of New Zealand. However, LiDAR DEM data is more accurate and preferred. For the Wellington region, therefore also the Petone area, the more accurate LiDAR data has been used (Paulik et al., 2019).

# 2. Asset Data

Asset data for two waters infrastructure was acquired from Wellington Water. This was used to investigate the exposure. However, due to time limitations on the research, only exposure in the sense of 'assets being affected by the hazard scenarios' will be investigated rather than assessing the predisposition of each type of element to be damaged or compromised. Due to the considerable size of the asset data this means that the system has to be analysed and critical nodes should be both prioritized and selected for testing exposure from the different hazard datasets.

## 2.1. Background Urban Drainage Systems

A distinction can be made between combined and separate Urban Drainage systems. The Petone infrastructure is mainly gravity based and a separate system. Urban Drainage systems handle two waters, wastewater and stormwater (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018). In general they can be divided into two types, a combined system where wastewater and stormwater are combined in the same pipe and a separate system. Hybrid systems are also possible, but not common.

### Combined Urban Drainage System

A combined system disposes of storm and sewer water, usually to a water treatment plant (WTP) in the proximity of the urbanized area. The water course in Figure 2 is a river or estuary, in the Petone area most of these outlets are connected to the Hutt River or the Wellington Harbour. In periods of relatively dry weather, the system carries mainly wastewater flow. To ensure sufficient discharge during these periods, gravity based drainage systems must be designed to work only in predominantly wastewater flow. However, during rainfall there is a significant increase in discharge flow through the sewers, requiring much larger pipes.

This would decrease performance during dry weather, and it is not economically feasible to provide this increased capacity for the entire system. In order to handle the increase in discharge due to stormwater, the flow is diverted into the natural water course, e.g. the estuary or river, using a combined sewer overflow (CSO). This causes pollution as both stormwater and untreated wastewater are diverted into the natural water course before reaching the WTP (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).

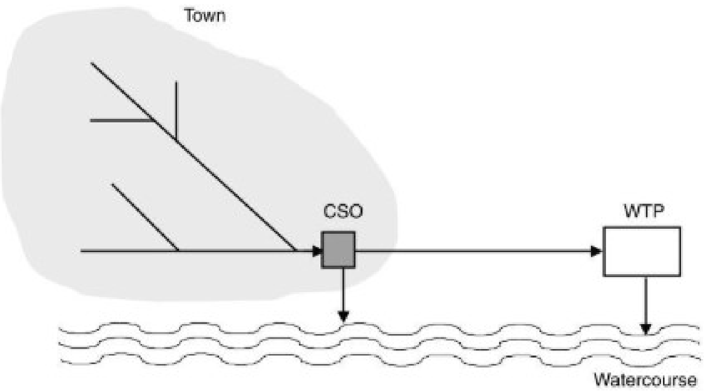


*Figure 2: Combined Drainage System, adapted from (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018)*

## Separate Urban Drainage System

More recently constructed drainage systems are usually separate. As can be seen in Figure 3, the storm and wastewater pipe systems are constructed separately, although usually in the same excavation trench, eliminating the need for an CSO (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018). The advantage of this separate drainage system is that it prevents pollutant spills in high stormwater discharge scenarios. Usually the stormwater pipes are the larger ones to accommodate the increased discharge during an intensive rainfall period, and the wastewater pipes are smaller to handle the more consistent but smaller wastewater discharge flow. To assume however that this removes pollution altogether is incorrect, as stormwater contains pollutants as well. Stormwater pollutants therefore remain an issue, as it is impossible to make sure no stormwater is going into the wastewater pipes. Stormwater can infiltrate the wastewater by means of infiltration and inflow. Infiltration can occur due to damages to the pipes, e.g. cracks and inflow can occur due to malpractice (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).

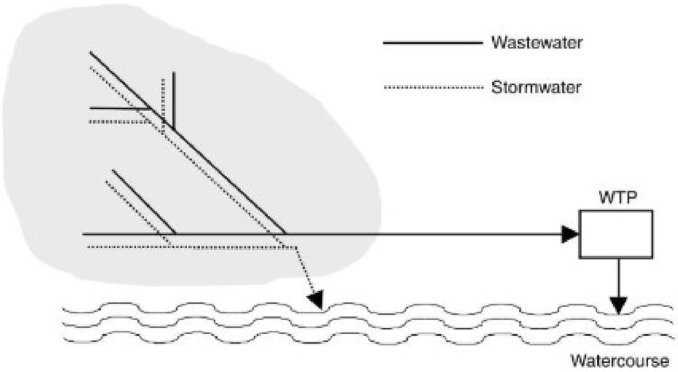


*Figure 3: Combined Drainage System, adapted from (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018)*

## Key Drainage System Components

In order to investigate and start prioritizing some of the assets in the Petone Urban Drainage System, it is important to first elaborate on the more important elements in the system. First some of the main components will be discussed, and after that some more specialized elements like pumping stations.

### *Sewers*

In the provided two waters assets for the Petone area, these sewers comprise of either stormwater or wastewater pipes. Materials of the provided assets consist of Reinforced concrete, Asbestos cement, PVC, UPC, steel cement for the stormwater pipes. For the wastewater pipes, these consist of Asbestos cement, High & Medium Density Polyethylene, PVC, Reinforced concrete, Steel, Steel cement and UPC. Current sewer pipes are usually circular in cross section. In calculations, there is usually the measurement of the invert level taken, which is the inner bottom of the pipe, whereas the crown level is the outer top of the pipe. The vertical alignment of the system makes sure the longitudinal profile of the system has enough land cover above the pipes. The horizontal alignment is the location of the network over the project area (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).

*Manholes*

Manholes make up the majority of the nodes in the by Wellington Water provided asset dataset for two waters infrastructure. The nodes act as an access point for inspection and cleaning, and are located where there is a change in direction, change in gradient, change in pipe size, head of runs and major junctions with other sewers (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).

*Gully Inlets*

Gullies collect runoff from roads and other paved areas via inlets, and form therefore the connection between the major and the minor drainage system. Usually there is an underlying sump. This sump is also a very common asset in the dataset. The gully is connected to the sewer by a lateral pipe.

*Inverted Siphon*

The aim of an inverted syphon is to allow flows to lower temporarily, for example to cross under canals or roads (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018). A disadvantage is that at lower discharge velocities, there is an increase in sediment deposition in this lower part.

*Culverts*

Culverts are also designed for carrying the flow underneath canals or roads, for both storm or wastewater. Culverts are usually straight circular or rectangular pipes, PVC or concrete.

*Pumping Station*

Pumping stations are needed to pump water out of or along the system if this cannot be done by gravity. There are quite a few in the area of study for both storm and wastewater systems in the Petone areas, as can be seen in Figure 5. For the wastewater, this is mainly necessary to pump the discharge to the Seaview WWTP. A gravity-based system is preferred to accommodate the necessary discharge, eliminating unnecessary maintenance. Since treatment facilities are usually not available in each natural sub-catchment, pumps are often necessary to overcome elevation difficulties. Depending on future adaptation, with regards to SLR, pumping stations will have an increasing role in keeping the current storm and wastewater systems running.

## 2.2. Petone/Alicetown Drainage System

The prioritized assets and conceptual system outline will be the input for the systems analysis, where other actors and drivers around the system and decision space are operating, identifying constraints or opportunities in this space. This would mean prioritizing certain elements and isolating them from the original shapefile. The scale of the analysis would be the study area, the Petone area and part of Alicetown.

As can be seen in Figure 4. The nearest Wastewater treatment plan (WWTP) is located on the opposite side of the Hutt river at the Seaview Area. There is also a Potable water treatment facility located in the study area opposite to the WWTP, however the potable water system is not included in the scope of this study when looking into affected assets. The trunk wastewater pipeline runs the length of the Esplanade, the main road along the coast.

What becomes apparent when looking at Figure 4, is the high number of wastewater pumps located in the vicinity of the coastline. The stormwater pumps are, as can be expected, placed in the lower parts of the system in the inner area of Petone. Therefore it is possible to more efficiently get the excessive stormwater out during heavy Pluvial flooding. The Wastewater pumps are placed in the vicinity of the wastewater outlets. Since the systems are gravity-based, there is the need at the end of the system, e.g. near the outlet, (near the Hutt river or the coastline), to pump the discharge flow to the necessary hydraulic head towards the WWTP.

*Figure 4: Pumping Stations and Pipe Network Petone*

# 3. RiskScape

Riskscape is a multi-risk modelling tool developed by the National Institute of Water and Atmospheric Research (NIWA) and GNS Science. It combines three important components as input, being a Hazard Module, a Vulnerability Module and an Asset Module(Schmidt et al., 2011). The unique aspect of this system is that it is designed to be a flexible tool that can adapt to different hazards and assets. Multi-risk hazard modelling is defined as follows:

*''Quantitative estimation of the spatial distributions of potential losses for an area (a confined spatial domain), multiple (ideally all) natural hazards, multiple (ideally a continuum of) event probabilities (return periods), multiple (ideally all) human assets, and multiple potential loss components (for each of the assets, e.g. buildings, streets, people, etc.)''* (Schmidt et al., 2011).

An advantage of using this multi-risk approach is to enable overlap of return intervals from different hazards to be examined, and how they affect an asset. This can help identify governing (most impacting) risks corresponding to different time intervals during the lifetime of the asset (Schmidt et al., 2011).

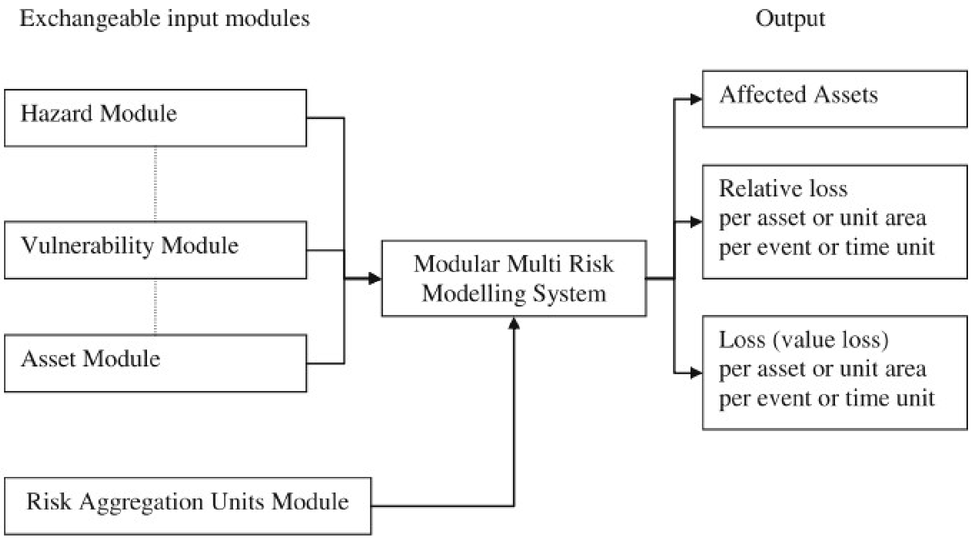


*Figure 5: Schematic Riskscape set up, adapted from (Schmidt et al., 2011).*

Hazard types for this study are categorized as SLR increments, in this case using a raster file for flood mapping. The program uses a set of functions for risk calculations, where the user is free to link to this module depending on the calculation. The type used for the exposure assessment will be a calculation of the affected, exposed, assets. This is done by overlaying the spatial extent of the hazard and the hazard exposure, onto the spatial representation of the asset module. In this case these are the Wellington Water assets, which is a spatial map. This results in the identification of exposure, or which assets are affected, in the area (Schmidt et al., 2011).

Other possibilities include calculation of relative, absolute, time averaged and space averaged loss (Schmidt et al., 2011). Figure 6 shows the RiskScape process and the different module possibilities. The first one is the asset exposure, which does not see the introduction of the fragility function. Adding the fragility function gives the possibility to calculate loss from a damaged or disrupt state. The first extra possibility is a relative, event specific and asset specific loss due to the introduction of Asset attributes in the fragility function calculating a damage ratio. The second possibility is an absolute, event specific and asset specific loss calculation due to the introduction of valuation for the asset. This is multiplied with the damage ratio in order to arrive at an absolute monetary loss. The third option is an absolute, time-averaged asset specific loss using the probability of hazard occurrence, therefore introducing risk.

This allows for losses to be calculated per time period. The fourth option sees the introduction of an aggregation module, allowing for an absolute, time-averaged, space-averaged loss. This is relevant when there is the need to identify an area with higher hazard impacts, resulting in an aggregated loss result per area (Schmidt et al., 2011).

It is not possible to run risk scenarios with different hazards, since interaction between multiple hazards and assets with their associated attributes is not possible to model in this system, however they often do occur simultaneously (Schmidt et al., 2011). Scenarios are based on the different hazards to which the assets are exposed. For the Marine Flooding hazard, scenarios are run until SLR reaches +1.2 m, with 0.1 m increments.

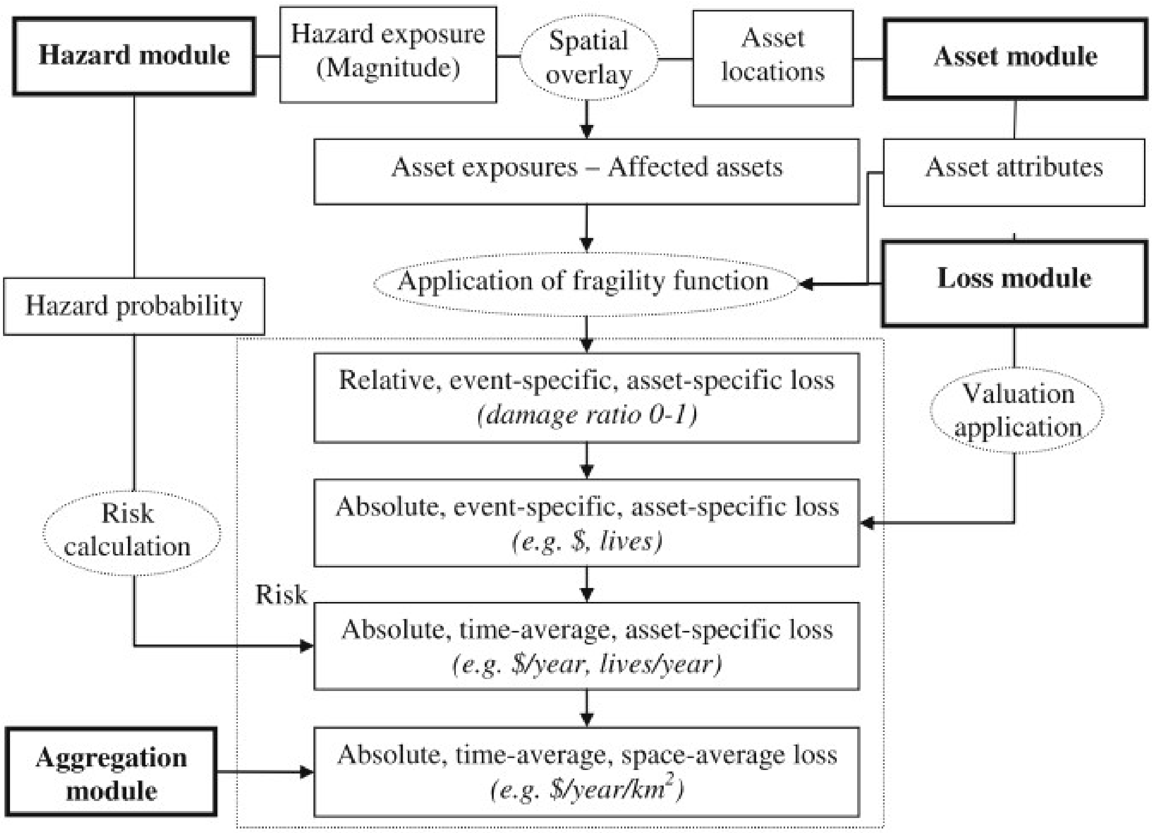
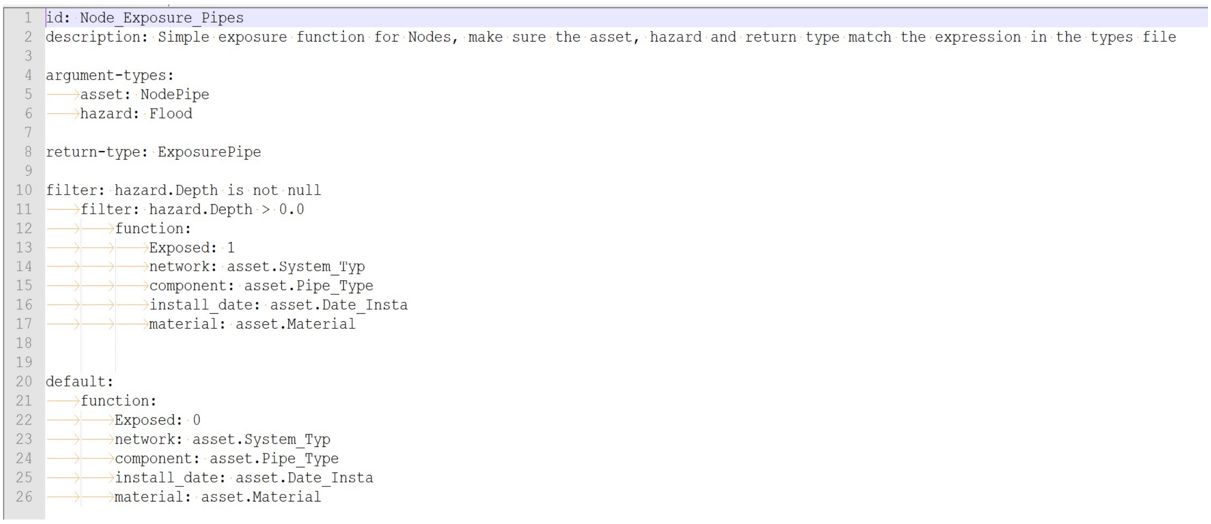


*Figure 6: Riskscape Modules. Adapted from (Schmidt et al., 2011).*

## Types of functions

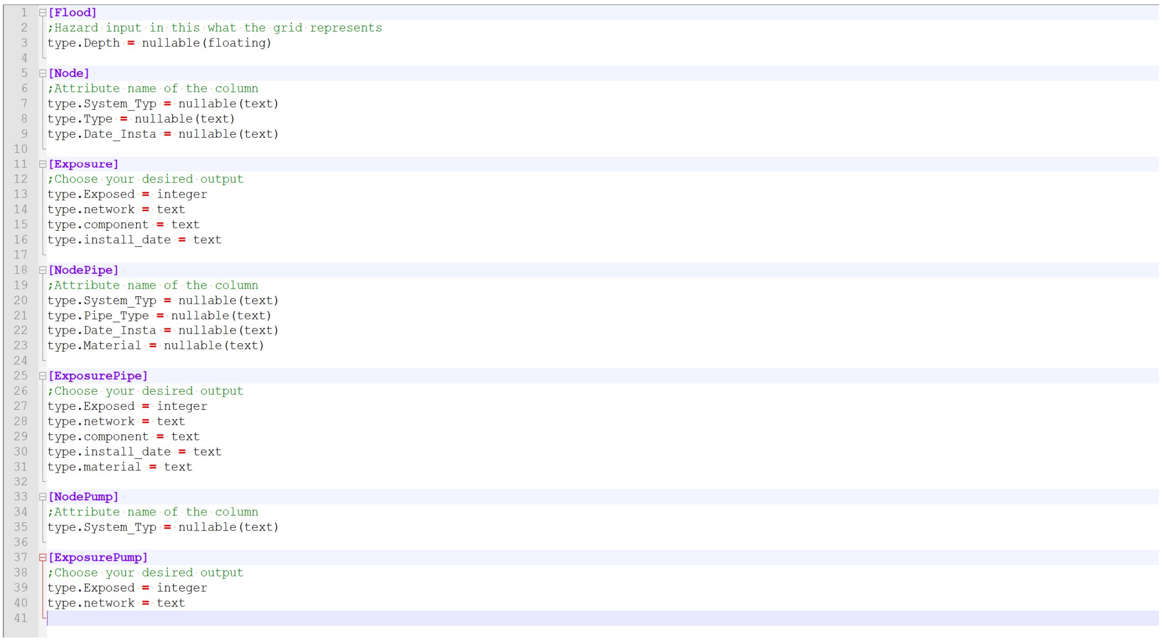
The function used in RiskScape is able to investigate exposure for an asset. It does so by identifying if the hazard is present at the location of the asset. This means it gives a very basic yes/no answer in terms of exposure. It can then verify the magnitude of the exposure, by checking the depth of hazard exposure, e.g. 0.1 metre or not. If the exposure passes this predefined threshold the function will turn to 1, whereas unaffected or below the threshold it will turn to 0.



```
id: Node_Exposure_Pipes
description: Simple exposure function for Nodes, make sure the asset, hazard and return type match the expression in the types file

argument-types:
    asset: NodePipe
    hazard: Flood

return-type: ExposurePipe

filter: hazard.Depth is not null
    filter: hazard.Depth > 0.0
        function:
            Exposed: 1
            network: asset.System_Typ
            component: asset.Pipe_Type
            install_date: asset.Date_Insta
            material: asset.Material


default:
    function:
        Exposed: 0
        network: asset.System_Typ
        component: asset.Pipe_Type
        install_date: asset.Date_Insta
        material: asset.Material
```

*Figure 7: Riskscape Function used*

The files contain three different types of modules (classes), which are hazards, assets and loss. This information cannot be predetermined by the function, the function will classify this for an analysis. Using the loss function requires a detailed prior assessment on the monetary value of the assets. Since this is not available this will not be used in the assessment. As can be seen in Figure 7, only the asset and hazard are defined for the argument types. Argument types specifies what functions expect for their inputs (CatalystNZ, 2018).



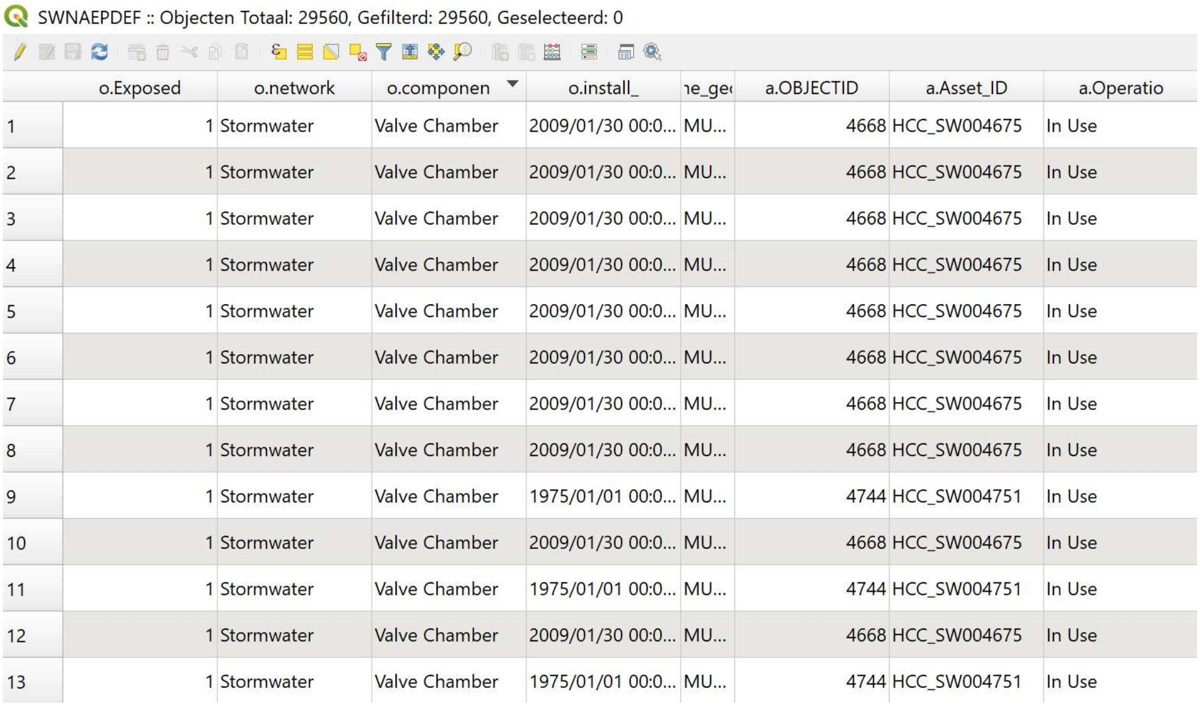
```
[Flood]
;Hazard input in this what the grid represents
type.Depth = nullable(floating)

[Node]
;Attribute name of the column
type.System_Typ = nullable(text)
type.Type = nullable(text)
type.Date_Insta = nullable(text)

[Exposure]
;Choose your desired output
type.Exposed = integer
type.network = text
type.component = text
type.install_date = text

[NodePipe]
;Attribute name of the column
type.System_Typ = nullable(text)
type.Pipe_Type = nullable(text)
type.Date_Insta = nullable(text)
type.Material = nullable(text)

[ExposurePipe]
;Choose your desired output
type.Exposed = integer
type.network = text
type.component = text
type.install_date = text
type.material = text

[NodePump]
;Attribute name of the column
type.System_Typ = nullable(text)

[ExposurePump]
;Choose your desired output
type.Exposed = integer
type.network = text

```

*Figure 8: Riskscape Argument Types used*

The asset, hazard and return types match the expression in Figure 8. Return types define the data type returned by the function(CatalystNZ, 2018). This is to select which fields with attributes should be taken from the input (asset) file, and what attributes should be included in the Riskscape output, the return type. As can be seen, the first column is adding the exposure by either adding a 1 or 0 to the asset. In the case for the pipes, it also includes the instalment date, material and what type of pipe it is. This results in the output being able to show what type of pipe, with attached age, is going to be exposed to the hazard at which SLR increment. This added condition component, together with asset lifetimes, is the first step looking into replacement opportunities for assets. The desired output is chosen per asset layer as not all the attributes uniform for all asset layers.

### Output

The same format for the output will be maintained as explained in chapter 2. For every type of asset, it is now possible to see at which hazard exposure the asset is going to be exposed. It is important to sort and visualize this in order to get an overview of the effect of the different increments. This will be set out in the next chapter, where there will be a script to prioritize the assets, also based on average lifespans of these assets, and this prioritized asset data with known thresholds to exposure is used as a start for retreat sequencing of two water infrastructure.



SWNAEPDEF :: Objecten Totaal: 29560, Gefilterd: 29560, Geselecteerd: 0

| | o.Exposed | o.network | o.componen | o.install_ | ne_ge | a.OBJECTID | a.Asset_ID | a.Operatio |
|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 2 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 3 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 4 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 5 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 6 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 7 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 8 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 9 | 1 | Stormwater | Valve Chamber | 1975/01/01 00:0... | MU... | 4744 | HCC_SW004751 | In Use |
| 10 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 11 | 1 | Stormwater | Valve Chamber | 1975/01/01 00:0... | MU... | 4744 | HCC_SW004751 | In Use |
| 12 | 1 | Stormwater | Valve Chamber | 2009/01/30 00:0... | MU... | 4668 | HCC_SW004675 | In Use |
| 13 | 1 | Stormwater | Valve Chamber | 1975/01/01 00:0... | MU... | 4744 | HCC_SW004751 | In Use |

*Figure 9: Riskscape output Columns*

# 4. Sequencing and Prioritization

The output from the RiskScape process gives an initial indication of what assets to focus on next. Visualizing this gives the potential to not only start looking more into relevant assets, but also start evaluating the more affected regions within the project area.

Wellington Water has provided documentation of the average lifespan of a variety of assets which can then be added to the original instalment date of the asset shown as an extra table column in QGIS. This can then further be visualized by selecting both replacements coming up, together with exposed assets. It then could be further selected by materials of these assets.

Prioritization of assets will be key to identifying the sequencing of options and to gain an overview of available options. The following steps are taken to sequence the data. First selection will be made upon the Riskscape results. These will then be aggregated into areas, to prioritize areas for further examination followed by the type of assets that are in the area.

## 4.1. Sewer Flooding: Systems and Classifications

In order to gain a better understanding of what a flooding of the urban drainage system entails there will be some background on the different levels of systems, how they interact, how to define thresholds for flooding, which could prove to be useful for setting adaptation thresholds (AT's) and what kind of approach can be taken in order to investigate this.

Butler, D., Digman, C., Makropoulos, C., & Davies, 2018 distinguish between the minor and the major system parts of urban drainage systems. The minor system is aimed at absorbing more frequently occurring storm flows by utilizing gully inlets, manholes and pipes. Major systems on the other hand include temporary storage areas and flood pathways on the surface, like roads and paths. Design pathways are planned, like retention basins and flood relief channels. If this is not the case but still acts like a pathway, it is labelled a default pathway. When the capacity of the minor system is exceeded, and the major system is utilized, the flow in the major system is labelled as exceedance flow.

The connection points between these systems are important. The key ones are outlined here. Gully inlets are entry points for stormwater from the major to the minor system, and when the minor system capacity is reached flow will not be able to enter it. Manholes are normal access points into the minor system. Upon reaching capacity, flow might be reversed. In extreme cases surcharged flow might reverse up through WCs and other household appliances. River outfalls are usually exit points for the minor system, however when waters rise in the receiving watercourse, or the ocean, it reduces the capacity of the minor system and could lead to exceedance. (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018). Three levels of analysis can be distinguished. Level 1 would suffice for a small area where the rational method can be utilized and exceedance flow is calculated by assuming minor system is already at capacity. The rational method is a design method where a preliminary drainage design can be calculated by hand (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018). Level 2 would be suitable for larger systems, where the minor system is still calculated with the rational method but the major system is modelled to examine surcharge and surface flooding. Level 3 consists of a level 2 approach with the addition of an interactive analysis and on site verification, as well as inlet capacity (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).

Then exceedance flow can be categorized. This enables adaptation thresholds to be identified in terms of affected assets. There are three thresholds that can be set, namely surcharging (minor system), surface flooding (minor system) and property flooding (major system). Threshold 1 is usually based on the design storm return period vs the hydraulic capacity of the pipe. Once threshold 1 is crossed, the system will begin to surcharge. Threshold 2 therefore refers to the maximum capacity of the system to handle stormwater without exceedance flow being generated, based on design flooding return period. For threshold 3 there is no consensus on a definitive return period, as this is difficult to establish (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).

## 4.2. Asset Prioritization

Asset prioritisation starts with identifying where the critical parts in the system are, and selecting which assets are the most important assets functionally. It is also important to start identifying opportunities for adaptation, as well as adaptation thresholds. This will also help keeping track of the large amount of data. In order to do this, criteria have to be established. The full process can be seen in Figure 10.

### Criteria

The first level of parameter is the type of asset. **Water treatment facilities** and **Pumping facilities** are vital non-standardized elements in the system specifically designed for the system purpose and with high replacement values. These are selected and examined first.

The second selection criteria will be finding a correlation between material and asset age. This will mainly focus on assets where there is a high density of assets that are up for replacement. The first step in this is to find the actual replacement dates for assets. This will be done for the pipe datasets. There is only limited data available for nodes, and the prioritized ones are extracted from the data set on the first level of parameter. Replacement dates of these pipes are calculated by adding average lifetime spans to the original instalment dates of the pipes. In order to get a better overview of the affected assets, they will be categorized by type of pipe, e.g. culvert or drainage and be given a corresponding priority. After this, spatial density is added on top of the selection e.g. when there is a higher density of replacements in a certain area coming up. To this there will be an addition of pipe materials to the prioritization. Even though there is no immediate hazard associated with asbestos pipes that are still in the ground, it is still preferable that they are to be removed and upgrades could provide an opportunity to get them out before other parts of the system. Wellington Water has no obligation to remove them before a certain date, however preferably they are removed as soon as practicable. Discharge pipes are another prioritized asset, as due to gravity-based systems these will be the first to be affected by the sea-level rise.

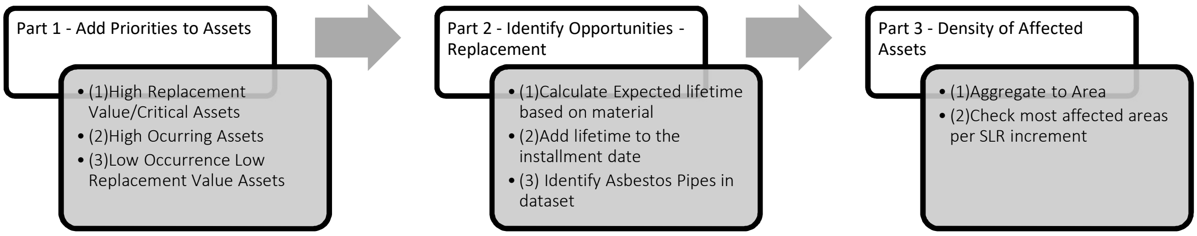


*Figure 10: Asset Exposure Analysis*

### Priority

Priority 1 assets are focussed on **quality** and involve assets that have a high replacement value like pumping stations. More **critical** parts of the system, like the discharge pipes into the Marine and Fluvial water bodies are also Priority 1. Priority 2 assets are focussed on **quantity**, being **important** but not critical to the system, like sumps and manholes. If these assets are affected however in large quantities, it does become a threat to the system. The script therefore identifies a threshold if a specific SLR increment affects either a number of Critical, number 1 assets OR if there is a significant increase in exposure of Important, Priority 2 assets.

### Stormwater Assets and Lifespan

In order to start selecting exposed assets, it is important to first look into the system. As can be seen in Table 2, there are 4 stormwater pumping stations in the area. These are some of the most critical elements in the stormwater system, therefore are Priority 1. The Nodes are mainly represented by sumps and manholes and therefore are defined as Priority 2. Lamp holes and undefined assets are Priority 3 as they are not critical.

*Table 2: Stormwater Assets*

| Exposed Assets StormWater | | | | |
|---|---|---|---|---|
| Type | Component | Amount (Study Area) | Description of the Component | Priority |
| Pump stations | | | | |
| Node | Pumping Station | 4 | Pumps excess stormwater out of the area | 1 |
| | | | | |
| Nodes | | | | |
| Node | Sump | 1299 | Stormwater connection between major and minor System | 2 |
| Node | Manhole | 1153 | Normal connection between major and minor System | 2 |
| Node | Outlet | 53 | Outlet stormwater system | 2 |
| Node | End | 5 | End stormwater system | 2 |
| Node | Inlet | 4 | Inlet stormwater system | 2 |
| Node | Undefined | 237 | Undefined | 3 |
| Node | Valve | 14 | Regulates the flow within the pipe | 3 |
| Node | Valve Chamber | 3 | Facilitates larger valves & allows inspection | 3 |
| Node | Lamphole | 3 | Inspection pipe for a lamp, outdated system | 3 |
| | | | | |
| Pipe | | | | |
| Pipe | Discharge | 8 | Outlet | 1 |
| Pipe | Main | 1418 | Main sewer | 2 |
| Pipe | Sump Lead | 1030 | Connection pipe to sewer | 2 |
| Pipe | Main Rising | 21 | Pressurized main sewer | 2 |
| Pipe | Culvert | 4 | Carry discharge flow underneath channels or roads | 2 |
| Pipe | Undefined | 129 | All abandoned, removed from dataset | - |
| | | | | |
| Connection Pipe | | | | |
| Pipe | Connection | 863 | Connections to the sewer | 2 |
| | | | | |

## Wastewater Assets and Lifespan

For wastewater assets a similar approach was taken. Pumping stations are mainly located at lower points of the system, like the Esplanade, and are Priority 1. The only wastewater treatment plant in the area is located on the other side of the Hutt river, in the Seaview area. Manholes make up the majority of nodes in the system and are Priority 2. Undefined nodes and lampholes or inspection points are Priority 3. Discharge pipes in the system are also Priority 1, the rest of the pipes are Priority 2. An overview of occurrence can be seen in Table 3.

*Table 3: Wastewater Assets*

| Exposed Assets WasteWater | | | | |
|---|---|---|---|---|
| Type | Component | Amount (Study Area) | Description of the Component | Priority |
| PumpStations | | | | |
| Node | Pumping Station | 9 | Pumps excess wastewater out of the area when this is not possible by gravity | 1 |
| | | | | |
| Nodes | | | | |
| Node | Treatment Plant | 0 | Prepares wastewater to return into the water system | 1 |
| Node | Manhole | 717 | Pumps excess wastewater out of the area | 2 |
| Node | End | 3 | Wastewater system end | 2 |
| Node | Lamphole | 50 | Inspection pipe for a lamp, outdated system | 3 |
| Node | Valve | 17 | Can regulate the flow within the pipe | 3 |
| Node | AirvalveChamber | 17 | Has installment date, regulates flow within the pipe | 3 |
| Node | Scour | 9 | Located at the lowest point of the system / pipe, smaller diameter therefore flushes the system | 3 |
| Node | Undefined | 1051 | - | 3 |
| Node | Chamber | 2 | Access to the system | 3 |
| Node | Septic Tank | 0 | Local collection of wastewater | - |
| Node | Scour Valve | 0 | Idem | - |
| | | | | |
| Pipe | | | | |
| Pipe | Trunk Main | 143 | Some are pressurised, large pipe to the treatment facility | 1 |
| Pipe | Discharge Pipe | 42 | Some are pressurised, outlet of system | 1 |
| Pipe | Rising Main | 2 | Pressurised sewer | 1 |
| Pipe | Main | 853 | Main sewer | 2 |
| Pipe | Service Connection | 0 | - | - |
| Pipe | Undefined | 0 | - | - |
| | | | | |

### Prioritization Script

In order to add the needed attribute data to the assets, a Qgis model has been developed in order to sort the output from RiskScape. The flow can be seen in Figure 11. The input on the left represents the output files from the RiskScape assessment, where the original assets files received an additional attribute column indicating a '1' for exposed and '0' for unaffected, for all SLR scenarios giving and idea at which level each of these assets become affected.

This section will not go through all the individual scripts but will discuss some of the important parts out. Table 4 shows the different output for each of the asset types. At the end they are combined into two datasets, one for pipes and the other for nodes.

*Table 4: Asset Attribute Modifications*

| Asset Type | Modifications | Output |
|---|---|---|
| Stormwater Pipes (SWP) | -Instalment Date to Year<br>-Year to Replacement<br>-Remove Abandoned Data<br>-Add Asset Priority | -Replacement Map<br>-Asbestos Map<br>-Priority per Asset Type per SLR increment |
| Stormwater Connection Pipes (SWCP) | -Instalment Date to Year<br>-Year to Replacement<br>-Remove Abandoned Data<br>-Add Asset Priority | -Replacement Map<br>-Asbestos Map<br>-Priority per Asset Type per SLR increment |
| Wastewater Pipes (WWP) | -Add Asset Priority | -Priority per Asset Type per SLR increment |
| Stormwater Nodes (SWN) | -Remove Abandoned Data<br>-Add Asset Priority | -Priority per Asset Type per SLR increment |
| Wastewater Nodes (WWN) | -Add Asset Priority | -Priority per Asset Type per SLR increment |
| Stormwater Pumping Station (SWPS) | -Add Asset Priority | -Priority per Asset Type per SLR increment |
| Wastewater Pumping Station (WWPS) | -Add Asset Priority | -Priority per Asset Type per SLR increment |
| | | |

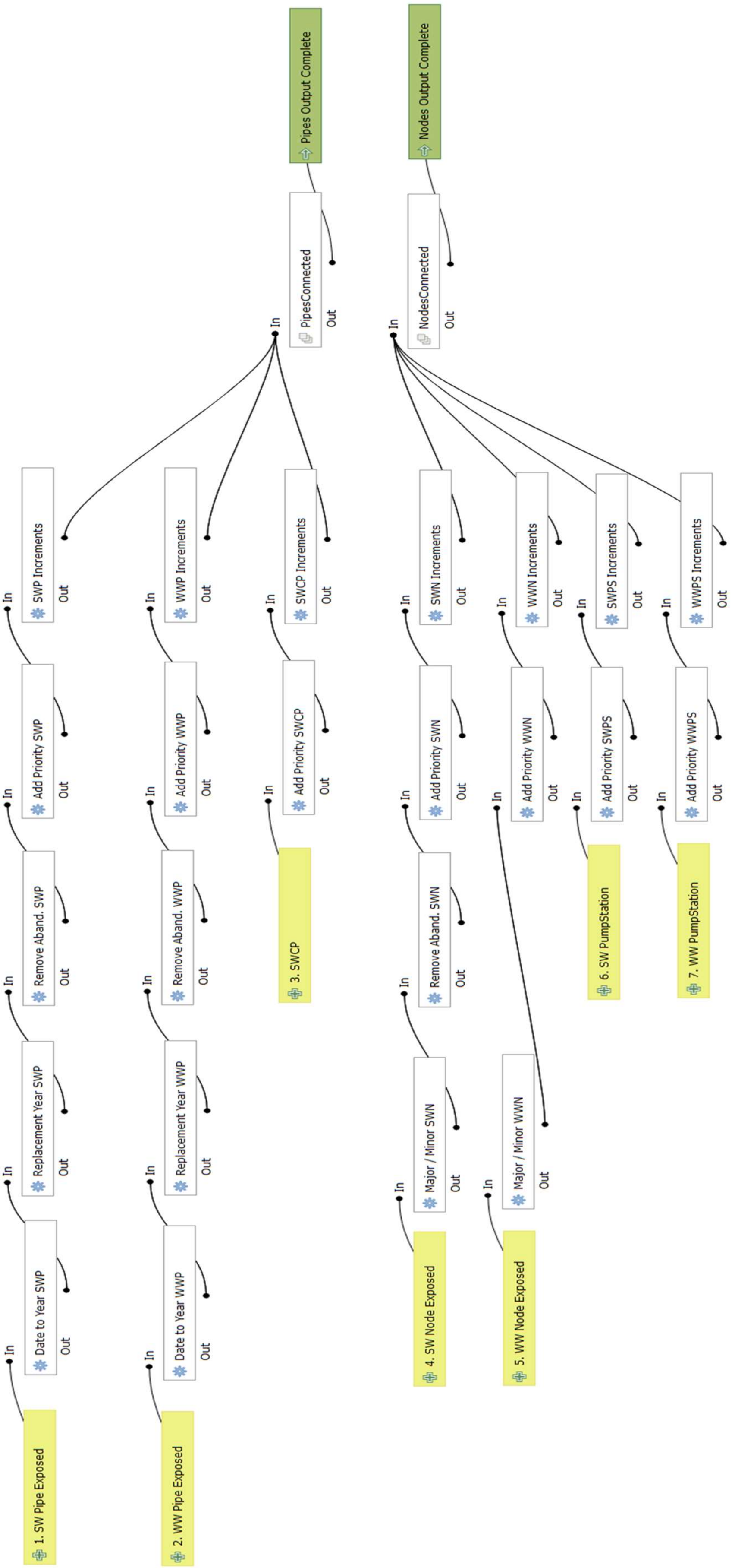
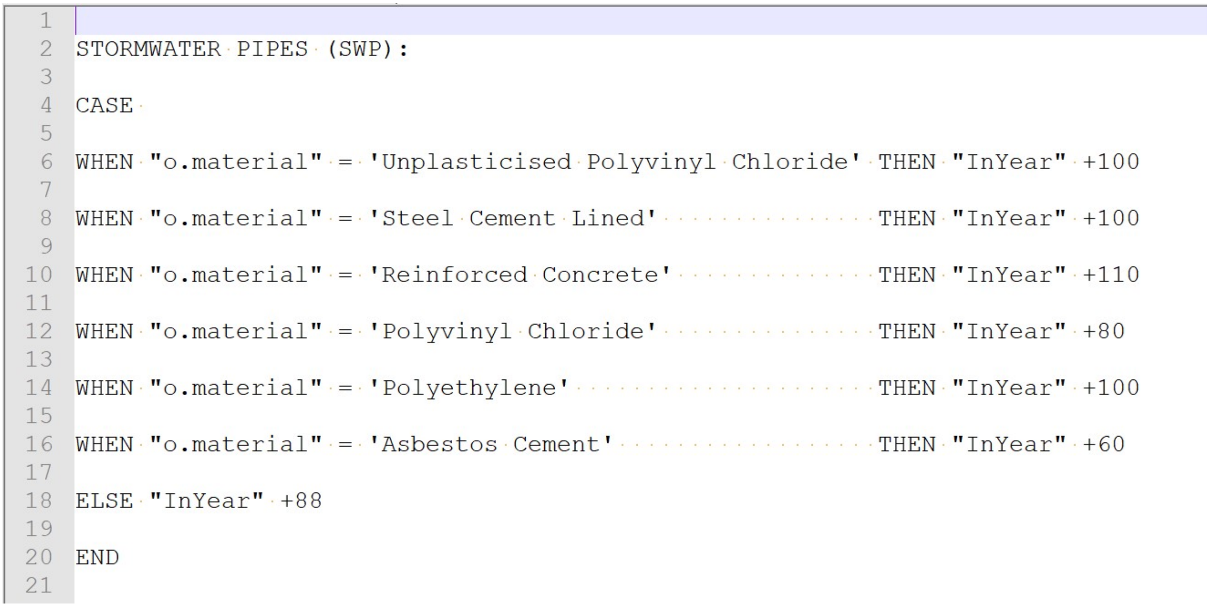


*Figure 11: Model Flow Asset Prioritization*

Pipes *(SWP, SWCP and WWP)*

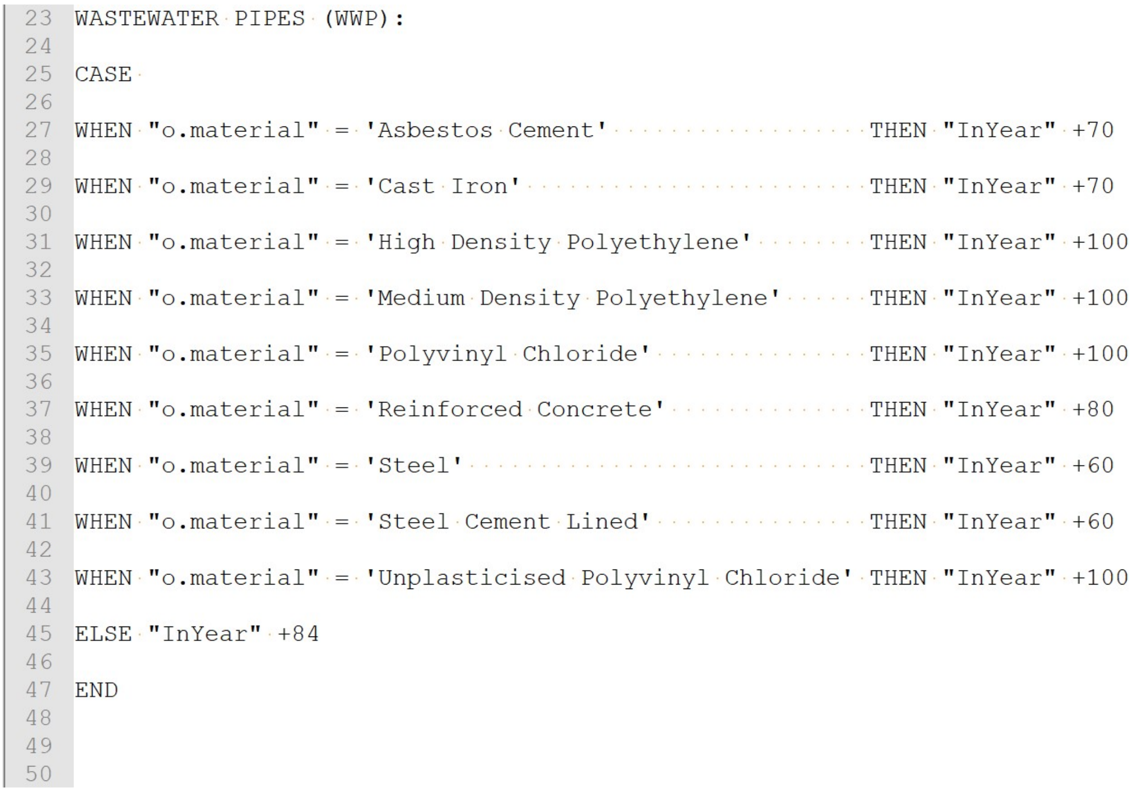
The output for SWP and WWP provides the opportunity to show expected replacement years. In order to do this the instalment date in the attribute data was converted to instalment years. Since it is based on average lifetime spans of the pipe assets this will only lightly affect the level of detail overall.



```

STORMWATER PIPES (SWP):

CASE 

WHEN "o.material" = 'Unplasticised Polyvinyl Chloride' THEN "InYear" +100

WHEN "o.material" = 'Steel Cement Lined'               THEN "InYear" +100

WHEN "o.material" = 'Reinforced Concrete'              THEN "InYear" +110

WHEN "o.material" = 'Polyvinyl Chloride'               THEN "InYear" +80

WHEN "o.material" = 'Polyethylene'                     THEN "InYear" +100

WHEN "o.material" = 'Asbestos Cement'                  THEN "InYear" +60

ELSE "InYear" +88

END

```

*Figure 12: Expected Asset Lifetime SWP*

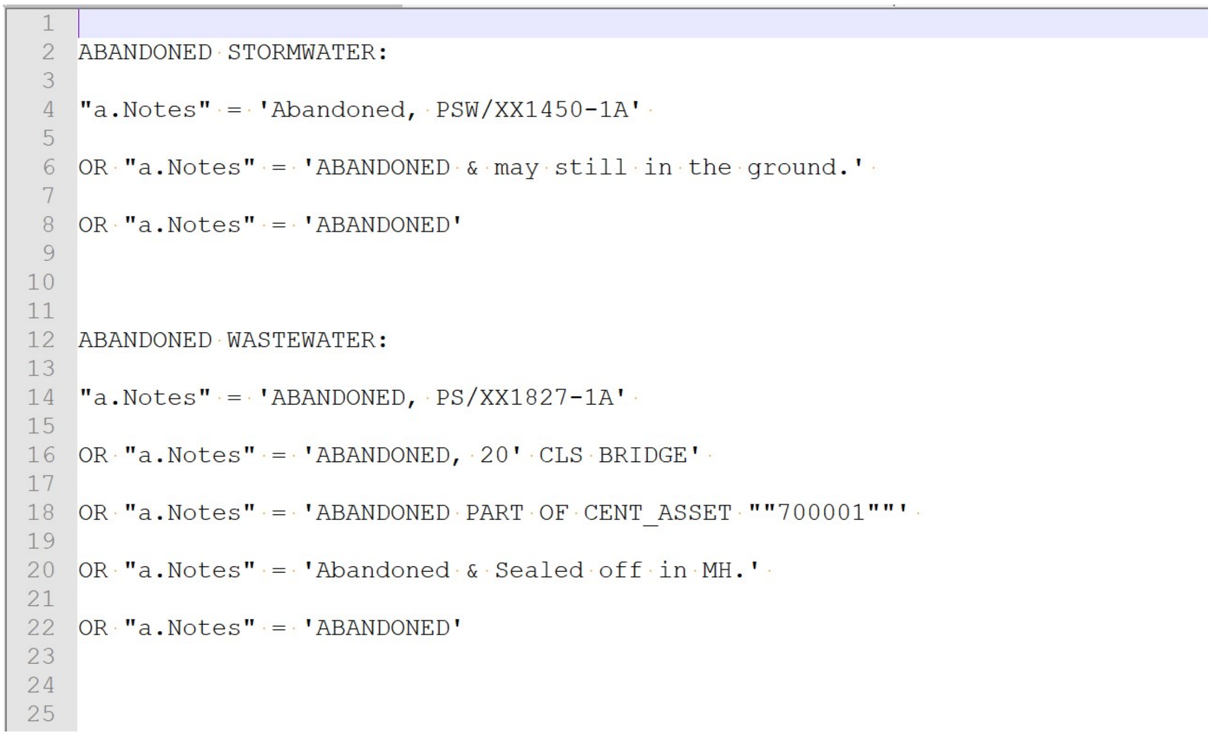
After this the individual lifespans will be added based on the material of the pipe. If there was no material specified, the average lifespan per material for either SWP or WWP was added to the instalment date, Figure 12 and Figure 13. Data was provided by Wellington Water.



```
WASTEWATER PIPES (WWP):

CASE 

WHEN "o.material" = 'Asbestos Cement'                  THEN "InYear" +70

WHEN "o.material" = 'Cast Iron'                        THEN "InYear" +70

WHEN "o.material" = 'High Density Polyethylene'        THEN "InYear" +100

WHEN "o.material" = 'Medium Density Polyethylene'      THEN "InYear" +100

WHEN "o.material" = 'Polyvinyl Chloride'               THEN "InYear" +100

WHEN "o.material" = 'Reinforced Concrete'              THEN "InYear" +80

WHEN "o.material" = 'Steel'                            THEN "InYear" +60

WHEN "o.material" = 'Steel Cement Lined'               THEN "InYear" +60

WHEN "o.material" = 'Unplasticised Polyvinyl Chloride' THEN "InYear" +100

ELSE "InYear" +84

END



```

*Figure 13: Expected Asset Lifetime WWP*

Abandoned datasets for both SWP and WWP were removed using the function ‘remove by attribute’. Unfortunately, the notation in the attribute data was inconsistent, and a line had to be added for each type not in the asset data. The notation for both Stormwater and Wastewater assets can be seen in Figure 14.



```

ABANDONED STORMWATER:

"a.Notes" = 'Abandoned, PSW/XX1450-1A'

OR "a.Notes" = 'ABANDONED & may still in the ground.'

OR "a.Notes" = 'ABANDONED'



ABANDONED WASTEWATER:

"a.Notes" = 'ABANDONED, PS/XX1827-1A'

OR "a.Notes" = 'ABANDONED, 20' CLS BRIDGE'

OR "a.Notes" = 'ABANDONED PART OF CENT_ASSET ""700001""'

OR "a.Notes" = 'Abandoned & Sealed off in MH.'

OR "a.Notes" = 'ABANDONED'



```

Figure 14: Attributes to remove Abandoned Assets

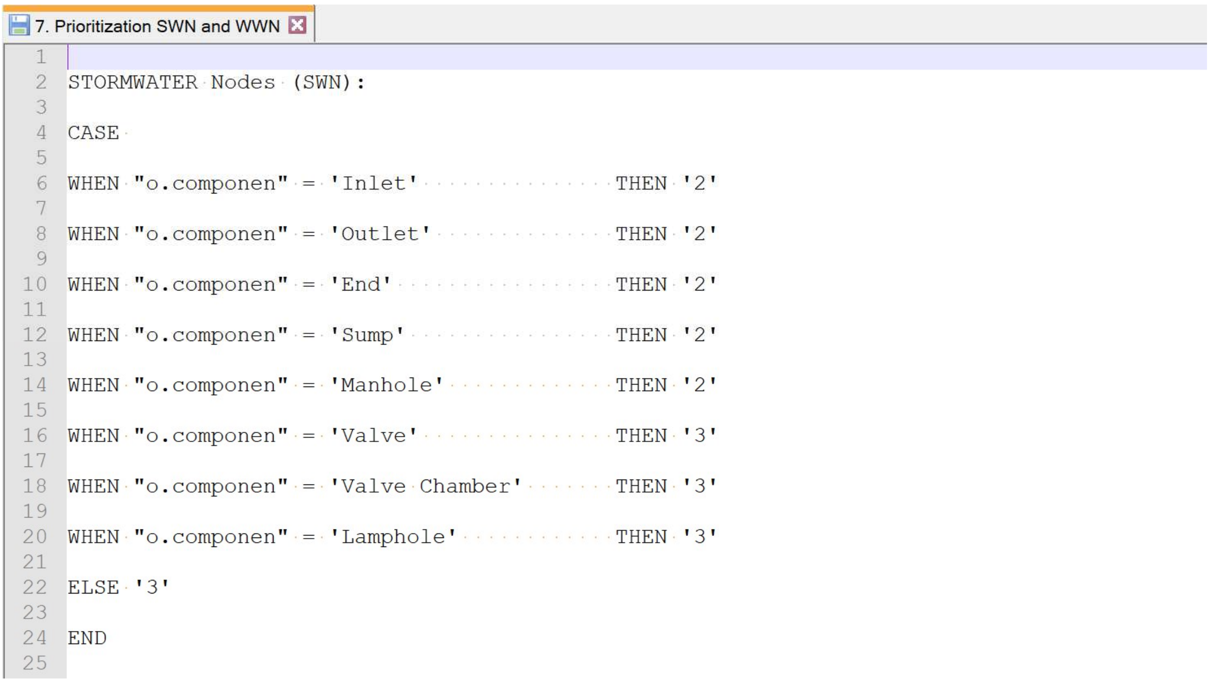
Finally, for SWP and WWP the priority will be added. This will be done based on priorities given in table 1 and table 2. An example of the script added to the QGIS model builder can be found in Figure 15, with corresponding attribute priorities per asset.

```

STORMWATER PIPES (SWP) PRIORITIZATION:

CASE

WHEN "o.componen" = 'Discharge'    THEN '1'

WHEN "o.componen" = 'Sump Lead'    THEN '2'

WHEN "o.componen" = 'Main'         THEN '2'

WHEN "o.componen" = 'Rising Main'  THEN '2'


ELSE '3'

END



```

Figure 15: Prioritization SWP

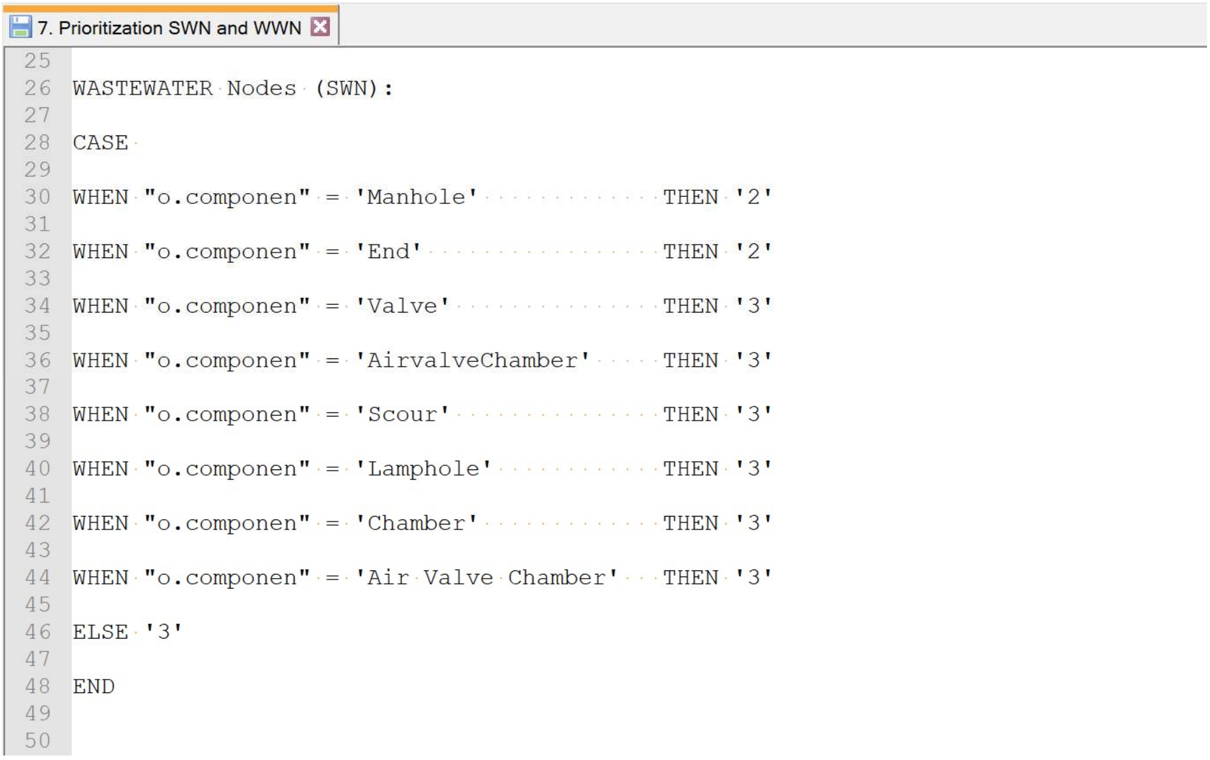
### Nodes and Pumps

As described in Table 3, for normal nodes and pumping stations the priority was added. These are as described in Table 1 and Table 2. For the stormwater nodes there was a possibility to remove abandoned datasets also, as this was provided in the attribute table. The output gives the option to visualize the exposed asset, per SLR increment, per Priority. Figure 16 and Figure 17 give the priorities added to the QGIS model corresponding with Table 1 and Table 2.



```
STORMWATER Nodes (SWN):

CASE

WHEN "o.componen" = 'Inlet'               THEN '2'

WHEN "o.componen" = 'Outlet'              THEN '2'

WHEN "o.componen" = 'End'                 THEN '2'

WHEN "o.componen" = 'Sump'                THEN '2'

WHEN "o.componen" = 'Manhole'             THEN '2'

WHEN "o.componen" = 'Valve'               THEN '3'

WHEN "o.componen" = 'Valve Chamber'       THEN '3'

WHEN "o.componen" = 'Lamphole'            THEN '3'

ELSE '3'

END
```

Figure 16: Prioritization SWN



```
WASTEWATER Nodes (SWN):

CASE

WHEN "o.componen" = 'Manhole'             THEN '2'

WHEN "o.componen" = 'End'                 THEN '2'

WHEN "o.componen" = 'Valve'               THEN '3'

WHEN "o.componen" = 'AirvalveChamber'     THEN '3'

WHEN "o.componen" = 'Scour'               THEN '3'

WHEN "o.componen" = 'Lamphole'            THEN '3'

WHEN "o.componen" = 'Chamber'             THEN '3'

WHEN "o.componen" = 'Air Valve Chamber'   THEN '3'

ELSE '3'

END
```

Figure 17: Prioritization WWN

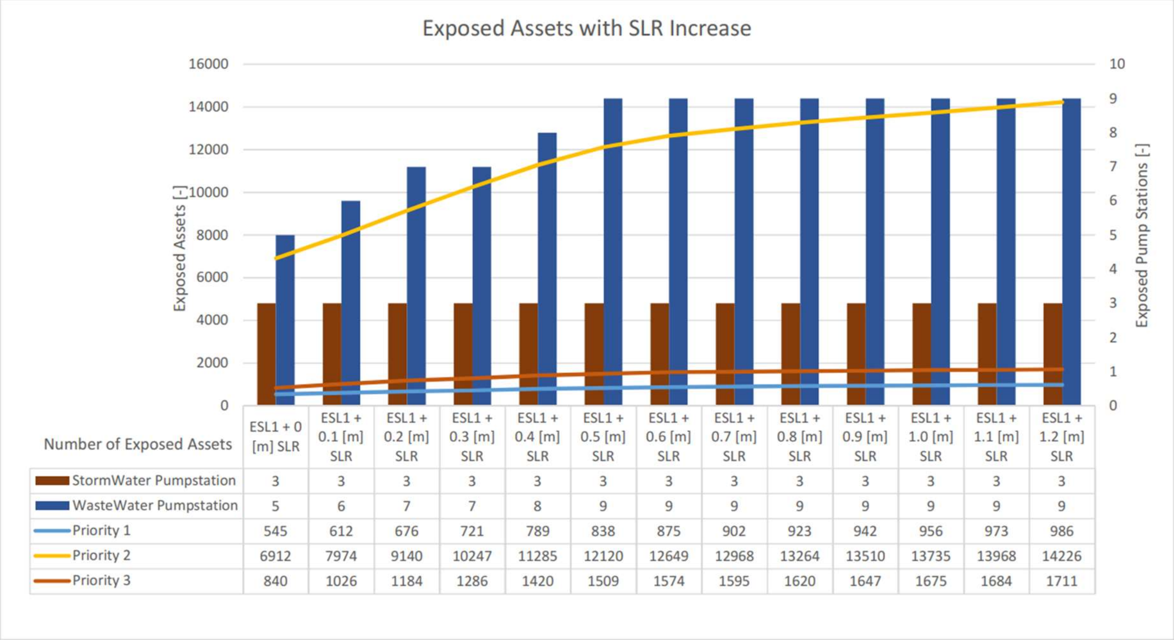
## 4.3. Exposure Results

Due to the project timeframe there is only limited possibility to quantify the priorities of all assets, however it is still possible to give a valid indication. As stated before, the assets from various input sources were therefore divided into three priorities, priority 1, priority 2 and priority 3. The aim is to assess, at a high level, what assets in the system are exposed at each SLR increment.

### Asset Exposure

Figure 18 shows the number of exposed asset per SLR increment. The left y-axis displays the total amount of assets, the right y-axis displays the amount of Pumping stations exposed. The bar charts represent the pumping stations, the line charts represent the total number of assets with different priorities. As stated before, the aim is to identify thresholds based on SLR scenarios, as opposed to time-based thresholds.

As can be seen in Figure 18, there is a steep increase in priority 2 assets in the area until around +0.50 *m*, +0.60 *m,* after which the increase in exposed assets per SLR increment starts to flatten out. A similar curve can be observed for priority 1 and priority 3 asset, albeit in smaller numbers. The next section will go more into detail on the geographic location of asset exposure per increment.



| Number of Exposed Assets | ESL1 + 0 [m] SLR | ESL1 + 0.1 [m] SLR | ESL1 + 0.2 [m] SLR | ESL1 + 0.3 [m] SLR | ESL1 + 0.4 [m] SLR | ESL1 + 0.5 [m] SLR | ESL1 + 0.6 [m] SLR | ESL1 + 0.7 [m] SLR | ESL1 + 0.8 [m] SLR | ESL1 + 0.9 [m] SLR | ESL1 + 1.0 [m] SLR | ESL1 + 1.1 [m] SLR | ESL1 + 1.2 [m] SLR |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| StormWater Pumpstation | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| WasteWater Pumpstation | 5 | 6 | 7 | 7 | 8 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| Priority 1 | 545 | 612 | 676 | 721 | 789 | 838 | 875 | 902 | 923 | 942 | 956 | 973 | 986 |
| Priority 2 | 6912 | 7974 | 9140 | 10247 | 11285 | 12120 | 12649 | 12968 | 13264 | 13510 | 13735 | 13968 | 14226 |
| Priority 3 | 840 | 1026 | 1184 | 1286 | 1420 | 1509 | 1574 | 1595 | 1620 | 1647 | 1675 | 1684 | 1711 |

*Figure 18: Asset Exposure under SLR, right y axis represents Pumpstation exposure*

Three out of four stormwater pumping stations are, using this static hazard approach, all immediately inundated at a current 1% AEP event. Since the location of these are inland from the coast, this might be a conservative estimation. Wastewater pumping stations are incrementally exposed until around +0.50 m SLR combined with the present day 1% AEP storm tide level. Since they are key to running the system now and adapting it to future challenges, a conservative estimation would still be valid. How representative this static hazard exposure was verified at the workshop.

### Preliminary Threshold Visualization

Based on the graph in Figure 18, some increments were chosen as 'Thresholds' to see where the greatest number of assets are affected at that SLR increment. Based on Figure 18, the aim is to find an increment where either there is an increase in Priority 1 assets exposed, or a large number of Priority 2 assets being affected, since there is a steep increase in assets affected until around +0.50 m, and then the number of affected assets eases off. Every increment in SLR where there was another increase in Pumping stations exposed, was also taken out. This results in Thresholds at +0.10 m, +0.20 m, +0.40 m, and+0.50 m in association with the present day 1% AEP storm tide level. The threshold label will then be added to each asset that has becomes 'exposed' at this SLR increment, so that this group can be isolated, selected and excluded for each threshold. The QGIS model in Figure 19 was used to achieve this, where the output is the density of exposed assets at the threshold.

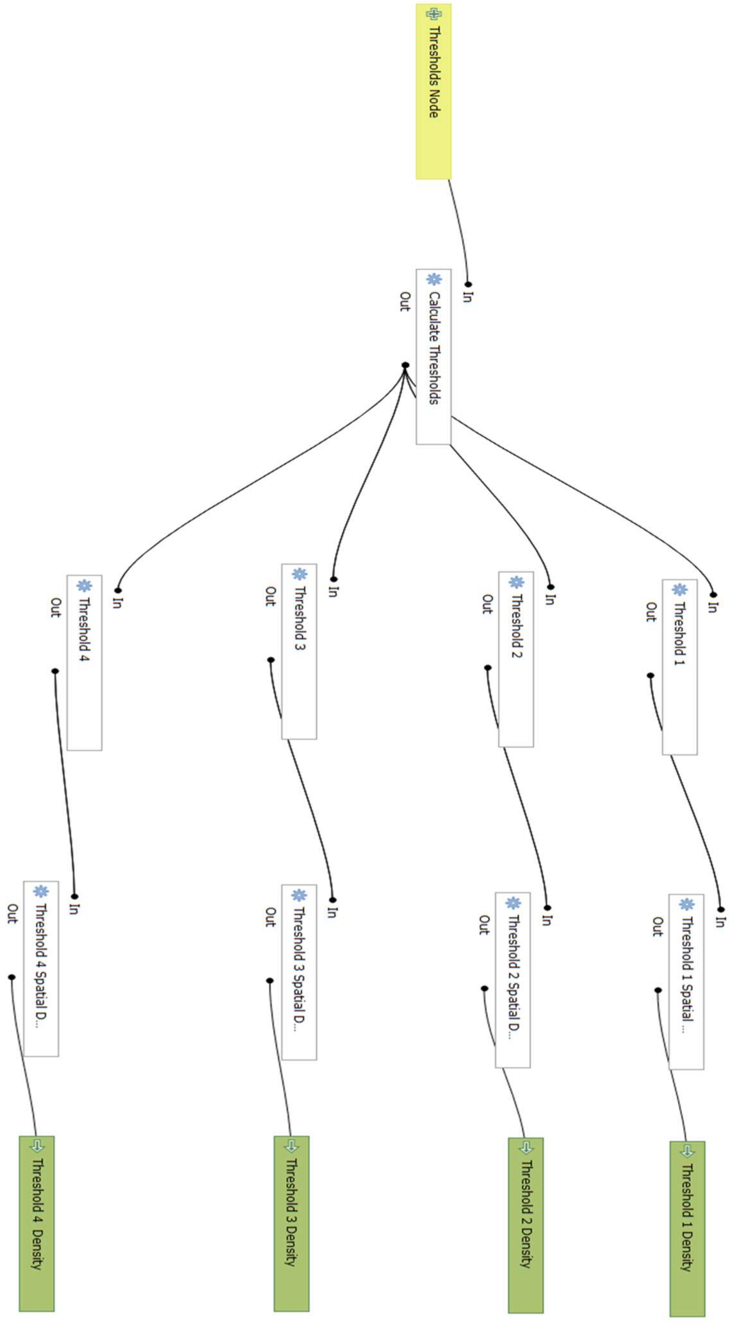


*Figure 19: Model to output Asset Exposure Density per Threshold*

The output for a current 1% AEP event can be seen in Figure 20. The algorithm used to produce this ‘heatmap’ is a Kernel Density Estimation. It interpolates between different points, and provides a value based on the occurrence of points in the proximity of an area. Although this produces non-quantifiable values, it is very effective in pinpointing a high occurrence of points, or in this case, assets. Given the high level nature of this assessment and the considerable number of datapoints in the asset datasets, this is a good representation of where asset exposure happens at different thresholds.

It can be seen in Figure 20 that during a present day 1% AEP event, there is a high density of assets exposed in the west lower side of the Petone area, between the two wastewater pumping stations. The reason for higher occurrence around the pumping stations was due to the increased amount of asset components in and around the pumping station. The other increased density areas was due to a high occurrence of wastewater assets. Comparing this to a present day 1% AEP event with 0.50 *m* SLR, which can be seen in Figure 21, it becomes clear that throughout the different thresholds, intensification of asset exposure occurs in these areas. This is an important observation, as it provides an indication of where to focus a closer examination of assets located in that area in terms of compartmentalizing or replacement. Furthermore, it becomes clear that intensification of hazard exposure occurs in the slightly elevated area behind the Esplanade, where the main wastewater pipes and wastewater pumping stations are located.

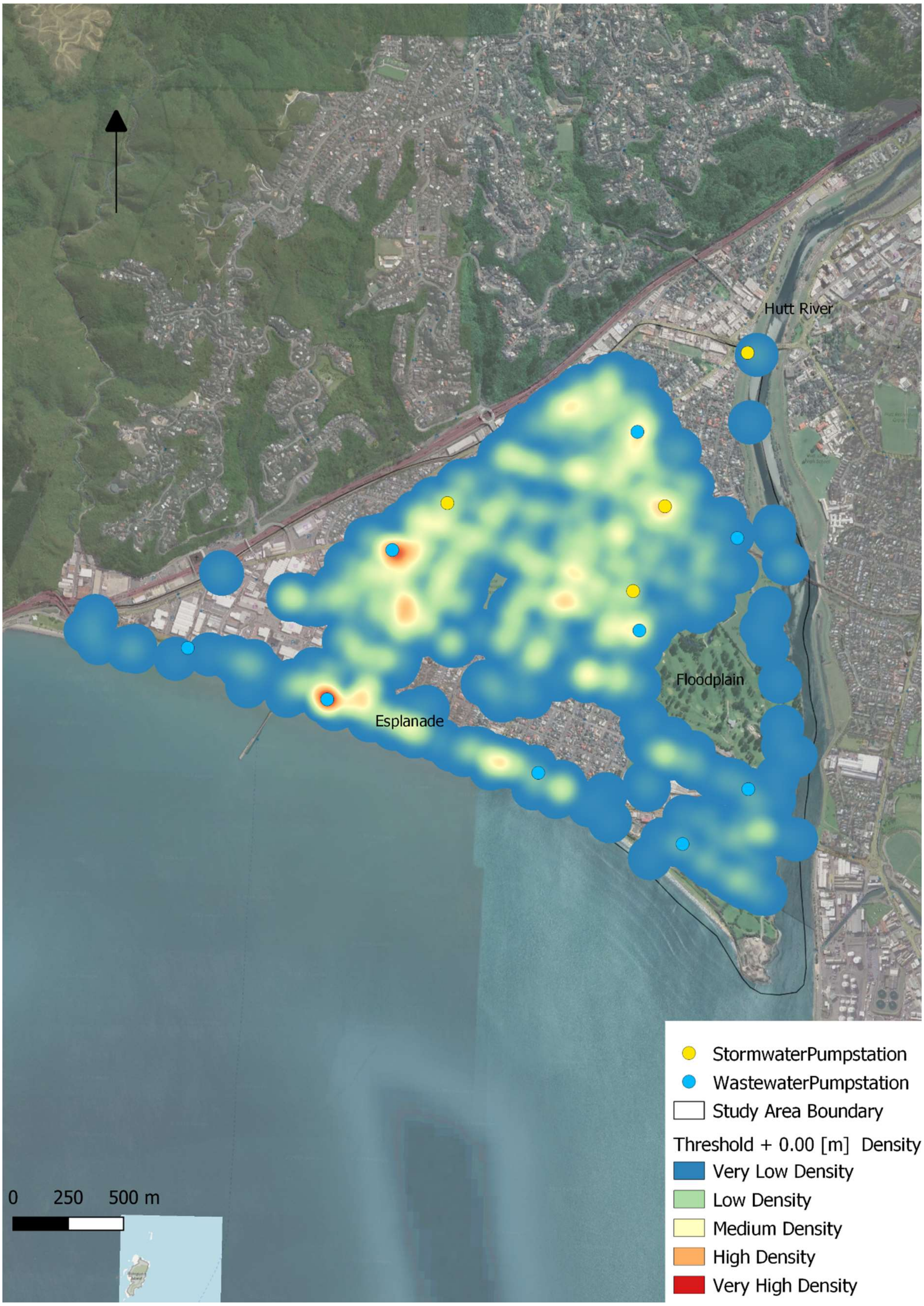


*Figure 20: Density of Exposed Assets at 1% AEP +0.00 [m] SLR*

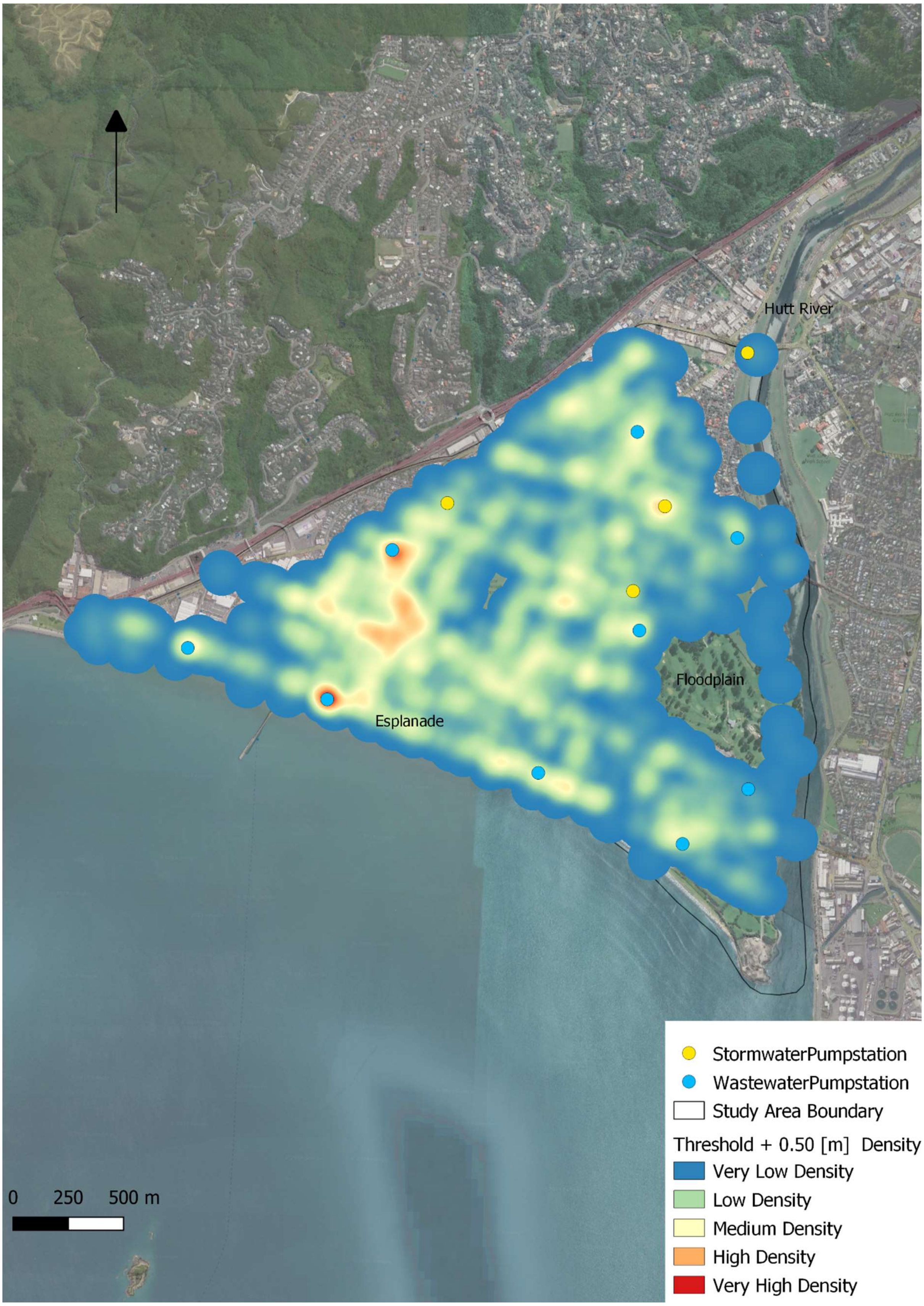


*Figure 21:Density of Exposed Assets at 1% AEP +0.50 [m] SLR*

### Opportunities

In the model of Figure 11, there is some extra data added in the attribute table for SWP and WWP. These are the average lifespans per asset type, as explained in Figure 12 and 13. This gives an opportunity to examine areas where pipe replacements are expected to be due. Also the location of remaining asbestos pipes can be examined.

#### *Replacements due*

For looking into coincidence of affected assets and SLR increments, for as far as this is possible, replacement values were calculated based on average lifespans of assets provided by Wellington Water. Occurrence can be seen in Figure 22, which corresponds with the geographic location in Figure 23. Figure 22 shows that a significant number of replacements were due in the mid 1990's through to the mid 2000's. There are lower number due in the next three decades with peaks starting after the 2060's. It should be noted that replacement of pipes does not occur based on asset life expectancy. Assets are not removed preventively. They are removed based on evaluation during inspection schedules, and when performance is compromised. It does however give a good indication of when to expect replacements to occur in the coming decades.

Figures 20 and 21 show a coincidence of pipes that were expected for replacement (red / orange) and the area where intensification of assets have occurred. This also is valid for intensification of exposed assets behind the Esplanade, which is starting to occur at the +0.50 m SLR scenario in Figure 21. When starting to think about adaptation options, or partial retreat, this would be an area to consider. Some considerations to be taken into account are Figure 23 also shows that some of the newest pipes are *also located* in this increased density area, while replacement intervals from 2060's to 2100's are mostly located in Alicetown.

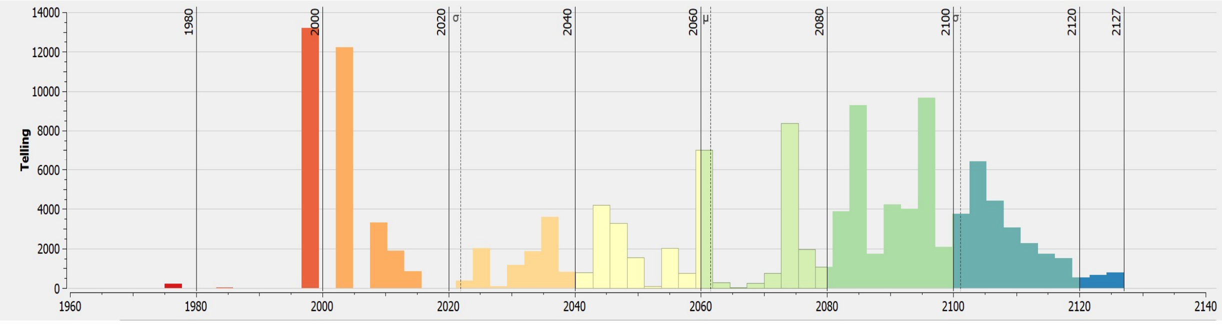


Figure 22: Replacement dates in SWP and WWP

#### *Asbestos Replacements*

Figure 24 shows the location of asbestos pipes. There is some coincidence with the area mentioned in the previous section, but the asbestos pipes are located mainly along the Esplanade. This is the main Petone wastewater collection sewer discharging towards the WWTP. There is no date that these assets have to be removed from the ground by Wellington Water (noting that no new asbestos pipes are being used as they are unlikely to be harmful when buried underground, rather they can become a hazard during replacement, e.g. cutting of the pipe). Should they be replaced, this would provide an opportunity to consider retreat or redesign of the system.

*Figure 23: Expected Replacement dates WWP and SWP*

*Figure 24: Location of Asbestos Pipes*

## 4.4. Adaptation Outline

This section outlines and discusses general adaptation options in preparation for the next phase which addresses the sequencing of the components of an eventual managed retreat (Olufson, 2019). For example, the short term actions and long term options and what types of options are available, are discussed and coastal hazard response types are adapted and used as a frame to fit the urban/coastal environment, as can be seen in Table 5.

For adaptation options in general, Butler, D., Digman, C., Makropoulos, C., & Davies, 2018 proposes the following considerations:

- Minor system, reduce or limit inflow (SUDS to infiltrate locally) or divert flows
- Minor system, Increase Capacity, e.g. improved cleaning or pipe upsizing
- Minor/Major system, store more flow therefore attenuate and reduce peak flow rates, storage can be provided in the minor or major system
- Major system, better deploy surface flow features
- Improved building flood resilience

Figure 25 shows differences in runoff rate *Q* for different environments. It can be seen that rural environments have a more consistent runoff rate whereas urban environments have a peak flow in runoff. This is undesirable, as sewers and pumps would have to be increased in capacity to deal with peak discharges for short times and are working under capacity for most of the operation time. This concept can also be applied to increases in hazards due to climate change. Increased rainfall, higher GWL levels and possible flooding of critical infrastructure will increase chances of encountering these peak discharges. The aim is therefore to look for ways to 'shave off' this peak discharge. This can either be done by 'delaying' part of the discharge to make sure that the runoff enters the system later (e.g. green roofs, swales), increasing storage capacity (retention basins, (sub) surface constructed wetland flows) or increasing capacity of the system (increase pipe and pump capacity).

These solutions can be implemented in tandem with managed retreat, or as pre-retreat options to keep L.o.s. acceptable until (partial) retreat occurs. The next phase of the project will start to investigate these options, combined with input from the workshop. Table 4 shows a general outline of the adapted framework of coastal hazard adaptation options.

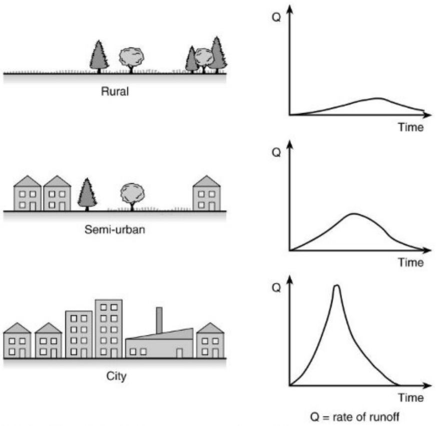


*Figure 25: Differences in peak runoff in different environments, adapted from (Butler, D., Digman, C., Makropoulos, C., & Davies, 2018).*

*Table 5: General Adaptation Options SW and WW*

| Stormwater Equivalent Planning Responses | | |
|---|---|---|
| **Adaptation** | **Two Water Adaptation** | **Options** |
| No Response | No Response | Treat emerging threats |
| Protect | Isolate and protect assets | -Stop banks protecting assets<br>-Isolate and protect high value assets, e.g. raise/water proof pumping stations<br>-Isolate outputs to protect from increases in Ground water due to SLR and pump excessive water out |
| Accommodate | Increase Capacity | -Replace pipes<br>-Lift system outlets<br>-Lift house systems<br>-Increase pumping capacity<br>-Increase pressurized systems<br>-Porous road paving |
| Advance | Polder | -Decrease groundwater table, decrease saltwater intrusion |
| Retreat | Retreat | -Sectoral retreat<br>-Compartmentalize system, allowing for intermediate retreat options, creating opportunities other adaptation options, e.g. storage facilities |
| Ecosystem-based adaptation | Increase Natural adaptive capacity (SUDS) | Delay Facilities<br>-Green Roofs<br>-Natural Parks<br>-Blue solutions<br><br>Storage Facilities<br>-surface flow constructed wetlands<br>-detention ponds / basins<br>-sub surface flow constructed wetlands<br>-extended detention basins<br>-lagoons<br>-retention ponds / basins<br>-sedimentation tanks |
| | | |

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# C Appendix 3

# Appendix 3

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## Adaptation Options for Managed Retreat

# Contents

# 1. Theoretical Background

An investigation into the literature on coastal adaptation was done in order to inform the relevant adaptation options to form pathways in an adaptive framework. This supplements the optioneering in the workshop as well as ensuring no options are overlooked in this stage of the project. Sea level rise (SLR) is going to affect the urban drainage system. It is clear that there will be adverse effects, like water getting into the outlet pipes decreasing the drainage capacity, the effects of inundation, salt water intrusion and flooding problems. However, the exact effect on a local area is seldom clear.

In the project plan there was already background on managed retreat literature, however it was important that there was a stronger background on specifically retreat of two water infrastructure, and how this is planned. It is not expected there are going to be any revolutionary new techniques available to implement this. Rather existing adaptation options working in tandem with managed retreat depending on the threshold established and lead times associated. This is why there will also be additional investigation into Sustainable urban drainage systems (SUDS) and Water Sensitive Design, as combining implementation of these could be useful.

### Urban Drainage SLR interaction

The adverse effects of sea level rise on the Petone urban drainage system will be described and discussed in chapter 4, where it was discussed during the workshop with stakeholders involved with two water infrastructure of the area. With regards to international literature, most of the studies either look into the spatial extent as a result of wave overtopping and the flooding of the pipes and nodes in the drainage system as a combined result (Gallien, Sanders, & Flick, 2014; Kulkarni, Eldho, Rao, & Mohan, 2014) or the effect of groundwater interaction with the drainage system in coastal areas (Archetti, Bolognesi, Casadio, & Maglionico, 2011; Su, Liu, Beheshti, & Prigiobbe, 2019). What we are looking for is the influence of sea level rise on the *performance* of current two-water infrastructure drainage systems. This includes stormwater drainage systems and the wastewater network excluding wastewater treatment plants (WWTP's). These studies are mostly done as a case study, as adaptation occurs at specific local scales relevant to the systems in place and the community they service.

The spatial extent of flooding in an urbanized coastal area is still a relevant topic to this research as SLR exacerbates these effects and more frequent inundation of the drainage system is to be expected. Gallien, Sanders, & Flick, 2014 found that a coastal drainage system actually reduces the spatial extend of flooding, on the condition that it is not running at capacity, it does not investigate the consequences on the urban drainage system of the high quantities of saline water entering the system. It also stresses the importance of avoiding static inundation models in favour of hydrodynamic models. Since a static bathtub inundation model is used in the exposure analysis for the study area, this is validated during the workshop, as discussed in chapter 4.

Su et al., 2019 investigates the relationship between infiltration in an aging urban sewer system and groundwater flooding in a coastal area. It concludes that when the pipes in the system are not repaired, there is an increased discharge of untreated sewage due to CSO overflow. Upon repair however, the water table rises resulting in groundwater floods, especially in coincidence with high tide. This is expected to increase due to SLR. This confirms the basis of discussion in the exposure assessment. A more comprehensive solution has to be looked into as opposed to not fixing the pipes, as this also brings along a range of negative consequences.

Joyce, Chang, Harji, Ruppert, & Imen, 2017 investigated the effect on green and grey drainage infrastructure under catchment rainfall runoff in combination with a hightide, and the effects of sea level rise with the aim to improve drainage infrastructure residence to coastal hazards. Green infrastructure is in this scenario described as low impact developments, LID's. These are adaptation solutions or SUD's for the drainage system like water detention ponds. It concludes that due to rise in the ground water levels as a result of SLR, LID's that increase imperviousness could result in increases in the local groundwater table. It does offer a reduction in peak flow aiding traditional grey infrastructure in the system. The increase found in the local groundwater table are an important consideration for implementation in the Petone area, as this is projected to be one of the main issues. Addressing peak discharge but stimulating the problem of increased groundwater levels by implementing these options in the wrong areas is not a desirable scenario.

Hu et al., 2019 investigates flood risk in Shanghai looking into three uncertainty factors, precipitation, the urban rain island effect and decrease in urban drainage capacity. This decrease in capacity resulting from land subsidence and sea level rise. It concludes that the model shows the decrease in drainage capacity caused by land subsidence and sea level rise will have the most significant contribution to inundation risk in Shanghai. This confirmed the observations from an extreme inundation event in 2015 where the high water level in the river prevented the drainage system to pump the excess in rainwater into the river. It therefore suggests taking this increase in water level into account when designing the drainage capacity.

Wdowinski, Bray, Kirtman, & Wu, 2016 discuss the influence of flooding hazards due to SLR in Miami. It acknowledges the lack of coastal hazard studies looking into flooding induced by rainfall, due to SLR decreasing the capacity of drainage systems as they are gravity based. Whereas traditionally been caused by heavy rain or a storm surge, there has been an increase in flooding frequency due to tide induced flooding. It was found that due to the reduced capacity in urban drainage as a result of SLR, the frequency of rain-induced flooding increased by 33%. In order to adapt, Miami beach switched to a pump-based system (Wdowinski et al., 2016).

Another study into Florida developed an adaptation toolbox for water, wastewater and stormwater utilities (Bloetscher, Heimlich, & Meeroff, 2011). Additionally, the adaptation options are outlined with triggers and costing scenarios. This gives a good input in outlining the adaptation options for the two water infrastructure. It is also discussed that increased groundwater levels due to SLR decreases storage capacity in the soil, compromising flow capacity of stormwater and coastal structures, where pumping stations will have to be installed to reduce ponding (Bloetscher et al., 2011).

Specific effects of sea level rise on wastewater infrastructure is discussed in (Friedrich & Kretzinger, 2012). It discusses the vulnerability of wastewater infrastructure like pipelines, manholes and pumping stations in a coastal area of South Africa, thereby drawing parallels to the exposure assessment of the Petone area. It also illustrates that to minimize the amount of pumping required, centralized parts of the wastewater system like WWTP's have been implemented in lower lying areas, creating a legacy effect as they are significantly more vulnerable to SLR in coastal areas. It also acknowledges the problems discussed in (Bloetscher et al., 2011; Wdowinski et al., 2016) that the change in sea level reduces the hydraulic gradient of the system, effectively reducing the natural capacity of the system. This increases siltation in the pipes (Friedrich & Kretzinger, 2012). In addition it also discusses the increased salinity in the groundwater, which gets in the manholes and pipes. Upon reaching the WWTP, this increased salinity can cause damages in the WWTP, as it is not adjusted to this increased salinity. The study also differentiated between different components in the system, giving pumping stations and treatment plants a higher priority, as done in the exposure assessment. The reasoning for this was that these pumps create the hydraulic head for the system, therefore when affected or exposed can have major impact on the system (Friedrich & Kretzinger, 2012).

Schoen et al., 2015 investigates the resilience of different wastewater system setups under a range of hazards. Out of these hazards, or challenges, Storm with increased surge and SLR were the most relevant to the hazards investigated in this research. It concluded that the results were similar for storm surge and SLR, and therefore only results for storm surge were presented. The options considered were a traditional, centralized potable& wastewater system, a system with composting toilets and on site grey water reuse with septic tank, a system with onsite treatment of solids, and a system with a pressure sewer. It was concluded that all systems were vulnerable to this, however it was found that greywater reuse and a blackwater pressure sewer were the most robust due to less environmental contamination during extreme events (Schoen et al., 2015).

Almeida & Mostafavi, 2016 found a considerable amount of interdependencies and cascading effects from SLR on different types of coastal infrastructure. They found that SLR can lead to sewage backup in septic tanks and conveyance pipes due to increase in GWL. Impacts from SLR were found to be higher water tables and reduced soil storage capacity, in turn resulting in increased frequency and severity of flooding due to precipitation (Almeida & Mostafavi, 2016). It also acknowledges increased corrosion due to increases in groundwater salinity, increased inundation on WWTP's placed in low areas to minimize required pumping, sewage overflow or backup due to decreased drainage capacity and increased tides influencing buried infrastructure (Almeida & Mostafavi, 2016).

Stancu, Cheveresan, Zaharia, & Poienariu, 2017 investigates climate change adaptation for Bucharest. SLR effects are not investigated since Bucharest is not located at a coastline, however increases in groundwater levels due to increased precipitation and snow melting (Stancu et al., 2017). It also states that increases in these water levels can have back water effects and reduce discharge capacity of the drainage system due to reduction in hydraulic capacity. It can also increase pressure on the WWTP's. It proposes for the solutions space to either discharge or store increased discharge until the system is normalized, three main categories of adaptation options, minimize the volume of runoff entering the collection system, increase transport capacity or storage capacity of the drainage system (Stancu et al., 2017).

## Managed Retreat Components

Preceding research has been done in order to identify different managed retreat approached. A recent thesis project by (Olufson, 2019) looked into recent examples of managed retreat, albeit with an economic focus, in order to identify what kind of components would be included in managed retreat, how would they be sequenced depending on the approach taken by the government and how these different components could be grouped. The following grouped components were identified

- Community Engagement, engagement and consultation on adaptation options and managed retreat implementation
- Planning and Preparing, Planning / rule changes, planning for reduces Los and development restrictions on at risk areas, monitoring and establishing trigger points
- Enabling Investment, Property acquisition, New community investment in the form of alternative land for relocation and development of new community facilities, Public infrastructure L.o.S. reduction and maintenance reduction
- Active Retreat, Public Infrastructure Relocation (Replacement/redevelopment of public infrastructure elsewhere, relocation of critical facility structures and relocation of community facilities), Privately Owned Infrastructure Relocation (Private companies begin to reduce/remove/relocate infrastructure and covenants on property are activated), Private property relocation and abandonment (relocation/abandonment of residential and commercial property and providing temporary housing), Removal of marine structures
- Cleanup, demolition, land rehabilitation and maintenance

These component groupings are a useful typology for approaching implementation of managed retreat, and sequencing options and actions. As stated before it is unlikely there will be any new options but the adaptive pathways approach for the two-waters systems is novel. Pathways will be a mix of traditional and WSUD adaptation options placed in these different managed retreat component stages. This also includes opportunities for re-purposing areas after the retreat of community housing.

There is limited literature available on sequencing of urban drainage while retreating from the coastline. Combing adaptation options for urban drainage with managed retreat typology gives a start on this. During the workshop the implementation times and adaptation options will be discussed. Some background on this will be key in order combine this and start looking into adaptive approaches.

## Water Sensitive Urban Design (WSUD)

Water sensitive urban design (WSUD) is: ''an integration of urban planning with management, protection and conservation of the urban water cycle, that ensures that urban water management is sensitive to natural hydrological and ecological processes'' (Wong, 2015). Whereas it traditionally was associated with stormwater management, it now integrates management of the urban water cycle into urban design (Wong, 2015). It therefore offers adaptation options that are also interesting for this study. Lloyd, Wong, & Blunt, 2015 look into applying the WSUD framework to Melbourne, as it is considered a forerunner of WSUD implementation, and acknowledge that many of its early implementation has been demonstrative and ad hoc.

(Wong, 2015) considers three implementation scales, being local, precinct and regional scale. For the cause of this research, the options for stormwater quality and detention will be considered. On the local scale, these include on-site infiltration, porous pavements, sand filters, bioretention planters, raingardens, vegetated buffers and on-site detention. On a precinct scale these are infiltration basins, porous pavement, sand filters, bioretention swales, bioretention basins, vegetated swales, urban forests, constructed wetlands, retarding basins and ponds. On a regional scale these are riparian buffers, natural channels, urban forests, constructed wetlands, retarding basins and lakes (Wong, 2015). Local and Precinct scale options will be the most applicable to the Petone area.

Over the years, these decentralized drainage options have been developed under different names, as also found in literature on adaptations options used in this research. S. M. Lerer, Mikkelsen, Jomo, & Sørup, 2018 looks into the development and timeline of these terminologies and outlines the most important ones. In order to have a better idea of the adaptations options, these will briefly be discussed. SUD, LID, LIUDD and BMP's are using a design with nature, or more natural, approach to stormwater drainage, but over the years have developed into a more holistic approach to integrate into the water system. WSUDS is described as '' philosophical approach to urban planning and design that aims to minimize the hydrological aspects of urban development on the surrounding environment (Fletcher et al., 2015).

Different definitions are given to these new stormwater management techniques include water sensitive design (WSUD), sustainable urban drainage systems (SUDS), stormwater best management practices (BMP's), green infrastructure (GI) and low impact development (LID) (S. Lerer, Arnbjerg-Nielsen, & Mikkelsen, 2015). It also raises the point that since most WSUDS are not buried on the ground like pipes, but are actually integrated into the surroundings, the urban area (S. Lerer et al., 2015). This could actually provide some opportunity for partial retreat, as these retention facilities could be based in the lower part of the drainage system, where partial retreat has occurred and therefore there is space available.

Siekmann & Siekmann, 2015 describes WSUD's as intensified use of surface detention using technical infrastructure, and notes that implementation in urban areas is still rare. The paper suggests that disconnecting drained areas is a first step to prepare drainage systems to climate change. This could also indicate an opportunity for partial retreat. The paper also concludes that these measures are easier to upgrade then traditional sewer systems. This means they have a higher adaptive capacity, which would be an advantage considering the challenges the Petone area is facing.

For stormwater, some of the more common BMP's are detention ponds, wetlands, ponds, biofilters, swales, adsorption filters, infiltration basins, porous pavement, green roofs and settlers (reference lecture). Joyce, Chang, Harji, Ruppert, & Imen, 2017 conclude that in areas affected by SLR, impervious improving solutions like porous pavement could actually increase the rise in the groundwater table, so these might not be very suitable to early exposed asset areas in the Petone Area.

### Adaptation options

Friedrich & Kretzinger, 2012 provides specific adaptation options for wastewater pumping stations, reasoning that increased GWL can directly affect pumping stations since they usually extend underground. The adaptation options suggested are lowering the GWL locally, due to the strategic placement of vegetation around the station, waterproof the underground structure of the pumping station, move electrical system to safe heights and use more corrosion resistant materials and parts. These would fit into either of the categories "protect" and "accommodate". Managed retreat would usually require moving the pumping station to higher ground (Friedrich & Kretzinger, 2012).

Schoen et al., 2015 also provides, in addition to the different options investigated, adaptation options for water services. These include emergency pumps to backup normal pumps, a non-return valve to prevent sewage, and modifying the pump to facilitate overflow to additional storage until the system returns to the normal state (Schoen et al., 2015).

Almeida & Mostafavi, 2016 aims to find adaptation options for different types of coastal infrastructure to SLR, and propose adaptation measures for different types of infrastructure from a survey of existing literature. They also propose adaptation options for retreat of a range of coastal infrastructure. Adaptation options were presented in similar format as the coastal adaptation options, namely protect, accommodate and retreat (Almeida & Mostafavi, 2016). As input for this, research only the adaptation options for stormwater and wastewater will be considered. It defines the categories as following:

*''Protection is to manage the hazards by reducing their likelihood of occurrence, accommodation is to manage hazards by reducing their impacts, retreat is to reduce exposure in a planned manner''*(Almeida & Mostafavi, 2016)

The adaptation category protect is aimed at protecting components for the water treatment from inundation. It is completely aimed however on mitigating wave impact from a flooding even, and only consider protection from flooding like seawalls and coastal marshes / mangroves(Almeida & Mostafavi, 2016). This would not be very suitable for the Petone area, as most impact is expected from the rise in GWL. For accommodate, increasing pumping capacity to reduce sewer backup due to SLR is recommended. Green infrastructure is also recommended like bioswales and raingardens Almeida & Mostafavi, 2016). For retreat, the recommendation is to raise pumping stations and important parts of the system Almeida & Mostafavi, 2016). This is not the same definition of retreat as in this research, and according to the IPCC (2019) this is a form of accomodating the infrastructure.

Bloetscher et al., 2011 developed an adaptation toolbox specifically for Florida, with the aim of being used for other locations also. There is also a time-scenario based approach for these adaptation options, with triggers for implementation and implementation barriers. Interestingly, these also include retreat of large areas of the city. Adaptation options for two water infrastructure include wastewater reclamation and reuse, re-engineering of canal systems, control structures and pumping and septic tank closure (Bloetscher et al., 2011).

Rosenzweig et al., 2007 investigates the adaptation work done for New Yorks City's water systems, therefore also drainage systems. Adaptation options considered for two water are redundant tunnels, alternative storage, a tide gate and increased pumping capacity. It also acknowledges the associated problem of backsurge in the early stages of SLR (Rosenzweig et al., 2007).

Rudberg, Wallgren, & Swartling, 2012 explores adaptations options for wastewater and water supply in the Stockholm region. Adaptation options for implementation, or implementing adaptive decisions, are investing in WW treatment technology, change standards like raising the minimum sewer connection levels, increase stormwater drainage capacity in new developments and change investment programs for renewal (Rudberg et al., 2012). It also emphasizes that a stormwater flooding will mainly have economic consequences, whereas a wastewater failure has both large economic and environmental consequences (Rudberg et al., 2012).

van Roon, 2011 looks into low impact urban design and development principles (LIUDD) in different case studies, outlining various adaptation options (albeit in new developments) that are relevant for this study. Adaptation options found in the case studies include wetlands, re-vegetation, at source stormwater treatment/detention (decentralized system), rain tanks and sewage effluent to water supply by recycling. It stresses that applying these principles are not a box-ticking exercise, and has to be approached in a systematic assessment to ensure relevance (van Roon, 2011).

The city of Rotterdam has developed a comprehensive climate change adaptation strategy, with adaptation options of interest to this study, as outlined in (Rotterdam Climate Initiative, 2013). Different adaptations have been proposed for different urban typologies with Rotterdam. General options can be found in Figure 1.

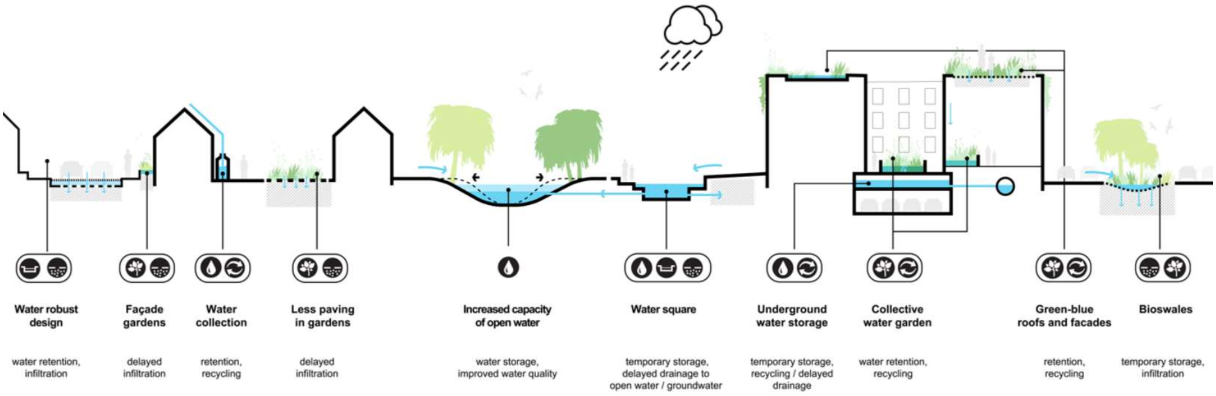


*Figure 1: Adaptation options for Rotterdam, adapted from (Rotterdam Climate Initiative, 2013)*

Adaptations options include dry-proof essential infrastructure, wet-proof (controllable) infrastructure, elevate important infrastructure / raised platforms / small compartment dikes, local rainwater infiltration using SUDS, reinforce dikes, implement tidal park, local floodwalls, water robust streets, collective gardens, water butts/ water squares for temporary storage and local infiltration, green roofs, water storage and reuse, multifunctional dike reinforcement and increased water storage using green solutions.

# 2. System Analysis

The first step in understanding the major components and stakeholder relationships acting in the two water system is setting up a system analysis. ISO 14090 encourages systems thinking to understand the complex, nonlinear and interconnected system the project is set in (Standard, 2019). Mapping boundaries and sub systems help to focus on what is relevant. Recommended way for creating an understanding of components is using the system categories in Figure 2. In Figure 3 the result of the categorizing can be seen.

Background and an example has been taken from a New Zealand specific study looking into cascading effects from a range of different hazards on the different infrastructure sub systems like a stopbank (dike) breach (Extreme event cascade), wastewater (SLR and coastal inundation cascade), stormwater (heavy rainfall cascade), transport systems (climate induced landslides), power &gas (storm event cascade) and water supply (drought cascade) (Lawrence, Blackett, Cradock-henry, & Nistor, 2018).

Note that the cascades for the stormwater and wastewater would be very relevant for the Petone area. The result of these cascades on the infrastructure where then used in conjunction with the CIrcle tool to identify cascading effects for a range of different districts like Christchurch and the Hauraki plains (Lawrence et al., 2018). This will be used as kind of a 'benchmark' making sure no major impacts or components within the system have been overlooked.

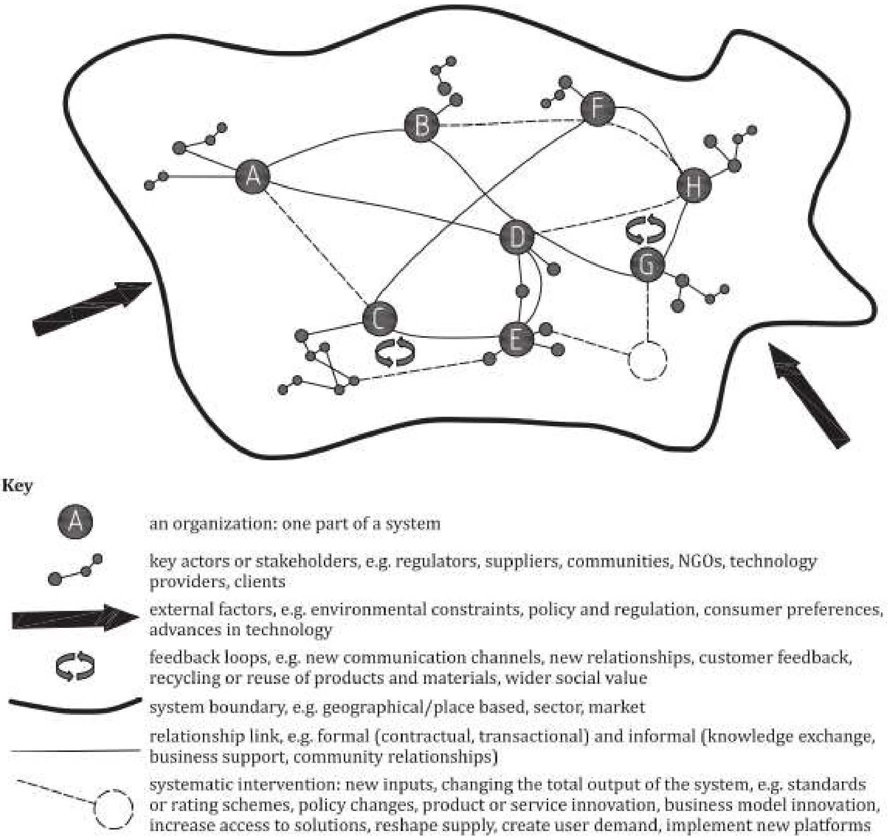


**Figure A.1 — Systems concept showing a general systems concept with interventions highlighted**

*Figure 2: Systems Concept, adapted from* (Standard, 2019)

### System Boundary

As can be seen in Figure 4, the decision was made to distinguish between a system and a sub system. The outer system boundary consists of the complete Petone and Alicetown infrastructure.

The storm and wastewater system will be seen as a subsystem within the Petone infrastructure. This allows for the possibility of mapping out the system components and interdependencies of the sub system, and their connections to the larger system in more detail (Standard, 2019). Based on the demarcation of this system boundary and sub-system boundary the components in these systems will now be described according to the ISO 14090 in (Standard, 2019).

### Organisation, part of a system

As specified in (Standard, 2019), organization means a comprehensive system component, ranging from an organization like a governmental intiative to an energy transmission grid. Since the system boundary is described as infrastructure in the Petone/Alicetown area, critical infrastructure will be included in the system. The aim of the project is to look into two water infrastructure, these will be chosen as the system organizations, with a sub system for both Stormwater and Wastewater. Other organizations included are potable water, and a more generic Petone infrastructure. This includes roads, electricity and gas.

### Key actors and stakeholders

Key stakeholders and actors are important to identify in order to get an overview of important influences on the different organizations within the system. The relation between them and the system components can be seen in Figure 4. The following stakeholders and actors have been identified:

- Wellington Water (WW)
- Hutt City Council (HCC)
- Greater Wellington Regional Council (GWRC)
- New Zealand Institute for Water and Atmospheric research (NIWA)
- Academic (VUW)
- Community / Local Businesses
- Insurance Companies including council asset insurers

In addition to this, their contribution and involvement with different governmental instruments, like the New Zealand Resource Management Act (1991) and the Local Government Act (2002), are also included. For instance the latter Act requires councils to develop 10-year Long-Term Plans and 30-year Infrastructure Management Plans and regularly update them engaging with the communities they service.

### External Factors

External factors in this case are hazards driven by climate change. The rationale used was to include hazards that were driven by climate change, but would compound to area specific system interventions. This resulted in external factors stressing the infrastructure being sea level rise (a), increased rainfall and therefore pluvial / fluvial discharge (b), increased periods of drought (c) and earthquakes (d). These will then in turn result in systematic interventions for the Petone/Alicetown infrastructure. Earthquakes are included for completeness, but are not included in the research solution space.

Systematic Intervention

New Inputs changing the total output of the systems, as a result of the external factors described above. In the global or main system these are results of these hazards. For the Petone/Alicetown infrastructure system these include Flooding (Marine Flooding (1), Pluvial Flooding (2), Fluvial Flooding (3)), Groundwater level increases (4) and liquefaction due to earthquakes (5). Liquefaction due to earthquakes will be left out of considerations in line with the established boundary conditions of the study.

These main four hazards lead in turn to a range of systematic interventions in the sub system for specifically both stormwater and wastewater. These include drainage problems as in the inability to overcome peak discharges, salt water intrusion and inundation. These direct impacts will be added to the CIrcle tool in Figure 8, where cascading effects as a result of these sub system interventions will be investigated.

Feedback Loops

Feedback loops are related to the involved stakeholders. For WW, HCC and GWRC these are Updated Models, Updated area assessments, new regulations (e.g. the +1.0 m for new constructions) and plans like the upcoming 30 year plan. Others include Asset maintenance and Asset upgrades.

The usage of these feedback loops is explained in more detail in (Lawrence et al., 2018), where it is emphasized that feedback loops develop when factors and or variables in the system are connected in a circular manner. Intervention or changes in the system can therefore not be realized when the system is approached as linear, and could lead to unintended consequences (Lawrence et al., 2018).

Relationship Link

These visualize the connections between the different components in the system. For example, how the organizations and key actors are connected, and how they are affected by systematic interventions and their link outside of the sub system.

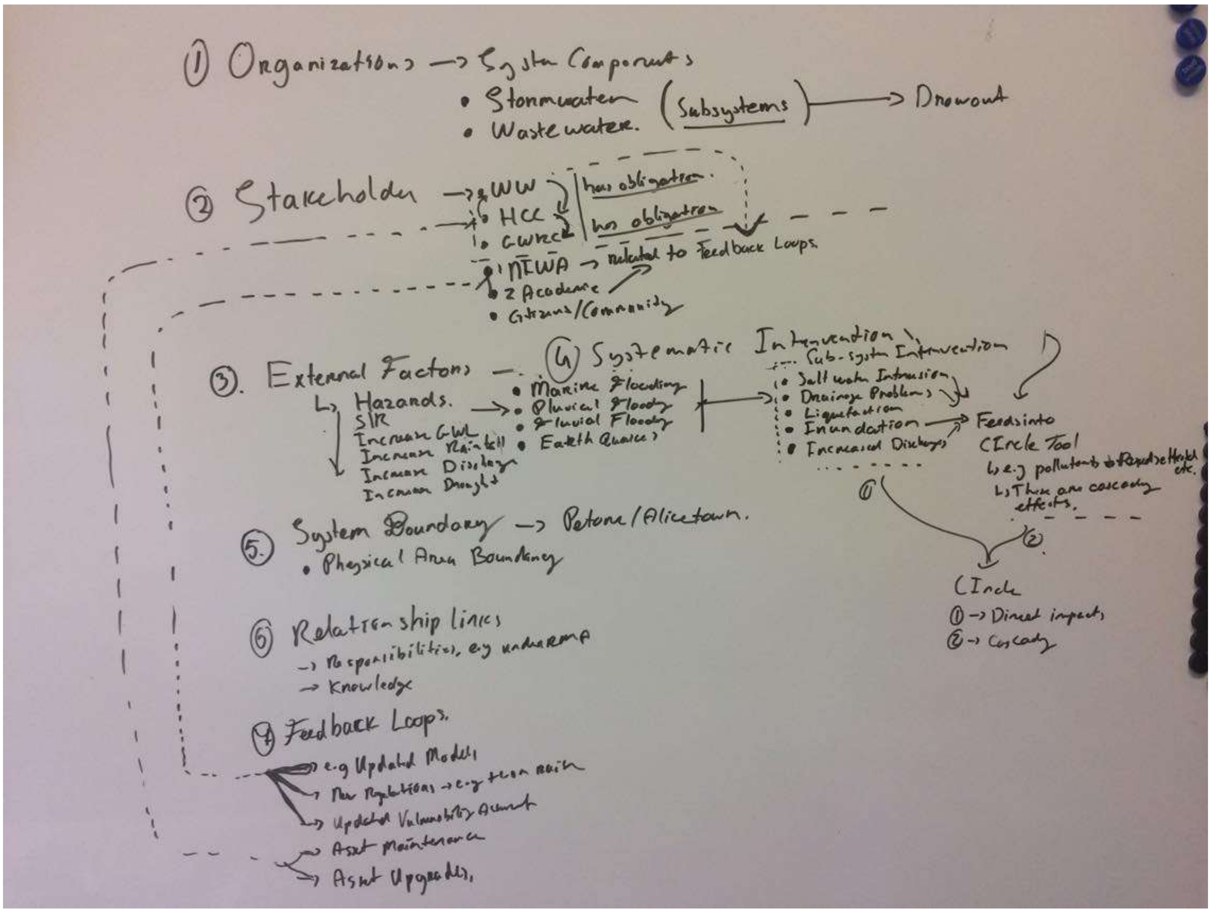


Figure 3: System Elements

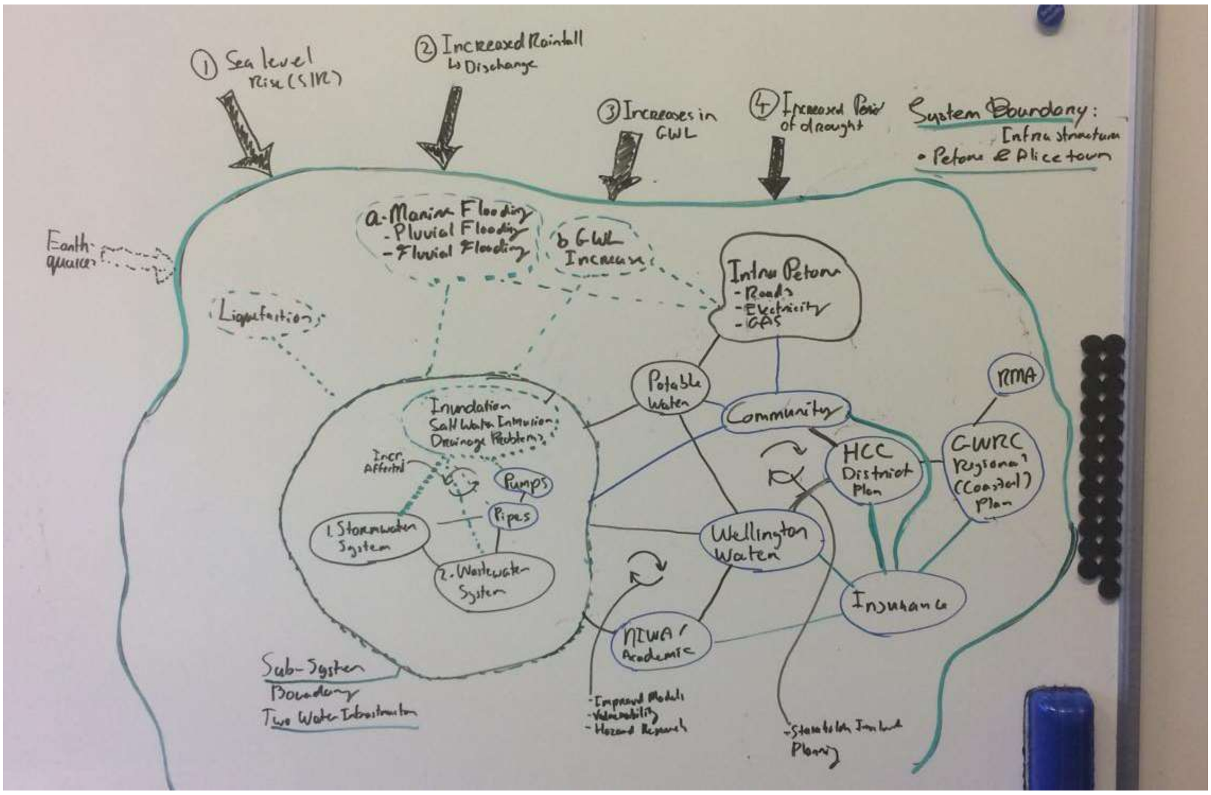


Figure 4: System for the Petone two water system and other infrastructure impacted by SLR

# 3. Workshop

As stated in the project plan, in order to get some input for adaptation options and feedback on the project so far a workshop was organized with a group of local experts from different background. This included a Marine flood risk modeller, a Fluvial flood risk modeller, head of Resilience of the HCC, planners from the HCC, and the Chief advisor for Stormwater from Wellington Water. Furthermore interdependencies or cascading effects were discussed using the CIrcle tool from Deltares.

## 4.1. Workshop Outline

In order to prepare the participants for the workshop, a pre questionnaire containing the workshop objectives was send to the participants to think familiarize themselves with the topic, or consider some thoughts before. Most of these were discussed in chapter two. The aim was to figure out different adaptation solutions, then go into specific optioneering for managed retreat, therefore the aim of the workshop was as following, to discuss and identify:

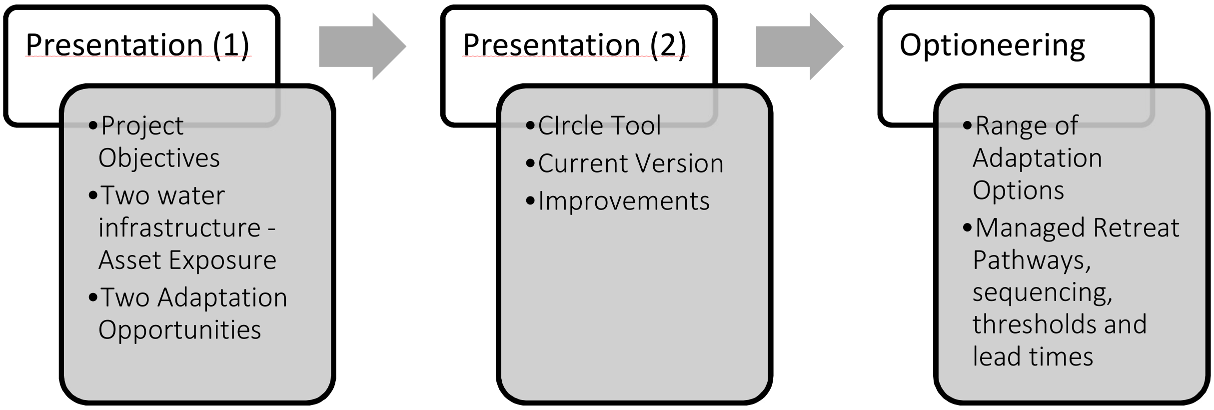
- Thresholds
- Lead times
- Currently Available options
- Innovative Solutions
- Timing of action – when to initiate options or pathways
- Conditions

After this associated lead times for these different options would be discussed, in order to get an idea of when signals and triggers would have to be implemented for the project. Participants were asked to consider:

- What options are available for adapting (two) water infrastructure to sea-level rise and how would you assess their capability to address both slowly rising seas and water tables, and extreme coastal storm tide, storm surge and rainfall events over a 100 year + timeframe?
- What associated lead time would be needed to implement each option?
- What would you describe as critical thresholds or indicators to evaluate performance of the Petone storm and wastewater system?
- What conditions would start the planning and implementation of an adaptive strategy?
- What would be a threshold for considering retreat of two water infrastructure as a realistic option? What conditions would determine the threshold? How would you describe a realistic service level while the hazards increases and how would you determine that?
- What kind of efforts to improve infrastructure performance would be feasible to invest in and for how long?

Workshop Process Flow

Figure 5 shows the process workflow used in the workshop. The first part involved a presentation on the work that has been done so far, after which there was the possibility to give comments on the work done so far on the project. Second part presented a conceptual developed CIrcle tool, where there was also options for suggestions of interdependencies or cascading effects that were not included in this version.



Presentation (1)

- Project Objectives
- Two water infrastructure - Asset Exposure
- Two Adaptation Opportunities

Presentation (2)

- CIrcle Tool
- Current Version
- Improvements

Optioneering

- Range of Adaptation Options
- Managed Retreat Pathways, sequencing, thresholds and lead times

*Figure 5: Workshop Process*

Participants

Participants of the workshop attended from the Hutt City Council (HCC), Wellington Water (WW) and Greater Wellington Regional Council (GWRC). Participants can be seen in Table 1. Participants of the workshop had a varied background. This was also the aim of the workshop, as this would aid the optioneering process in the sense that there would be a lot of different approaches presented. This also helped with looking at system thresholds and options from different perspectives, which will be discussed later in this paragraph.

*Table 1: Workshop participants, affiliation and title*

| Participant | Affiliation | Background |
|---|---|---|
| 1 | HCC | Senior Advisor Sustainability and Resilience |
| 2 | HCC | Head of Resilience |
| 3 | HCC | Planner |
| 4 | WW | Chief Advisor Stormwater |
| 5 | GWRC | River Modeller |
| 6 | GWRC | Marine Modeller |
| | | |

## 4.2. Workshop Output

Figure 6 shows part of the discussion with regards to thresholds. The right side resembles the Wellington Harbour area, where the sea level is rising. Then comes the initial rise in elevation just after the esplanade and initial part of the Petone area. Since at the moment both the wastewater system and stormwater system operate mainly on gravity, this is going to significantly affect the hydraulic gradient, which in turn is going to largely affect the capacity of the discharge flow. It is expected that the threshold for the drainage system to function is around a SLR of around 0.30 m for Petone Alicetown, and 0.50 m for Udy street. The community in Udy street is already not able to get flood insurance. These are already serious consequences that are only going to increase. Both thresholds are, although uncertain in exact timing, certainly going to be reached and have to be anticipated. The current 'treat problems as they emerge' technique is not going to be sufficient. A first step is already taken as all new development has to be raised by +1.0 m in order to be approved. It was discussed that these streets would be a good start to look into compartmental retreat. Looking at the section in Figure 6, it would also be a possibility to elevate complete WW and SW system and bypass these areas completely.

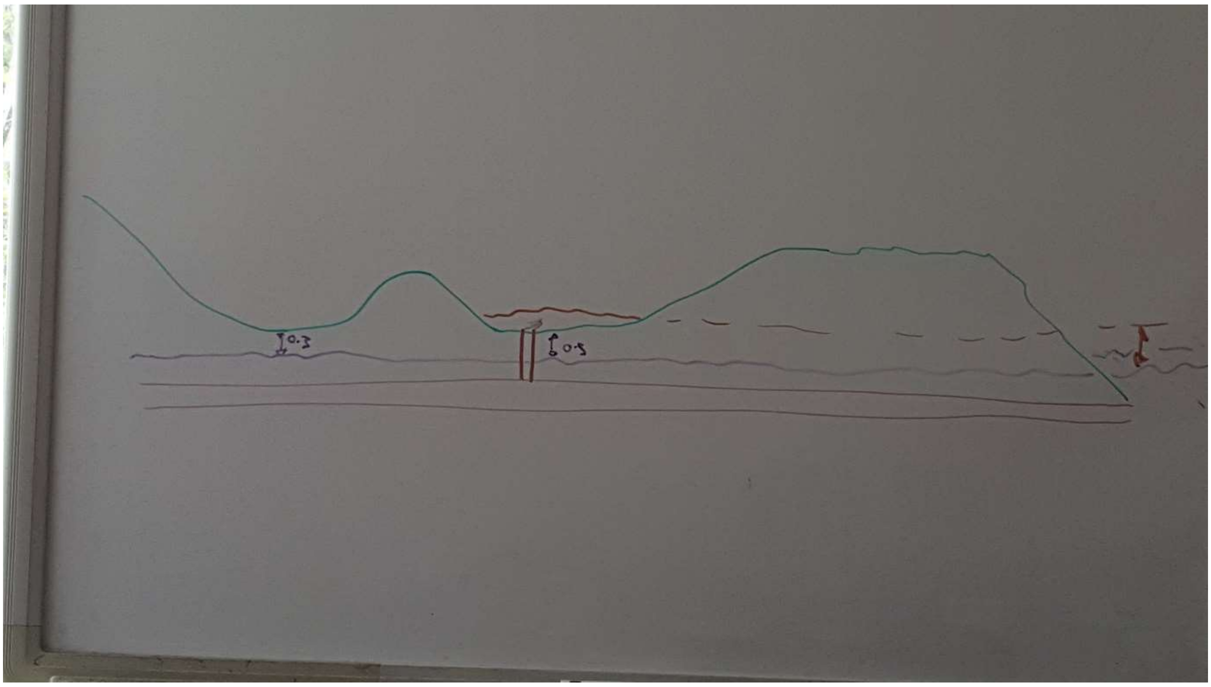


*Figure 6: Conceptual section of the study area used during the workshop to elaborate on the loss of discharge capacity, ponding and the +0.30 m Threshold (Drafted by Participant 4)*

Table 2 shows the notes taken during the workshop by Dr Lawrence. In conjunction with the poster this is the output from the workshop. It can be seen in Table 2 that the layout is in sync with the workshop planning, meaning the notes are sorted in chronologically. The first part concerns the questions and topics discussed during the presentation. The second part concerns the discussed levels of service for both SW and WW. After that the thresholds for the Petone two water system are discussed. The last part includes the optioneering, there associated thresholds and lead times and constraints are noted. Figure 7 shows the workshop poster. Since the notes were written during the workshop, and are still a bit chaotic afterwards Table 3 shows the important outcomes.

*Table 2: Workshop Notes*

| Discussed Topics & Output |
|---|
| Questions Raised with Regards to the presentation |
| 1) Question with respect to GWRC inundation modelling (Rick to follow up to compare with what he has used)<br>2) Change the colours on the density map so red is deeper and blue shallower (Rick to do)<br>3) Questions re age of pipes and maintenance schedule. Some have not been replaced as per schedule. These are monitored and replaced based on condition and performance. There is a capacity v water quality trade-off.<br>4) White board drawing explains the potential threshold for groundwater rising on the SW and WW system. Based on gravity and shift to pumped system and limit for pumping. 300mm of SLR seems to be the threshold in Alicetown and 500mm in Udy Street.<br>5) Impact of salt water on pipes is an issue that will increase as sea level rises. Rainfall and SLR will affect the capacity/ leakiness/ functioning of SW/WW system. |
| Levels of Service for Stormwater and Wastewater |
| 6) Three levels of service for SW and WW<br>• Removal of WW (pH??)-> salt in pipes-> upsets balance in treatment plant<br>• Regular rainfall (dry, healthy homes)<br>• Acceptable level of flood protection (ability to obtain flood insurance) Note Udy Street already cannot get flood insurance) = this affects whether base line is current level of protection or something else. |
| Thresholds |
| 7) Thresholds. Only new services are affected by reduction in level of services balanced against the cost to council of maintenance and repair. After a flood event there is a spike in public concern. Factors that influence council decisions are<br>• Affordability as economic damages increase<br>• Cannot fix the system anymore<br>• No longer a contained system<br>• Regular overflows to property or watercourses<br>• Property owners can't afford to upgrade their own part of the system<br>• GW at surface most of the time<br>Q regarding whether these are acceptable to the community. Process at present ad hoc. |
| Optioneering |
| 8) Options<br>• Move to a vacuum system<br>• Retention storage and slow release<br>• Water sensitive design incl. less hard surfaces to increase infiltration<br>• Managed retreat pathways = asset design to reduce the amount of retreat needed by pumping to the threshold first=create storage by removing people/ creating a pond in the lowest point= new houses elsewhere build above an inundation level and houses on stilts or build up land and pump constantly. This would need to be built into subdivision and building consents. 20% increase in rainfall and 1 m SLR suggested as planning guidance [note doesn't match with coastal guidance] |

- Note minimum of 500 homes in Alicetown = lowest levels affected and could introduce planning measures to transition these.
- Use DAPP to identify cost/ vulnerability impacts
- Look out 150 years and lock in planning controls/ reduce dependence on pumps/ reduce population density
- Lead time =
    - Big pumps =10 years
    - Planning 2 years
    - Accelerated removal of waste water= 5 years
    - Pressure or vacuum system roll out could be done in compartments doing WW and SW at the same time
    - Optimise storage and water sensitive design
- Constraints are
    - Alternative sites for housing growth are constrained in the Hutt because of multiple hazards elsewhere
    - Community cannot absorb more than around 2% rate increases
- A strategy of baby steps suggested

Figure 7 shows the post its in the pre identified categories for the workshop. Table x is the 'translated' version of this, which, combined with the notes in Table 2 form the main output from the workshop. There is also an end questionnaire which will be discussed later.

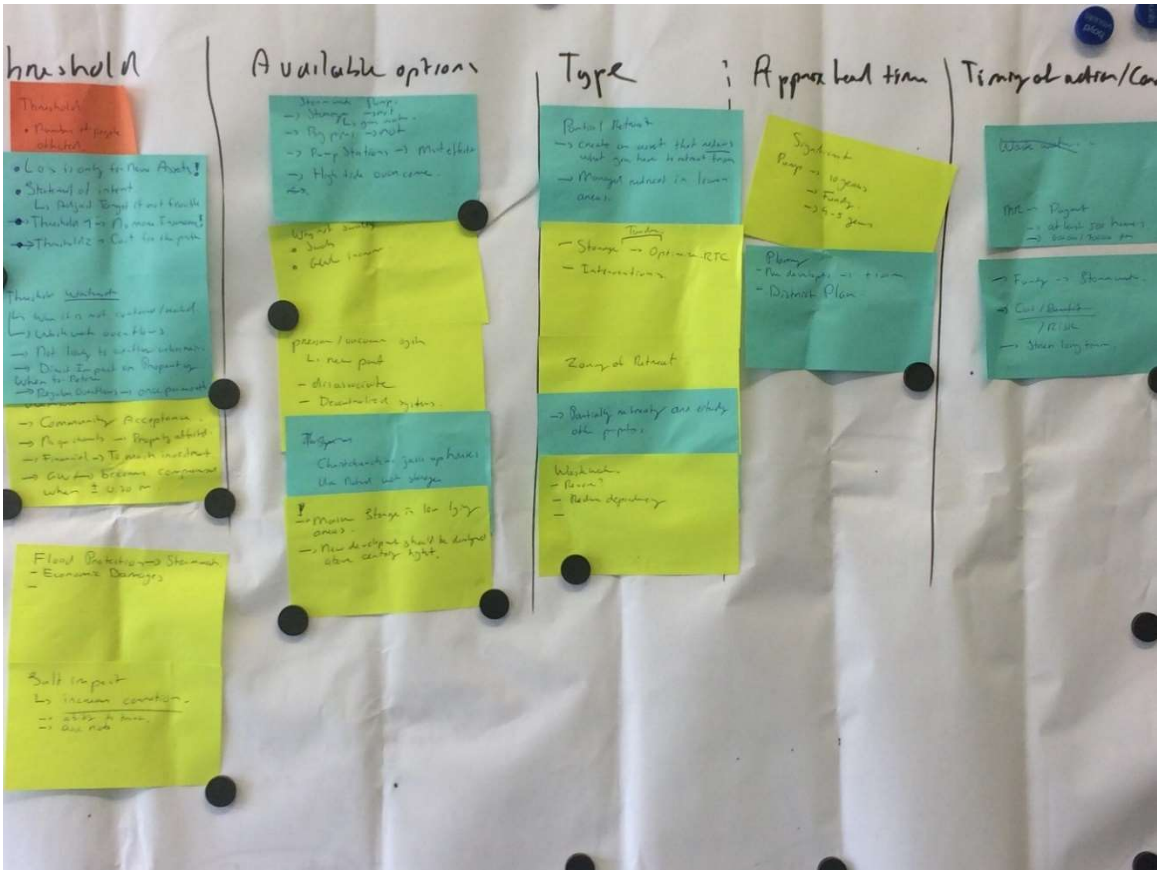


*Figure 7: Grouped workshop input*

*Table 3: Grouped information from Figure 9*

| Threshold | Available Options | Types | Approx. Lead Time | Timing of Action / Conditions |
|---|---|---|---|---|
| Number of people affected | Grey Water Storage | Partial Retreat | Pumps<br>-10 years | MR<br>-At least 500 homes |
| L.o.s. is only for new Assets<br>Statement of Intent ->adjust target if not feasible | Bigger Pipes | -Create an asset that reduces what you have to retreat from | -4-5 years for funding | -600000 to 700000 Costs per home |
| General:<br>-No more insurance<br>-Cant fix the problem | Increase Pumpstation Capacity | Zoning of Retreat | District Plan is coming up for 30 yrs | Funding SW Cost/Risk Stress long term |
| Wastewater:<br>-When it is not contained / sealed<br>-Wastewater Overflows<br>-Not likely to overflow except for coincidence with heavy rain<br>-Direct Impact on Properties<br>-Petone is already experiencing regular overflows, approx 1 per month | Overcome High Tide | Tandem Retreat-Combine with Storage and Interventions | | |
| Wastewater:<br>-Community Acceptance<br>-No open channels -> property affected<br>-Financial -> to much investment<br>->GW->Becomes compromised around +0.30m | Pressure / Vacuum system | Partially Retreat and extend lifetime other properties | | |
| Stormwater:<br>-Economic Damages | Swales / Porous Asphalt | Wastewater<br>-Remove<br>-Reduce Dependency | | |
| Salt water impact from SLR<br>-Increases Corrosion<br>-Impact ability for water treatment | Disassociate / Decentralized system | | | |
| | Elevated houses | | | |
| | Create Storage in Lower areas | | | |

Discussion of output

As can be seen in Table 2 and Table 3, the most important system thresholds identified were the possible future scenario where

- +0.30 [m] of SLR until GWL is seriously affected
- +0.30 [m] of SLR until hydraulic capacity is seriously reduced
- Regular Wastewater Overflows
- Affordability as economic damages increase
- Cannot fix the system anymore
- No longer a contained system
- Regular overflows to property or watercourses
- Property owners can't afford to upgrade their own part of the system
- Property owners are not able to get insurance for their property
- GW at surface most of the time, ponding

These discussed thresholds will then be combined with the thresholds in the exposure assessment. This should give a good start of the threshold of the *Petone Two water system.* For the thresholds of the *individual adaptation options* these will be based on the application of these options. Since there was only limited time for discussion during the workshop, it was not possible to discuss these topic in detail, and mainly thresholds for the two water system were discussed. It was proposed that when conceptualizing some adaptation options, it would be good to create an asset that reduces what you have to retreat from, to use in tandem with retreat and therefore optimize its effectiveness. Regarding the optioneering output, the most important adaptation discussed can be divided in the following main categories

- Pumping Stations
- Increase Capacity
- Decentralize / Local Infiltration / Reuse
- Pressurize / Vacuum the system
- Create Storage in lower areas / overcome high tide
- Increased Imperviousness

Increased imperviousness is, as discussed in the theoretical background, a great approach to infiltrate stormwater more locally, therefore reducing peak discharges in the drainage system. Examples of this are porous asphalt or bioswales. Both in literature and in the workshop it was suggested that implementation of these measures would locally result in an increase in groundwater levels in lower elevated areas, and therefore increase the groundwater table. Therefore this would not be a good solution in the lower lying parts of Petone, but could be considered for implementation in the right areas, for example more elevated, alleviating the discharge towards the lower lying areas in the Petone area.

It was also acknowledged that more effort until now has gone into thinking about stormwater adaptation then wastewater adaptation. This is why during the optioneering there were no concrete adaptation options for wastewater. Also in the background literature, there were limited options available for wastewater adaptation. Either there was a consideration for fixing leaks, adjusting pump station capacity or decentralize the system. For the purpose of this research however this is still a valid level as we are not looking into component level solutions as this would not fit the level of detail in the conceptual DAPP.

As stated in the project plan and exposure assessment, a static bathtub approach modelling map was used to identify exposed areas. This meant that there was a level of detail missing in the exposure assessment due to time constraints. In the workshop, two characteristics were discussed with the intend of verifying it with experts who have been working with more in depth models of the area. The first was the spatial extend of the flooding, and the second was the assets affected over different SLR increments.

In order to have suggestions on where to focus next, an end questionnaire was drafted. The responses can be seen in Table 4. The end questionnaire consisted of the following questions for the workshop participants:

- Are there important considerations missing?
- What would be your approach for establishing corresponding service levels for the optioneering done today?
- Thoughts on the project so far
- Thoughts on improvement

*Table 4: Suggestions Workshop Questionnaire*

| Respondent | Suggestions |
|---|---|
| Head of Resilience (Participant 1) | *''Seems to me that there will be challenges to establishing Service levels, because ultimately this will depend on what the community finds acceptable (which could change pre and post an event).*<br>*On the other hand, I think as much as possible it needs to be measurable (sea level rise thresholds linked to particular performance or cost levels, frequency of certain events, etc), as opposed to more subjective things like survey results out of the community.*<br>*I am not fully clear whether we can fully link service level to the options, because ultimately the options are ways to attain certain service levels, so they presumably the same for all options?''* |
| Chief Advisor Stormwater (Participant 4) | *''Key issues for me were to focus on the service that the three networks provide rather than the networks themselves. By focusing on the service opens up alternative solutions than more infrastructure. The 3 services in this area:*<br>*- Provide safe and healthy homes by the removal of regular rainfall.*<br>*- Provide acceptable level of flood protection (particularly focused on floor level protection).*<br>*- reliable removal of wastewater for the protection of public health.*<br>*Another issue we discussed was the impact on groundwater on these services. When the groundwater is at the surface it will have a big impact on all three. thin indicates that 300mm of SLR is a key trigger point as ground water will be on the surface regularly.''* |

# 5. Cascading effects and interdependencies - CIrcle Tool

The CIrcle tool – Critical Infrastructure: Relations and Consequences for Life and Environment – is a tool developed by Deltares to analyse and visualize cascading effects of infrastructure networks, to address awareness on critical infrastructure dealing with climate change related topics (Hounjet, 2014). It does so by dividing critical infrastructure into different categories, with the possibilities to add direct effects and establishing links, cascading effects, between the different categories. This as currently critical infrastructure (networks) are being addressed individually, rather than an interconnected entity, neglecting cascading effects from other parts of the network (Hounjet, 2014).

In order to start a CIrcle project it is important to first chose the different categories. For this project the drainage system, stormwater and wastewater pumps, stop banks (dikes), main roads and public health were chosen. The aim is to start linking these sectors with different interactions with a group of experts in a workshop session in coincidence with a GIS analysis (Deltares, 2015, 2017; Hounjet, 2014) Due to time constraints with the workshop, and since the participants were largely unfamiliar with the tool, it was decided to prepare the tool and discuss the results during the workshop, and then add or remove alterations and different connections afterwards with suggestions from the workshop participants.

Figure 8 shows the preliminary setup of the circle tool. Each of the coloured elements in the Circle represent one of the different sectors. The coloured connection lines represent indirect consequences of the even in this sector, or in other words cascading effects.

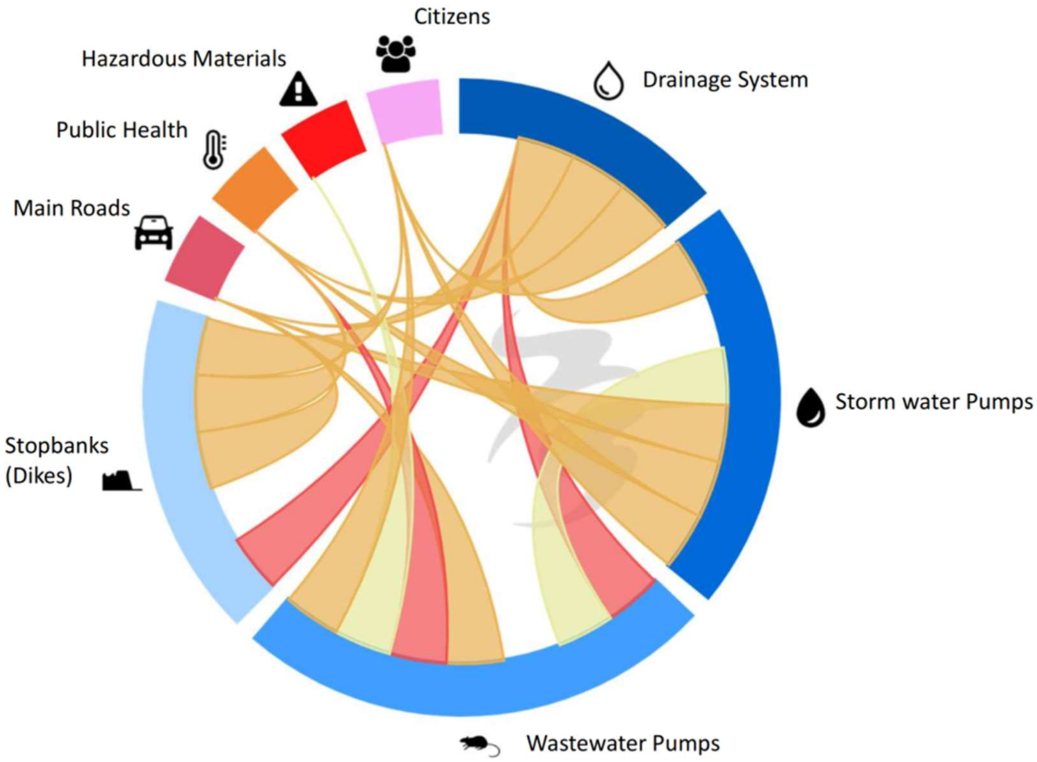


*Figure 8: Critical infrastructure and cascades using CIrcle*

### Direct Impacts

Direct impacts were added to each of the different sectors, based on the findings from the exposure assessment. Increments were added resulting in the thresholds for stormwater pumps, wastewater pumps and the drainage system. After the workshop, thresholds identified during the workshop were also added to the direct impacts for the different critical infrastructure cascades. In addition to this, the cascades investigated in (Lawrence et al., 2018) for storm and wastewater will also be used to make sure that nothing is overlooked. Direct impacts, therefore input into the CIrcle tool can be found in table 5.

*Table 5: Critical infrastructure direct impacts*

| Direct impact on: | Description |
|---|---|
| Water | From the exposure assessment:<br>Priority 1 - 0.70 [m]-Wastewater Outlets -Main Discharge Pipes<br>Priority 2 - 0.50 [m]-Manholes -Sumps<br>Priority 3 - 0.70 [m]-Low priority/occurrence<br><br>From the workshop:<br>Groundwater Threshold – 0.30 [m]<br>Reduction in Hydraulic Capacity – 0.30 [m] |
| Water pumps | Stormwater Pumps become Immediately affected during a current extreme event:<br>0.0 [m] 3/4 Stormwater Pumps Affected<br><br>Increased corrosion in electrical and pumpstations, therefore reduced asset lifetime |
| Wastewater pumps | During extreme event increments [m]:<br>0.00 5/9 Pumps<br>0.10 6/9 Pumps<br>0.20 7/9 Pumps<br>0.40 8/9 Pumps<br>0.50 9/9 Pumps<br><br>Increased corrosion in electrical and pumpstations, therefore reduced asset lifetime |
| Dikes/stopbanks | Increased extreme events due to SLR put increasing stress on the stopbanks |
| Main roads | The Esplanade becomes affected:<br>0.00 [m] during an extreme event. Serious exposure and therefore damage starts to occur at 0.30 [m] |
| Public health | |
| Hazardous materials | Asbestos Pipes that could fail and become exposed during an extreme event |
| Citizens | Inconvenience due to Ponding or Overflows |

## Cascading effects

This paragraph will states the cascading effects, interdependencies, between different critical infrastructure as a result of thresholds reached due to the input in the previous paragraph. This is visualized in Figure 8. Cascades can be found in Table 6.

*Table 6: Critical infrastructure cascades*

| From: | To: | Description | Severity |
|---|---|---|---|
| Dikes | Main roads | Flooding due to a Stopbank Breach | significant |
| Dikes | Public health | Flooding due to a Stopbank Breach | significant |
| Dikes | Citizens | Flooding due to a Stopbank Breach<br>No Possibility to get insurance anymore<br>Increase in Cost | significant |
| Dikes | Water | Drainage System cannot handle water discharge | severe |
| Wastewater pumps | Public health | Sewer Overflow, Health Implications | severe |
| Wastewater pumps | Citizens | Sewer Overflow<br>No Possibility to get insurance anymore<br>Increase in Cost | significant |
| Wastewater pumps | Water pumps | Wastewater Infiltration into Stormwater System, increased stress on pumps and pollutants | severe |
| Wastewater pumps | Water | Increased stress on the rest of the Drainage System | severe |
| Wastewater pumps | Main roads | Road overflow with wastewater pollutants | significant |
| Wastewater pumps | Hazard Materials | Increases pressure through old asbestos pipes | minor |
| Water pumps | Water | Increased Stress on the drainage system | significant |
| Water pumps | Main roads | Road Overflow / Inundation | significant |
| Water pumps | Public health | Stormwater Flooding | significant |
| Water pumps | Wastewater pumps | Stormwater Overflow | minor |
| Water pumps | Citizens | Stormwater Overflow<br>No Possibility to get insurance anymore<br>Increase in Cost | significant |
| Water | Main roads | Overflow due to reduced hydraulic capacity as a result of SLR | significant |
| Water | Public health | Overflow due to reduced hydraulic capacity as a result of SLR | significant |
| Water | Citizens | Overflow due to reduced hydraulic capacity as a result of SLR<br>No Possibility to get insurance anymore<br>Increase in Cost | significant |

# 6. Adaptation Options

This section discusses the different two water adaptation options identified in literature and discussed during the workshop. The first part will discuss the full list of options. The following parts discuss the high-level adaptation options per strategy, their trade-offs and associated failure conditions. The last part of the chapter will focus on area selection, parameters used to determine an area and selection of specific area targets.

## 6.1. General Adaptation Options

All options from the literature, SLR exposure assessment and workshop have been grouped and can be found in Appendix 1. The options have been framed around the adaptation strategies discussed in (IPCC, 2019). This to make a distinction between the different possible approaches for the area. In the coming paragraph this list of options will be divided into high level adaptation options where the trade-offs are discussed. The discussed adaptation options are no response, protect, accommodate and nature-based adaptation. Of the strategies presented in (IPCC), advancing and retreat have been removed when transferring these options into high level adaptation categories. Advancing has been removed since it was not considered a suitable option considering the cost and relatively small size of the Petone area. Retreat has been removed as, apart from changes to the current system, there are no specific retreat options for the two-water infrastructure. Rather, it is the phasing between these existing adaptation options that allows for retreat in other areas. Butler, D., Digman, C., Makropoulos, C., & Davies, 2018 propose the following high-level approaches, corresponding with the protect and accommodate approaches:

- Minor system, reduce or limit inflow (SUDS to infiltrate locally) or divert flows
- Increase Capacity, e.g. improved cleaning or pipe upsizing
- Minor/Major system, store more flow therefore attenuate and reduce peak flow rates, storage can be provided in the minor or major system
- Major system, better deploy surface flow features
- Improved building flood resilience

## 6.2. No Response

No response is the current strategy utilized in the area. This does not mean that the system is not maintained, it is being maintained continuously, rather it is not proactively prepared for future increased stresses on the system from SLR and climate-change. Problems are being treated as they arise. The advantage of this approach is that no big investment has to be made in the short term, rather costs remain consistent. The disadvantage is that, due to changing stresses on the system, these disruptive interventions will not only become increasingly frequent, but once the current system has reached its threshold major investments will be necessary to continue achieving the required L.o.s.

*Table 7: No response adaptation options*

| No Response | Area Specific Options | Pro's | Con's |
|---|---|---|---|
| Repair Pipes | Close off leaks | Short Term<br>non Expensive | Long Term complete replacement costs |

## 6.3. Protect

Lowering the groundwater level around critical infrastructure would be mainly applicable for the pumping stations that will be affected by SLR. This will delay the water reaching the pumping station and causing damage to corrosive parts in the pumping station. Advantage of this is that initially current pumping stations in place can remain functional. Vegetation would also be an inexpensive short term no regret option to implement. SLR however will undo this GWL lowering gradually and this option will see a decline in performance and gradual increase in costs to keep the increased water away from the asset components, eventually facing complete replacement costs.

Preventing undesirable inflow is already being done in the Petone area, mostly for pipes. The method uses valves to prevent inflow in the system during high tide. As SLR increases this will become an increasingly more structural measure to protect the system from inflow. The advantage is that it can be applied to the current drainage system. Permanently closing off the outlets ceases the function of the drainage system. Therefore, the system will at this point not function anymore, this will be the failure condition of this adaptation option.

The last two options for protect, dry and wet proofing critical infrastructure assets fall in a similar category. Whereas Wet-proofing allows non-essential parts of the asset to be flooded, dry-proofing completely separates the asset from the water. This can also be an opportunity to incorporate robustness into this option. Implement it as a dry-proofing solution, and when different parts of the infrastructure start to flood use it as a threshold to move to a different adaptation solution. Depending on the type of implementation, this solution can be adjusted to be effective for a long time. Once the threshold is reached however, the whole system needs to be replaced. An overview can be found in table 8.

*Table 8: Protect adaptation options*

| Protect | Pro's | Con's |
|---|---|---|
| Lower Groundwater Level artificially around Assets | Relatively inexpensive, easy to implement | Limited mitigative capacity |
| Dry - Proof | Long term beneficial, especially together with increased pumping capacity | When waterproofing is exceeded, expensive to replace |
| Wet - Proof | Long term beneficial, less expensive then entire waterproofing of the structure | Inundation of other parts, could shorten overall lifespan |
| Prevent undesirable inflow | Effective in the short term | Once threshold is exceeded, cannot be upgraded, whole system needs to be replaced |

## 6.4. Accommodate

Raising the system and sewer outlets would be a way to make sure the water does not get in the pipes anymore at current water levels. Over the course of different SLR increments this will be a recurring situation. This option will both be in design as expected lifetime a limited option. With regards to lifetime, this is as the SLR will keep increasing the problem will starts to occur again. The biggest issue however is the implementation. As most of the drainage system is designed to be a gravity-based system, raising the outlets will significantly reduce this hydraulic capacity. This means that the system in place only allows for a limited increase in outlet levels before having to switch to a pressurized system to overcome this hydraulic loss.

To overcome this need it is also possible to replace the pipes and nodes. With regards to the loss in hydraulic capacity, there is the possibility to raise the sewer connections in the system, so that the hydraulic gradient is restored. This is also only possible to a limited extent. With regards to the increased discharges in the system, it is possible to increase the pipe diameters by replacing the pipes. Pressurizing the system is also a way to overcome the initial stages of SLR. Increased corrosion and vulnerability of the pumping stations, and the need for increasing pumping station capacity over SLR increments will reduce the lifetime of this option under SLR. Major disadvantage is that it is not possible to do this for part of the system, the whole system has to be adjusted. This option would be applicable long term. Pumping stations are going to be under increasing stress as a result of SLR. Increasingly pressurized systems and increased discharges mean pumping capacity has to be increased. Increased GWL due to SLR means that there is a risk of pumping stations flooding, especially since they are partly located underground. Raising the pumping stations would be a way of accommodating. Failure conditions of this is when the SLR again leads to flooding of the pump station components. An overview can be found in table 9.

*Table 9: Accommodate adaptation options*

| Accommodate | Pro's | Con's |
|---|---|---|
| Raise Sewer and Outlets | Prolongs usage of gravity-based system | Can only be raised a limited amount, relatively expensive for small SLR extension |
| Increase capacity pipes & nodes | Prolongs usage of gravity-based system and increased discharge capacity | Become Obsolete when System is eventually replaced |
| Pressurize Sewer | Prolongs usage of the drainage system Considerably | System becomes considerably less flexible |
| Increase Pumping Capacity | Effective | Expensive to implement, when threshold is reached, non-upgradable |
| Raise Pumping Stations | Effective and will prolong the lifetime of the drainage system considerably | Very Expensive |
| Decentralize System (Local treatment and Infiltration) | Long term effective/Flexible/Upgradable | Initially expensive, more 'invasive' for community, unusual practice |

## 6.5. Nature Based

Nature based solutions are mainly derived from WSUD approaches, as explained in the theoretical background. The aim is to use nature-based adaptation options to aid the drainage system in adapting. The two fundamental ways for this are either delaying entrance to the drainage system in an extreme event, temporarily storing or facilitating local infiltration. This will be done until the system has normalized again and is not working at full capacity anymore after an extreme event.

What has to be taken into account is that many of these options require extra space. Since the Petone area is a relatively dense developed area it might prove difficult to implement these options on a large enough scale in order for it to be effective in mitigating SLR impacts. Combining the larger options with later retreat stages, where space is created, would therefore increase the effect of these options. It would also extend the liveability of other parts of the Petone / Alice town area. Storage of excessive discharge is considered effective and can be integrated in many urban community facilities. Failure conditions would be dependent on the hazard. When considering SLR increments, an increase in the GWL that leads to inundation of the storage facility needs to be considered. This will start with ponding but will increasingly start to fill up the storage facility. When considering increased discharges, when the system is unable to handle the discharge the storage facility can overflow.

On site treatment, applicable to both storm and wastewater, is a way of decentralizing the drainage system. For wastewater this is limited as stormwater can be more effectively treated and reused as grey water. This decentralized approach reduces the need for all peak discharges to flow to the outlets / treatment facilities in the system, mitigating the negative impacts of the reduced hydraulic capacity due to SLR. This can be done with the help of biofilters, either reintroducing the treated stormwater as greywater or reduce the load on the WWTP by using natural solutions to pre filter the wastewater before releasing it towards the WWTP. An overview can be found in table 10.

*Table 10: Nature based adaptation options*

| Nature Based | Pro's | Con's |
|---|---|---|
| Biofilters (On Site Treatment) | Re use, decreased stress on treatment plant | Not always possible to fully reuse |
| Local Infiltration | Can be integrated into surroundings, ecosystem benefits | When GWL gets too high, ponding occurs |
| Discharge Storage | Handles discharge, ecosystem benefits, community benefits, adaptability | Spatial Requirements |
| Discharge Delay | Delays discharge, short term no regret, ecosystem benefits | Some options might require space or integration into public facilities and spaces |

Increasing imperviousness to aid local infiltration is also a double-edged blade. On the one hand it decreases stress on the system during an extreme event. As stated in the theoretical background however, this increase in imperviousness works both ways and might have the opposite effect in coastal areas, like Petone, where the imperviousness allows for the groundwater table to rise further without this increase. It is therefore important that when implementing this in the Petone/Alice town area, it is implemented in lesser effected areas on the upper part of the drainage system to mitigate and reduce discharge to the lower parts of the drainage system. The system failure conditions are when SLR causes the water levels to also reach these areas, and the increase in groundwater table is accelerated due to this increased imperviousness.

Delay of discharge can be done with increased nature-based solutions like green roofs, rain gardens and re vegetation. These are relatively easy to implement in the short term and quite robust. Green roofs implementing in the higher parts of the Petone area reduce stress on the lower parts of the system. Failure conditions would be when the discharge capacity is exceeded.

## 6.6. Managed Retreat Area Selection

Retreat will eventually be necessary at different stages for the entire study area – it is mostly a matter of when this will be needed (due to the uncertainty of the rate of change in SLR). The sequence of retreat will be different for different areas within the project area. This is because not all areas are the same in terms of how and when they are affected by SLR (i.e. different adaptation thresholds) and opportunities to make interventions for different areas. This also include facilitation by other areas to implement retreat in the whole project area. Since retreat in this context is therefore essentially a spatial shift in retreat phasing, there is a need to divide the project area into smaller sub areas, each with their unique retreat strategy.

Three areas were identified using cross sections of the study area from a DEM file (1) and asset exposure information with respect to exposure densification over SLR increments (2). The interrelations between the areas were explored using the parameters set out in Table 11. The first row in table 11 defines the Area strategy. Eventually all areas will retreat, therefore the strategy noted here is the first in the sequence. Asset exposure and intensification, elevation classification (DEM), pumping station exposure, coastline proximity and area opportunities come from the exposure assessment.

It is the coincidence and parallel implementation between the area specific solutions that enable retreat of services spatially in a managed way. Consequently an holistic perspective, is used by examining the implementation of area specific solutions for all areas and their inter-relationships.

*Table 11: Retreat area parametrization*

| Parameters | Area 1 | Area 2 | Area 3 |
|---|---|---|---|
| Area Adaptation Strategy | Retreat | Protect/Retreat | Accommodate |
| Type of Development/Land Use | Residential | Residential | Industry/Residential |
| Asset Exposure level | High Intensification | High Intensification | Low Intensification |
| Pumping Stations Exposure | Medium | High | Low |
| Elevation Classification | Low | Medium | Medium |
| Coastline Proximity | Medium | Close | Far |
| Area Opportunities | Legacy Effects, Old Pipes and Asbestos | Medium to new pipes | Medium to new pipes |

### Area 1

Retreat is the strategy identified as the initial sequence for this area. The area has a high asset exposure over SLR increments. It is the highest exposure level in the study area. A high concentration of assets can be correlated to either a high density of residential development, or an industrial area. In terms of pumping stations, there are both stormwater and wastewater pumping stations affected. The area also has a low elevation sump, in combination with a medium coastline proximity and therefore will be particularly vulnerable to the SLR threshold of +0.30 [m].

Opportunities for Managed Retreat through the spatial relationships that can facilitate Managed Retreat are also present in the area. The first opportunity is that the area has a high number of expected pipe replacements due, in combination with a high number of asbestos pipes. By not replacing the pipes and thus continuing use of the current system until retreat begins and leaving the asbestos pipes in situ since removal would create health and safety risks, creates an opportunity.

The second advantage is that, since the system won't be used anymore, even with considerably reduced hydraulic capacity, this can create redundancy in the system. By rerouting stormwater through the old drains this creates an increase in capacity in the other areas. It also creates the opportunity to repurpose this area with the aim to both create extra drainage capacity, as well as provide community and ecosystem benefits in the form of public spaces.

### Area 2

The first strategy in the retreat sequence for this area is Protect. Due to the close proximity of the area to the coastline, retreat might be expected to be the first action. It also has a high asset exposure like Area 1. The elevation of Area 2 however is higher and therefore not located in a sump, despite coastline proximity, and Area 2 is critical for the pressurized wastewater system in the lower Petone part. The area already has been artificially reinforced with a seawall and dune planting in front of the sea wall was observed. To allow for this part to retreat, the storm water system would have to be isolated or completely re-routed.

Pipes in the area are not expected to require replacement soon, therefore opportunities in other parts of the system may facilitate retreat. The advantage of doing this is that the current system can remain in place, since it is a critical pressurized part that will become increasingly affected. For that to happen, adaptive capacity will need to be created in other parts of the system like Area 1, until retreat is initiated in this area.

### Area 3 – Accommodate

The first strategy for the area is accommodation. There is a low exposure of assets affected for SLR increments and for critical infrastructure like pumping stations. The area is located the furthest away from the coastline in the study area and has a relatively high elevation in relation to the other areas. Initiation of retreat phasing will therefore be at high SLR increments. This means that this part of the two-water system in its current form will be utilized for the longest duration of time. Accommodating the system and in the process also capitalize on opportunities arising for this replacement are important components of this strategy.

Opportunities with this strategy is the creation of mitigative capacity for the lower parts of the Petone drainage system. This means that it has the possibility to optimize retreat. What this means is that it would *maximize* the effectiveness of retreat in the low 'sump' parts of the Petone area. This means effectively creating a *reduction* in discharge towards the other areas. Furthermore, the area will need to adapt to increased stresses on the system. These include, from the system analysis, increased rainfall intensities and increased groundwater levels. This in turn results in increased pluvial flooding, increased saltwater intrusion, reduced hydraulic capacity and inundation.

# 7. Sequencing (Pathways)

This chapter will focus on combining the results from the exposure assessment, workshop, system and cascades and adaptation options into a conceptual DAPP. The first section will focus on summarizing the system thresholds as an output from the workshop and exposure assessment. The second part will summarize the findings from the high level adaptation options, and their associated ATP's. The last section will combine them into a conceptual DAPP allowing for visualization between different areas, retreat phases and interaction between different implementation methods per area.

## 7.1. System Adaptation Thresholds

System adaptation thresholds emerge from both the exposure assessment and expert input during the stakeholder workshop which comprised a mix of quantitative and qualitative threshold indicators. Thresholds denote when the current system performance is unacceptable and/or unsustainable. For example x cm of SLR (quantitative) and community tolerability of impact (qualitative).

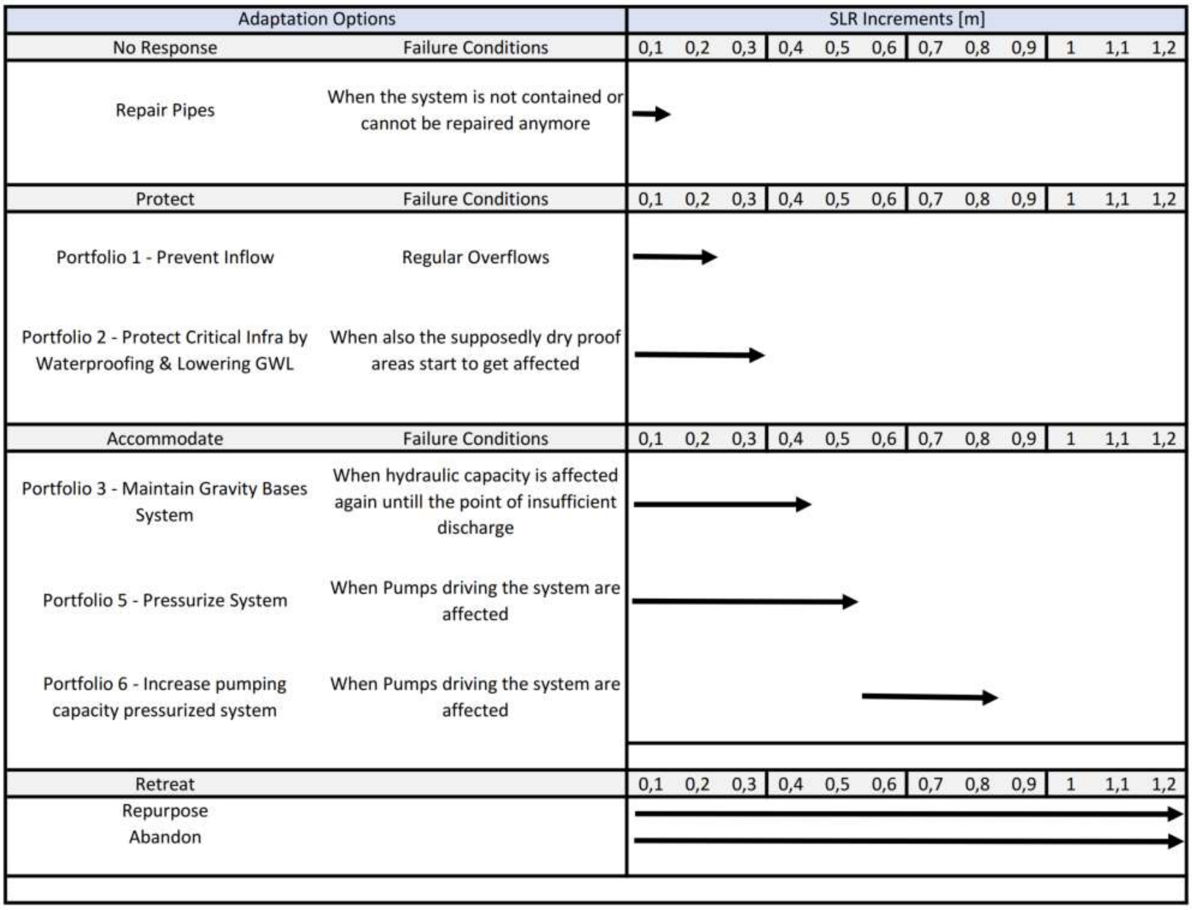
From the exposure assessment and workshop, the quantitative thresholds identified are 0.30 m, 0.50 m and 0.80 m of SLR increments for different assets in different areas. This allows for generating expected pathway scenario-based lifetime and failure conditions. The 0.30 m threshold is associated with the gravity-based system and regular ponding due to increases in GWL. The 0.40 m and 0.50 m thresholds are associated with the wastewater pumps becoming increasingly exposed, all of them by the time 0.50 m is reached and the major increase in the number of manholes and sumps exposed. At 0.80 m, the number of assets affected over different SLR increments tails off. This means that the biggest stresses on the system occur in the first 0.80 m of SLR increments.

The qualitative thresholds are related to observed unacceptable performance from a community and a service provider perspective. The thresholds comprise physical consequences including increasing wastewater overflows, regular ponding due to increased GWL and regular overflows to properties or watercourses.

## 7.2. Option Thresholds

Option (Pathway) thresholds are determined per adaptation option based on their failure conditions. Initially this was done for each of the options. During the research it became clear that a lot of the options would have to be implemented together. Therefore the list of options is simplified into pathway portfolios of actions that would be taken together to achieve the objectives, which can be seen together with portfolio failure conditions in Figure 9. Failure conditions are based on the type of option and the system thresholds. Initially, pathway thresholds were defined per conceptual area 1,2,3, each with their AT. This was to tailor the high-level option categories to area specific option sequences and to optimize the performance of the options in the area.

By calculating the performance of pathways over a range of SLR increments per Sub Area and visualize this with a graph enables identification of possible levels of service across the different SLR increments, depending on the adaptation options chosen. It is decided not to continue with this approach for this study as it would require consideration of an area specific option for each high level category, in each sub area. Dividing up a number of areas would simply be too time consuming because of the detail generated.



| Adaptation Options | | SLR Increments [m] |
|---|---|---|
| **No Response** | **Failure Conditions** | 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1 1,1 1,2 |
| Repair Pipes | When the system is not contained or cannot be repaired anymore | |
| **Protect** | **Failure Conditions** | 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1 1,1 1,2 |
| Portfolio 1 - Prevent Inflow | Regular Overflows | |
| Portfolio 2 - Protect Critical Infra by Waterproofing & Lowering GWL | When also the supposedly dry proof areas start to get affected | |
| **Accommodate** | **Failure Conditions** | 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1 1,1 1,2 |
| Portfolio 3 - Maintain Gravity Bases System | When hydraulic capacity is affected again untill the point of insufficient discharge | |
| Portfolio 5 - Pressurize System | When Pumps driving the system are affected | |
| Portfolio 6 - Increase pumping capacity pressurized system | When Pumps driving the system are affected | |
| **Retreat** | | 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1 1,1 1,2 |
| Repurpose<br>Abandon | | |

*Figure 9: Pathway Thresholds*

During development of two water adaptation portfolios planning options were added to the portfolios in preparation of retreat. Land use planning changes are not consequently related to infrastructure adaptation options, which is different for each area, but in which retreat phase these adaptation options (pathways) are based. A good example is the current planning requirement to raise new development by a mandatory +1.00 m. Table 25 and Table 26 in Ministry for the Environment (2017) are used to illustrate possible planning changes alongside two water retreat, signalling retreat phases identified in Olufson (2019). These are discussed per retreat phase.

### Adaptation Portfolio

The adaptation portfolios outlined in Figure 9 are discussed in this section by area. This will combine the option pathways in the portfolios, the failure conditions and planning signals. The adaptation options within the portfolios are discussed in section 4.3.

### Area 1

#### Portfolio 1 – Prevent Inflow

Adaptation pathways in this portfolio include implementing a non return valve and closing of parts of the system during extreme events. Failure condition occurs when the water is continuously above a level that does not allow to discharge the excess water without pumps, which occurs at +0.20 m. In Area 1 Portfolio 1 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2) and Enabling Investment (3). Associated Planning Conditions with this Portfolio are therefore Conditional Rules, Plan changes and no development.

Portfolio 2 – Protect Critical Infrastructure

Adaptation pathways in this portfolio include dry / wet proofing critical infrastructure like pumping stations and lowering GWL locally around pumping stations with using e.g. vegetation. Failure conditions occur when the gravity based system ceases to function at +0.30 m. In Area 1 Portfolio 2 is related to the retreat phases until Repurposing, at which point the area will be re zoned. This means the area will be anticipated to have a different planning purpose. Active Retreat (4) has a planning condition of closed zoning, meaning the community is actively being moved away from this area.

Area 2

Portfolio 3 – Maintain Gravity Based System

Adaptation pathways in this portfolio include raising nodes and pipes, increasing capacity nodes and pipes and increasing local infiltration and filtering. Failure Conditions occur at the threshold of +0.40 m. In Area 2 Portfolio 3 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2) and Enabling Investment (3). Associated Planning Conditions with this Portfolio are therefore Conditional Rules, Plan changes and no more development.

Portfolio 4 – Pressurize the Drainage System

Adaptation pathways in this portfolio include pressurizing sewers, increasing local infiltration and filtering and adapting pumping stations. Failure conditions occur when the pumps driving the system fail at the threshold of +0.50 m. In Area 2 Portfolio 4 is related to the retreat phases until Repurposing, at which point the area will be re zoned. Active Retreat (4) has a planning condition of closed zoning, meaning the community is actively being moved away from this area.

Area 3

Portfolio 3 – Maintain Gravity Based System

Adaptation pathways in this portfolio include raising nodes and pipes, increasing capacity nodes and pipes and increasing local infiltration and filtering. Failure Conditions occur at the threshold of +0.40 m. In Area 3 Portfolio 3 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2). Associated Planning Conditions with this Portfolio are therefore Conditional Rules and Plan changes.

Portfolio 4 – Pressurize the Drainage System

Adaptation pathways in this portfolio include pressurizing sewers, increasing local infiltration and filtering and adapting pumping stations. Failure conditions occur when the pumps driving the system fail at the threshold of +0.50 m. In Area 3 Portfolio 4 is related to the retreat phases of Community Engagement (1), Planning and Preparing (2). Associated Planning Conditions with this Portfolio are therefore Conditional Rules and Plan changes.

Portfolio 5 – Replacing and / or Raising Pumping Stations
Adaptation pathways in this portfolio include replacing pumps for increased capacity, raising the operating height of the pumps. Failure conditions occur when the pumps driving the system fail at the threshold of +0.80 m. In Area 3 Portfolio 5 is related to the retreat phases until Repurposing, at which point the area will be re zoned. Enabling Investment (3), Active Retreat (4) has a planning condition of closed zoning, meaning the community is actively being moved away from this area.

## 7.3. Conceptual DAPP

After the options were developed they were grouped in terms of costs and time needed for the implementation based on the lifetime and adaptive capacity of the options. This was done using the managed retreat components identified in Olufson (2019) in order to group the different phases displayed in Figure 9. This provides an accompanying 'road map' where each pathway indicates which component of MR is being initiated, and what the actions should be associated with this stage of the retreat.

To illustrate changes in retreat phasing, phases are implemented alongside a traditional DAPP approach. Signals and Triggers are also implemented into each of the DAPP's for the different areas. These are not pathway signals and triggers, but specifically for retreat. This is why some pathways can have multiple signals on one pathway sequence. The trigger is the point where active retreat is initiated, signals indicate a change in retreat phase. Signals are included qualitatively as a result of the workshop. Triggers are linked to the mix of quantitative and qualitative thresholds established for the study area. Pathway triggers and signals are not included as the level of detail required would not be feasible for this study. It is decided to focus on the inclusion of retreat phasing into the phases.

Failure conditions were determined by portfolio, rather than portfolio per area. Some loss of detail has occurred here as different portfolios with pathway options have different failure conditions within different areas. This is also noted in section 4.4.3. For example, Portfolio 5 would not be applicable in area 1 as the pump inundation at low SLR would cease the pumps as they will pump salt water into the system. It does not matter in this case how much the capacity is increased. By iterating and determining the strategy for each of the areas and accompanying it with possible portfolios (preselecting) the conceptual DAPP could be developed and used illustratively within the timeframe of the study. Another component not included in detail in the pathways is costing. Preliminary considerations were made during development of the portfolios but not enough to quantifiably weigh them in relation to other portfolios. How to improve on this and its relevance is outlined in the discussion.

### Area 1

Area 1 has a retreat objective. These pathways are mainly feasible short to medium term because of the low elevation of this area. The focus is therefore on protecting the current system until the point of retreat. Post retreat repurposing options are considered for this area. Due to the low elevation, this area would be suitable for creating extra flood detention, also with nature based options, in the two water system. This way the area repurposed both to provide community amenity by creating ecosystem and recreational benefits and have a positive effect on the discharge capabilities for the two areas. All portfolio options are outlined and a conceptual pathway outline is presented in Figure

10. Threshold for this area is a SLR of +0.30 m as the current gravity-based system ceases to function. The retreat trigger is placed at +0.25 m where around this increment regular ponding and an inability to overcome tide for discharging is expected.

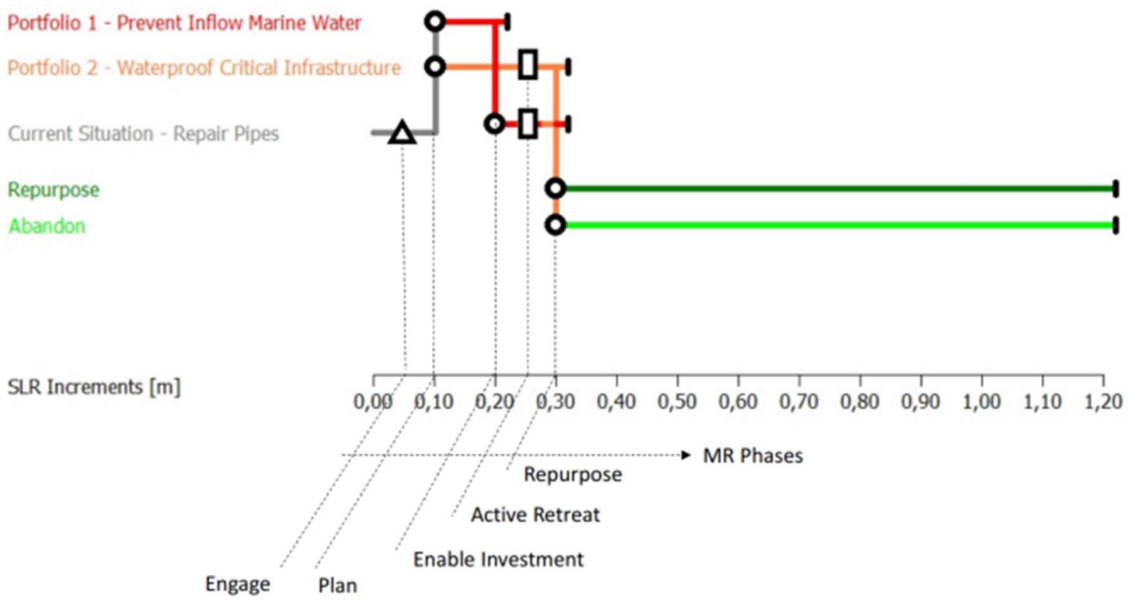


*Figure 10: Pathways Area 1*

Area 2

Area 2 has a retreat objective, but at higher SLR increments than Area 1. This means that pathways should function above the ATP of area 1, which for area 2 is +0.50 m. This results in pathway portfolios that are more focused towards accommodating the existing infrastructure to longer term changes. This could be raising the level of the sewerage system and increasing capacity to the pipes and nodes, in conjunction with nature-based solutions like promoting local infiltration, or switching to a pressurized system. The conceptual DAPP is outlined in Figure 11. There are two approaches illustrated for this area. The first is to maintain the gravity based system as long as possible. Although costs are not quantified in this conceptual DAPP, raising the whole system is extremely expensive, causes major disruption for the community and is limited by the burial depth of the pipes. Before the retreat trigger there would have to be a change to the pressurized pathway portfolio. This is also an expensive option but would be able to maintain service until the retreat trigger for Area 2. Due to the proximity to the coastline, repurposing options could be a natural buffer or recreational zone in between the coast and retreated Area 1.

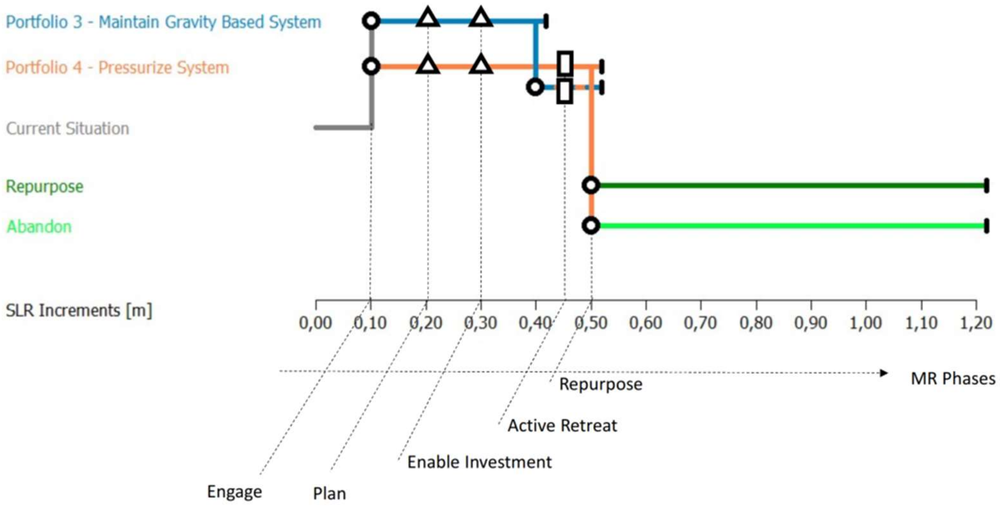


*Figure 11: Pathways Area 2*

### Area 3

Area 3 has the highest ATP for retreat, +0.80 m. Therefore, more long-term options, like combining longer term accommodating options, increased pumping station capacity with a pressurized system, are considered. The conceptual DAPP is outlined in Figure 12. Area 3 has initially a similar portfolio choice as Area 2, where a decision is made between accommodating the gravity based system or switching to a pressurized system. The lifetime of the pressurized system can be extended by initiating the portfolio to increase pump capacity and / or heighten pump elevation. The retreat trigger for this area is pump failure due to a combination of pump inundation and increasingly more saltwater being pumped through the system due to increases in GWL.

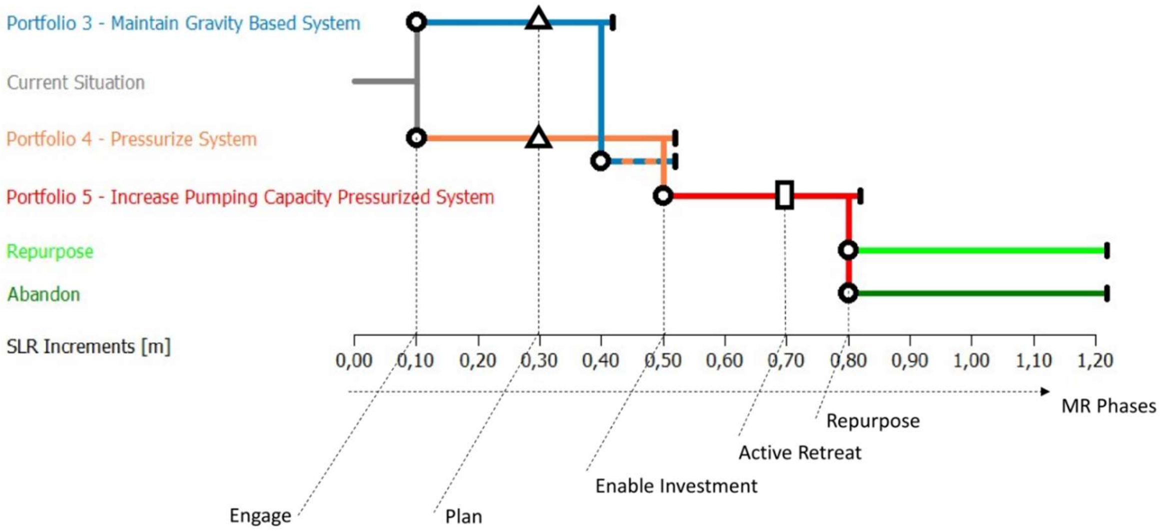


*Figure 12: Pathways Area 3*

### Area Interaction

The parallel implementation of pathway portfolios in each area and the interaction between the portfolios when implemented provides an opportunity to optimize the use of the different options across the whole study area. The possibility of having a visual overview between the different portfolios and pathways in each of the three areas enables the system to be adjusted using a range of different adaptation strategies to achieve the retreat. For example, implementation strategies in the higher elevated part of the study area allow for reduction in discharge in lower parts. This results in lower requirements for adaptation or buys extra time before a pathway in another area has to be changed. This increased flexibility to influence one area by implementing other adaptation options in different areas is crucial of being able to buy more time across the Petone system while the planning and costing of the adaptations are developed and the engineering design undertaken for the retreat over time.

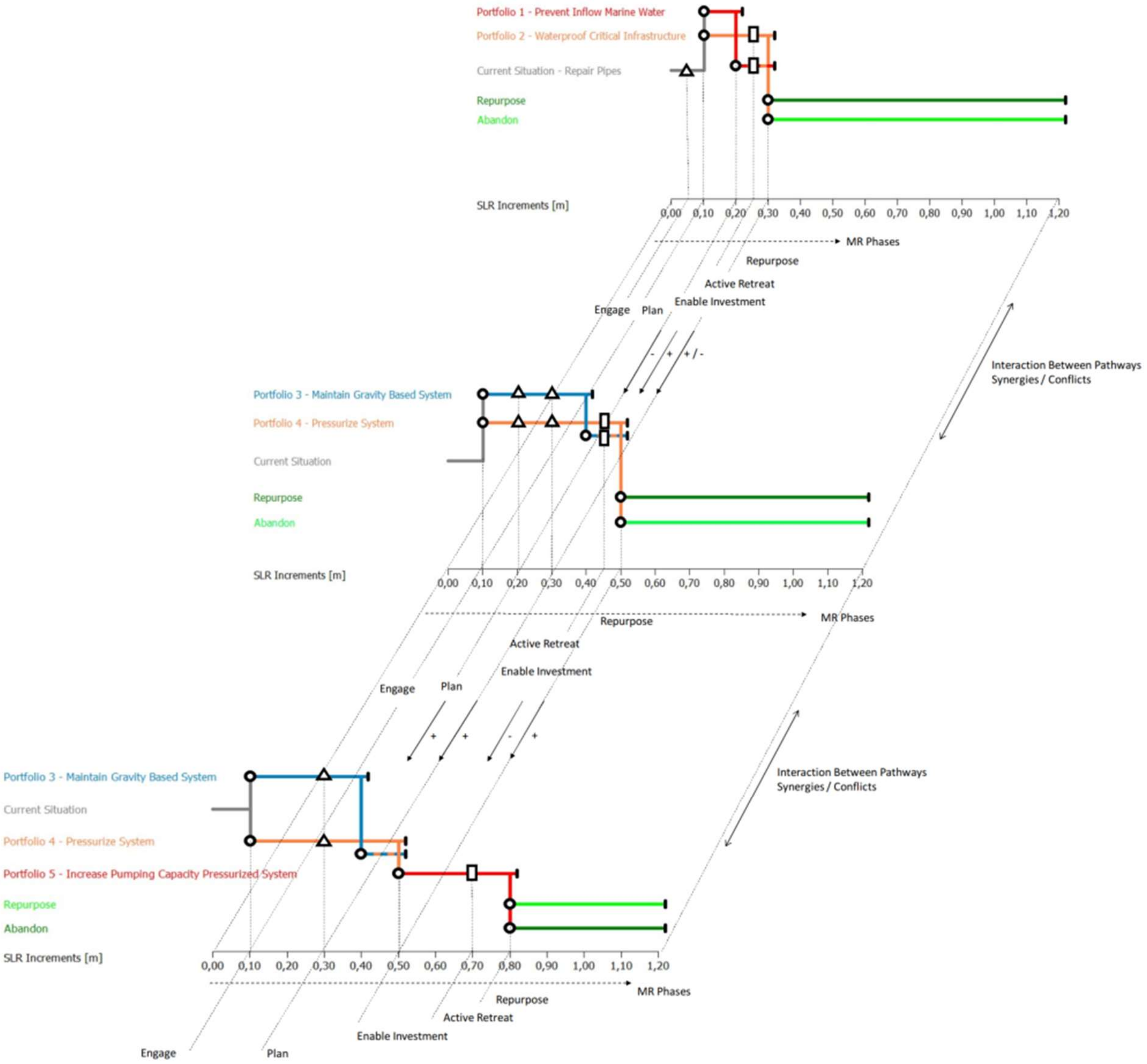


*Figure 13: Conceptual Pathways illustrating Synergies and Conflicts between pathways*

Implementation of an interactive conceptual DAPP assessment for the Petone area is shown in Figure 13. All areas will retreat eventually, but sequencing will be different. The synergies and conflict between pathways in different areas are marked with the arrows showing Synergies (+) and Conflicts (-). Figure 13 shows a conceptual way of indicating the interaction between different pathways in different areas providing an overall dynamic strategy for the area. It first starts with a DAPP for each of the sub areas across the study area. These pathways are selected from the portfolio pathways in

Figure 9, based on the sub area strategy and pathway failure conditions. The thresholds identified for the Petone area are added to the x axis, indicating the need for pathway changes for the current drainage system. For the areas targeted for managed retreat, retreat phases are indicated also along the x axis of the DAPP. Aligning these pathways for each of the areas allows for the visualization of interaction between different areas. Figure 13 shows Synergies and Conflicts between pathway portfolios throughout different retreat phases in each sub area.

This approached also allows for illustrating positive and negative feedback between different options and pathway strategies, depending on the phase of the retreat. For example, initial stages of retreat could create redundancy in the system by leaving the pipes in the ground, but not have the extra discharge from residential / commercial use. This offers a positive effect on the rest of the Petone drainage system. Over time the capacity of this system will decrease, and the assumption is that it will not be upgraded indefinitely because there will be a retreat when conditions meet the trigger point, and there is no benefit from doing so. During repurposing however, retention space could be created to allow for increased water storage capacity that could have amenity and recreational value for the remaining and wider community in the Hutt valley. This again has a positive effect on the pathways implemented for the other areas.

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# Appendix 1 – Adaptation Options

| Adaptation options Stormwater and Wastewater | | | | |
|---|---|---|---|---|
| No Response | Treat Emerging Threats | Applicability | Type | Source |
| Repair | Locally fixes problem | Short Implementation time, Short term effectiveness | SW/ WW | Literature / Workshop / Dialogue |
| | | | | |
| Protect | Protect/Isolate critical infra | Applicability | Type | Source |
| Plant vegetation around pumping station or critical nodes | Locally lower the groundwater table | Short term No regret | SW/ WW | Literature |
| Waterproof underground structure pumping stations | Protects electrical parts and could be accommodated with more corrosion resistant parts | Medium Term | SW/ WW | Literature / Workshop / Dialogue |
| Dry-proof essential infrastructure | Make sure no water is able to enter the perimeter of the critical infra, e.g. isolate outlets | Medium Term | SW/ WW | Literature |
| wet-proof (controllable) infrastructure | Allow controllable flooding, but makes sure critical infrastructure is wet proof | Medium Term | SW/ WW | Literature |
| Real Time Control - RTC | Real Time Control, optimize behaviour of important infrastructure, for example valves, based on certain levels, optimize overcoming tidal difficulties | Medium Term, in tandem with upgraded infrastructure | SW/ WW | Lecture Slides / Workshop |
| local floodwalls | Protect important infrastructure | Long Term | SW/ WW | Literature |
| multifunctional dike reinforcement | Protect important infrastructure | Long Term | SW/ WW | Literature |
| | | | | |
| Advancing | Polder | Applicability | Type | Source |
| Tidal Gate | -form of advancing, controlling water levels | Long Term | SW/ WW | Literature |

| | | | | |
|---|---|---|---|---|
| Move Seaward, reclaim and create buffer | -Decrease Groundwater Table, decrease saltwater intrusion | Long Term | SW/ WW | Literature |
| | | | | |
| Accommodate | Accommodate | Applicability | Type | Source |
| Elevate / Raise Sewer / Re Engineer | | | | |
| Raise minimum sewer connection level (for future developments) | Makes sure the infrastructure is higher up | Short term no regret for new development | SW/ WW | Literature |
| elevate important infrastructure / use elevated zones | Water doesn't reach infra | Medium Term | SW/ WW | Literature / Workshop / Dialogue |
| Re-engineering of Pipes,Canals& control structures | Replace pipes, lift system outlets, lift house systems | Medium Term | SW/ WW | Literature / Workshop / Dialogue |
| Pumping Stations | | | | |
| Raise Pumping Stations | Protects pumping stations from SLR | Medium Term | SW/ WW | Literature / Workshop / Dialogue |
| Increase Pumping Station Capacity | Increase capacity, energy intensive, big investment, increased vulnerability | Medium Term | SW/ WW | Literature / Workshop / Dialogue |
| Modify Sewer | | | | |
| Add a non return valve to prevent sewage overflow | This could help with preventing water going up the pipes in early stages of SLR | Short term | SW/ WW | Literature |
| Pressurized / vacuum sewer | Removes decreased drainage capacity due to change in hydraulic gradient | Short - Medium Term | SW/ WW | Literature / Workshop / Dialogue |
| Septic Tank Closure | Protects from overflow | Short Term | WW | Literature |
| Decentralize System / Treat and store more locally | | | | |
| Facilitate Overflow to additional storage | Delays discharge until system is normalized | Short - Medium Term | SW/ WW | Literature |
| Water treatment at Source/decentralized | Decentralizes the system | Short - Medium Term | SW/ WW | Literature / Workshop / Dialogue |

| | | | | |
|---|---|---|---|---|
| Increase imperviousness / Porous Pavement | Increases filtration, however could result in increases in local groundwater tables | Short Term | SW | Literature / Workshop / Dialogue |
| | | | | |
| Ecosystem Based Adaptation | Increase Natural Adaptive Capacity | Applicability | Type | Source |
| Wastewater Onsite Treatment / Grey Water Reuse/ Decentralize | | | | |
| Onsite treatment of solids | Eliminates need to move solids to centralized treatment | Short - Medium Term | WW | Literature |
| Wastewater reclamation and reuse | Decentralized the system | Short - Medium Term | WW | Literature |
| Sewage effluent to water supply / Sand Filters | Reuse for gray water | Short - Medium Term | WW | Literature |
| Retention / Detention / Basins delay & store water | | | | |
| Retention Ponds | Allows for temporary storage capacity during high rainfall events | Short - Medium Term | SW | Literature / Workshop / Dialogue |
| Detention Ponds | Allows for temporary storage capacity during high river discharge events | Short - Medium Term | SW | Literature / Workshop / Dialogue |
| Infiltration Basins | Allows for local infiltration stormwater and collection | Short - Medium Term | SW | Literature / Workshop / Dialogue |
| water butts/ water squares | temporary storage and local infiltration | Short - Medium Term | SW | Literature |
| Constructed Wetlands and lakes | Allows for temporary storage capacity during high river discharge events | Medium-Long Term | SW | Literature / Workshop / Dialogue |
| implement tidal park | Increase Biodiversity->Robustness | Medium-Long Term | SW | Literature |
| Reuse of of stormwater / Local Infiltration / Water Robust Streets/Blue Solutions | | | | |
| Biofilters | filter pollutions out of stormwater | Short - Medium Term | SW | Literature |
| (Bio) / Vegetated Swales | Channels designed to filter pollutions out of stormwater | Medium Term | SW | Literature |

| | | | | |
|---|---|---|---|---|
| Adsorption Filters | filter pollutions out of stormwater | Short - Medium Term | SW | Literature |
| Green Roofs | Delay Rainwater infiltration into the system | Short - Medium Term | SW | Literature / Workshop / Dialogue |
| Raingardens | Bioretention, locally infiltrates stormwater | Short - Medium Term | SW | Literature |
| water storage and reuse | temporary storage and local infiltration | Short - Medium Term | SW | Literature / Workshop / Dialogue |
| Bioretention Planters | filter pollutions out of stormwater | Short - Medium Term | SW | Literature |
| Vegetated buffers | filter pollutions out of stormwater | Short - Medium Term | SW | Literature |
| Re-vegetation | Promotes local infiltration | Short - Medium Term | SW | Literature |
| Rain tanks | Provides Temporary storage | Short - Medium Term | SW | Literature |
| Sedimentation Tanks | Storage | Short - Medium Term | SW | Literature |
| Urban Forests | local infiltration | Medium-Long Term | SW | Literature |
| | | | | |
| Retreat | Retreat | Applicability | Type | Source |
| Retreat pumping stations | Move them to an elevated location | Medium-Long Term | SW/ WW | Literature |
| close / compartmentalize higher elevated parts system | Close off lower lying parts and move | Medium-Long Term | SW/ WW | Literature / Workshop / Dialogue |
| Sectoral Retreat | Allow for intermediate retreat | Medium-Long Term | SW/ WW | Literature / Workshop / Dialogue |
| | | | | |

## Search Terms used:

For Adaptation Options
"SUD" AND "WSUD" AND "BMP" AND "LID" AND "Urban Drainage" AND "Climate Change"
’’Water Sensitive Design’’

For the impact of SLR on Coastal Urban Drainage Systems:
’’Urban Drainage’’ AND ’’Coastal Flooding’’
’’Urban Drainage’’ AND ’’Climate Change’’ AND ’’Water Sensitive Design’’
’’Urban Drainage’’ AND ’’Integrated Coastal Zone Management’’
’’Urban Drainage’’ AND ’’Sea Level Rise’’ AND ’’Climate Change’’
’’Urban Drainage’’ AND ’’Climate Change’’ AND ’’Sea level Rise’’ OR ’’Tide’’ OR ’’Coastal’’
’’Water Sensitive Urban Design’’ AND ’’Sea level Rise’’

For Wastewater:
"wastewater" AND "Adaptation" AND "Climate Change"
"wastewater" AND "Adaptation" AND "Climate Change" AND ’’Coastal’’

For Case studies Miami:
"Miami" AND "Sea level rise" AND "Wastewater" AND "Stormwater" AND "Utilities"

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