Article

Preparing for Sea-level Rise through an Adaptive Managed Retreat of a Two-Waters Network

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Abstract: Frequent flooding from sea-level rise (SLR) is one of the immediate climate change impacts affecting low-lying and exposed coastal communities. These communities rely upon the delivery of three-waters services for wastewater, stormwater and water supply. Due to ongoing SLR, managing these networks will increasingly be a challenge. This raises the issue of how local government can reconcile maintaining levels of service as the impacts of climate change and their uncertainties worsen over the coming decades (and beyond). Can they be adapted over time to retain levels of service or will they eventually require retreat and if so at what adaptation threshold? This paper explores managed retreat of two-waters infrastructure (wastewater and stormwater) as an adaptation option using a Dynamic Adaptive Pathway Planning (DAPP) approach. In the study, we use DAPP to frame the retreat of two-water networks, developing a combination of an area specific retreat strategy, pathway portfolios, retreat phases, land use change signaling and identify pathway conflicts and synergies. Repurposing retreated areas by utilizing Water Sensitive Urban Design (WSUD) options was found to extend retreat thresholds for adjacent areas. A systematic 'routine' developed in this study provides a structured approach for managed retreat of two-water infrastructure with the aim to reduce future disruption from flooding, signal land use changes early and allow for gradual budget adjustments by the agencies to manage expenditure over time. This approach helps inform and improve the decision-making process for the agencies and the communities they serve, by providing a stepwise process that can be communicated spatially and visually, thereby making a retreat adaptation option more manageable.

Keywords: managed retreat; dynamic adaptive policy pathways; sea-level rise; water infrastructure; stormwater, wastewater, coastal flooding, climate change

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1. Introduction

Sea-level rise (SLR) is one of the more immediate climate change impacts affecting low-lying and exposed coastal communities globally [1–5] and in New Zealand [6–9]. Consequences and compounding hazards induced by SLR include more frequent flooding, increased erosion and increased groundwater levels, saltwater intrusion, liquefaction risk and drainage problems. In New Zealand, rising sea levels especially threaten coastal infrastructure, communities and low-lying ecosystems [10]. National-scale assessments indicate that three-waters infrastructure (wastewater, water supply and storm water) have the greatest exposure of the investigated coastal infrastructure, to SLR [8,11,12].

According to the IPCC, uncertainty in climate change-driven future mean sea level rise is relatively small up to 2050 and in the order of about 0.3 m. Beyond ≤30 years the uncertainty range widens considerable and is highly dependent on future emissions as well as potential climatic tipping points [5]. In New Zealand, Hughes [9] identify that the increase in local groundwater tables resulting from SLR is severely impacting storm water and wastewater systems and pumping stations, but only mildly affects pressurized parts of the conveyance system. It is expected that the increase in mean sea level (rather than episodic coastal flooding events), will have the most wide-ranging impacts on the performance of drainage systems. Several studies highlight decreases in drainage discharge capacity [13–16] and groundwater table issues [13–15,17,18] in coastal environments as a result of SLR.

The reliance of coastal communities on the delivery of utility services such as wastewater, stormwater and water supply raises the question of how a local government or water agencies, which deliver such services, can maintain adequate levels of service as the impacts of climate change and their uncertainties worsen over the coming decades (and beyond). Can they be adapted over time to retain the required levels of service? Or is the only and/ or most cost-effective adaptation option a managed retreat, and if so at what adaptation threshold? Both of these latter questions beckon a third one, namely how such a retreat strategy can be developed and implemented in a staged manner over time?

This study examines these questions through a study of the Petone and Alicetown area, of Lower Hutt near Wellington, New Zealand (Figure 1). The area was historically settled in the late 19th and early 20th centuries to the point where the flood plain of the Hutt River is now largely urbanized (Figure 1). The Petone area is identified as the most vulnerable geographic unit within Hutt City Council, together with the Seaview area, a reclaimed area located next to Petone [19]. Despite the presence of one of New Zealand's most comprehensive flood protection schemes on the Hutt River, protecting the largely urbanized area of the Hutt Valley from fluvial flooding [20], Paulik [8,21] have shown that the wider Wellington region (including Hutt City) has some of the highest pipeline exposure to rising coastal hazards and some of the highest associated replacement costs of all three-waters infrastructure in New Zealand. They attribute this to the effect of SLR compounding larger, infrequent coastal flooding.

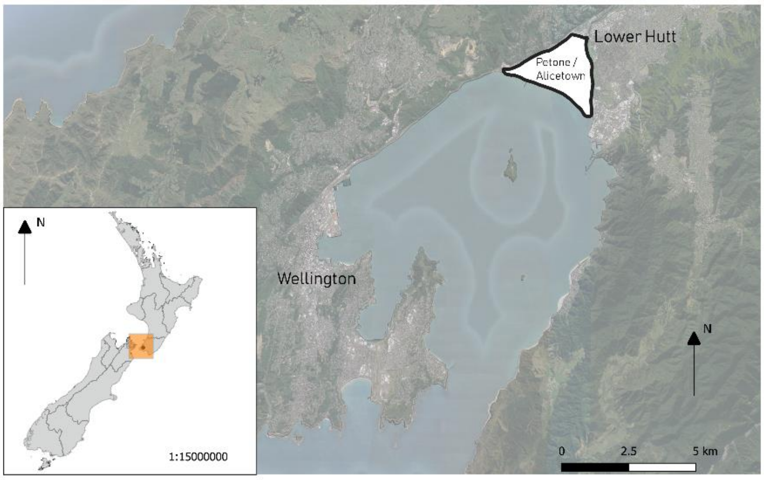

Figure 1: Study Area in Hutt City, Wellington region New Zealand

The local government in New Zealand has a statutory mandate to address the effects of significant natural-hazard risk and climate change, which extends to assessing the delivery of services and the wellbeing of communities. This includes planning to avoid and mitigate adverse effects of natural hazards, reduce flood risk, and encompasses delivery of water services. To date the approach taken by the local government has largely been to address impacts of flooding on the three-waters infrastructure as they emerge [22]. This strategy may suffice in the short term (provided any inevitable service failures can be managed acceptably) but may compound the impacts and constrain future options in the coming decades as the effects of SLR reach adaptation thresholds locally.

Therefore, in order to keep providing reliable services in the context of deepening climatic uncertainty, the limited available resources to upgrade networks will need to be invested strategically in climate adaptation [23].

In this paper, we develop a managed retreat strategy that can anticipate the onset of SLR-related impacts by exploring a number of early actions and longer-term pathways that can allow an orderly and transparent transition to retreat, before physical damage thresholds are reached. We specifically investigate the possible spatial sequencing of the retreat and Levels of Service (L.o.S) of two-water infrastructure (stormwater and wastewater), alongside a community retreat from the coast.

Background

Several district and regional councils in New Zealand are implementing or considering managed retreat as a response to a range of different hazards [24,25]. In this study we define managed retreat as planned retreat that removes people and their assets away from hazards such as sea-level rise and flooding - pre-emptively and permanently [25].

Siders [26] concludes that managed retreat often takes place *ad hoc*, focuses on risk reduction and is typically isolated from broader societal goals. Instead, they recommend long-term strategic retreat aimed at contributing to 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 [26].

The increasing and unfavorable conditions in low-lying coastal areas in New Zealand due to SLR, has motivated consideration of managed retreat as an inevitable adaptation option [25], including the retreat of two-waters infrastructure, in tandem with, or before or after, community retreat. To investigate these options, we apply a conceptual Dynamic Adaptive Policy Pathways approach (DAPP) [27] to the current two-waters infrastructure and to the interface between water services and a community retreat. Hence, adaptation of wastewater and stormwater networks is not exclusively a technical issue, rather it encompasses socio-political dimensions since the infrastructure serves the needs and well-being of the people in the area who are affected by the impacts of SLR impacts and therefore also need to adapt [23,28]. New Zealand's national coastal hazards and climate change guidance recommends a multi-future scenario approach for integrating SLR projections into land-use planning and engineering design, with the primary purpose of stress-testing adaptation options and actions against locally-determined adaptation thresholds [6,29].

The DAPP method [27] aims to facilitate Decision Making under Deep Uncertainty (DMDU) [30], and is well suited for planning infrastructure and community development over time under uncertain changing conditions. DAPP allows for a range of options and alternative future pathways to be explored, accounting for uncertainties and changes over time, to reflect that, policy actions have an uncertain design life and may become ineffective sooner or later as boundary conditions change [31]. DAPP has been adopted in the New Zealand national coastal hazards and climate change guidance [6] with the aim of moving practice from static and time-bound planning to dynamic decision making that enables adjustments over time without creating lock-in of policy decisions [29]. To facilitate this shift in practice to implementable decisions, critically requires the involvement of stakeholders using for example a serious games approach [32] and collaborative decision making [33]. Pathway changes occur when it is clear that the current management will fail to meet the objectives of the strategy - an adaptation threshold, AT. Before the threshold is reached there will be signals that another adaptation option (a pathway that can reach the service performance levels), should be initiated [31]. For example, the ongoing SLR often will reach social coping capacities before the physical threshold is reached [34].

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AT's are defined as the thresholds where boundary conditions are exceeded due to an increasing severity of the hazard and new actions are needed to ensure acceptable performance levels. Thresholds can be identified using technical, environmental, societal or economic indicators [31,35]. An adaptation threshold is found by modelling the system and placing it under increasingly larger stress [36]. AT's can also be identified through moderated processes using scenarios with different conditions representing the stress, using sensitivity testing. Signals and triggers in the DAPP provide early warning (e.g. drop in system performance) and the point at which pathway changes need to be initiated [34]. After a continuing decrease of asset performance due to changing environmental and climatic conditions, a trigger (decision point) is reached to change or implement an option on a different pathway. The trigger needs to build in an implementation window (lead time), appropriate to the next pathway, to ensure the performance of the network does not drop under the pre-agreed adaptation threshold.

While the DAPP approach has previously been applied at the community level and for large-scale projects (e.g. the Delta Project in The Netherlands [37]), little research has so far been undertaken on its applicability as a framework for addressing the adaptation of stormwater and wastewater networks. Notable exceptions include [35,38]. They [35,38] applied a DAPP approach in Singapore and London respectively to investigate stormwater management and infrastructure adaptation pathways using preselected trajectories based on a cost benefit analysis, to enable a better understanding of adaptation timing. Radhakrishnan [39] applied a DAPP approach to the case of fluvial flood protection in the urban setting of Can Tho, Vietnam by adding a coping capacity component, reflecting the community coping capabilities at different scales and derived no-regrets actions by combining short term citizens initiatives with long term planning measures that could potentially delay AT's.

2. Methodology

An integration of different concepts can facilitate the conceptualization of two-waters infrastructure retreat in the context of incremental SLR. Using the DAPP approach, pathways were developed by utilizing adaptation options for two-waters infrastructure to maintain services until the retreat adaptation threshold of +30 cm of SLR, agreed by stakeholders (see below), was reached.

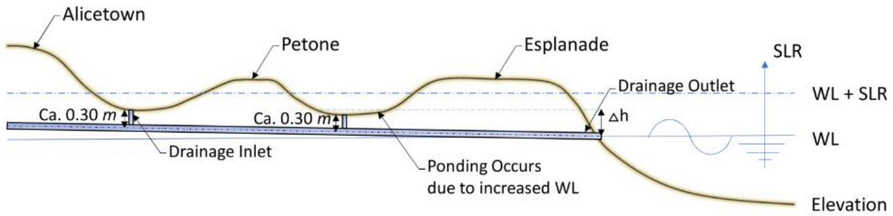

Figure 2: Conceptual Cross Section of the Two Water Network Petone

The study area is serviced mostly by a gravity-based drainage system. Discharge points of such drainage systems are often located at the lowest elevation points of populated areas to maximize hydraulic heads [40]. Therefore, changes in tail water level as a result of SLR have a considerable impact on the hydraulic discharge capacity of the system. This is exemplified in Figure 2 illustrating the conceptual cross section of the elevation and gravity-based drainage system in the study area. Within this domain the vulnerability of two-water assets to SLR was assessed by (a) the amount of exposed two-waters infrastructure assets, (b) how they are affected, (c) at which SLR increment they are affected, (d) and at which spatial location within the study area and each of the two-waters networks this takes place. A schematic overview of our analysis framework is shown in Figure 3 and discussed below.

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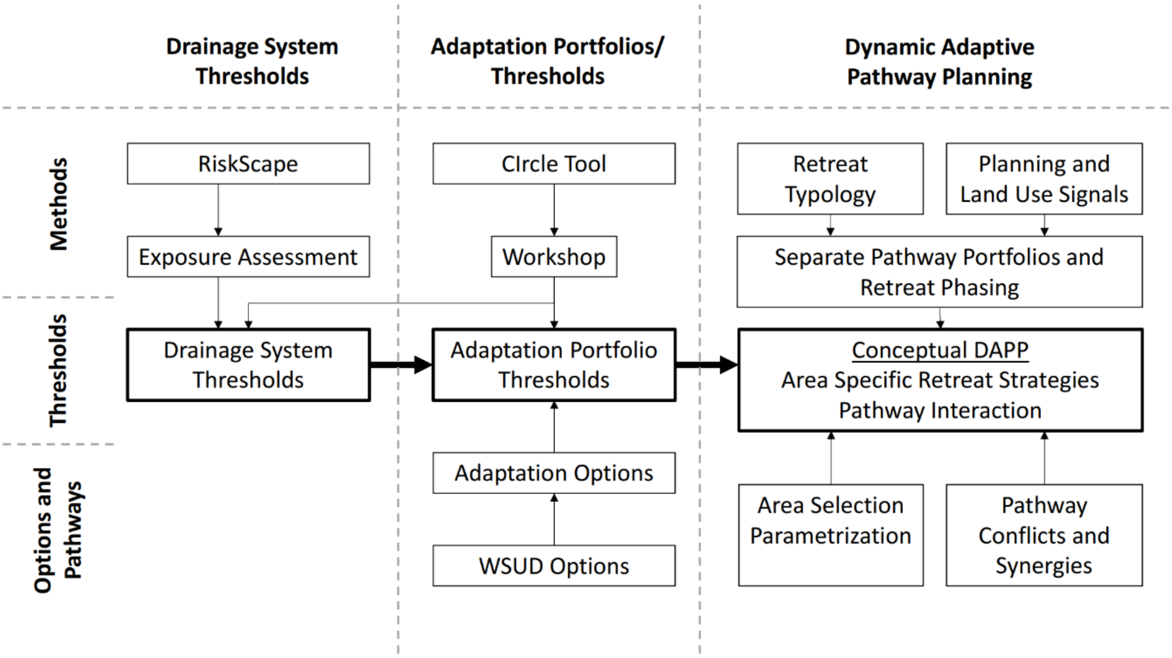

Figure 3: Methodological Framework

Drainage and Stormwater System Thresholds

Drainage System Thresholds were determined from the combined output of a (spatial) exposure assessment and expert elicitation from a workshop held during the research (see below). This resulted in a mix of quantitative and qualitative input. To examine the spatial risk exposure of assets in the study area, hazard data layers for the present-day 1% annual exceedance probabilities (AEP) of coastal flood water levels combined with 0.1 m increments of SLR (relative to present mean sea level) from [8] were used. In this dataset, the coastal flood level comprised storm-tide and wave setup water level in Wellington Harbour [8]. These derived hazard layers were overlain with selected two-waters infrastructure asset data layers, comprising polyline and point data that determined the spatial exposure to coastal flood hazards. The overlays for increments in SLR were mapped onto asset layers for exposure up to +120 cm SLR using RiskScape software [8]. RiskScape is a decision-support and visualization tool that combines the three layers from a Hazard Module, a Vulnerability Module and an Asset Module [41] to generate a spatial realization of exposed assets at risk from infrequent coastal-flood events while taking into account SLR (hazard) increments in the study area.

Adaptation Portfolios / Thresholds

Because retreat AT's for drainage and stormwater infrastructure vary over the study area (due to topography), area specific retreat strategies were introduced dividing the total domain into subareas. This was achieved in parallel with the identification and definition of local adaptation options and adaptation thresholds (conditions under which the option fails to meet objectives). Adaptation options (pathways) were selected from both the literature and expert input from stakeholders, responsible agencies and academics. In order to adapt the current two-water drainage system to the point of active retreat, a systematic approach was used to create a portfolio of adaptation options at subarea level. The adaptation option thresholds summarized the findings from the high-level adaptation options, and their associated AT's.

These elements of our methodology were elicited through a workshop organized with a group of local experts across different functions and professions from the agencies responsible for water infrastructure, land use planning and asset management, to investigate possible adaptation options and drainage system thresholds. During the workshop, interdependencies and cascading effects were identified using the CIrcle tool. The CIrcle tool – Critical Infrastructure: Relations and Consequences for Life and Environment - is a tool developed by Deltares, The Netherlands to analyze and visualize cascading effects of infrastructure networks, to address awareness of critical infrastructure under hazard conditions including from climate change [42]. It does so by dividing critical infrastructure into different categories, with the ability to add direct effects and establish interdependencies and cascading effects, between the different categories under stress (e.g. overland drainage flow, stormwater network and wastewater pumps, stop banks). This aided the optioneering process used and helped with the development of system thresholds and options from different perspectives. One of the options considered was Water Sensitive Urban Design (WSUD), since related methods offer a reduction in peak flow that can extend the use of traditional grey infrastructure in the system [18] and maintain service levels. Siekmann [43] describe WSUD as the intensified use of surface detention and suggest that disconnecting drained areas is a first step in preparing drainage systems for climate change impacts and that it is an easier measure to upgrade than traditional sewer systems, because of a higher adaptive capacity. All options considered took into account that increased perviousness could result in increased ponding [18] in the lower elevated parts of the study area due to the rise in ground water levels caused by SLR.

Dynamic Adaptive Pathway Planning

In order to choose a retreat approach for the infrastructure, a typology, or sequence of phases has to be assumed. Here we adopted the same typology as outlined in Olufson [44] a basis for the implementation of managed retreat, by sequencing options and actions. The typology sets out the following retreat phases: Community Engagement (1), Planning and Preparing (2), Enabling Investment (3), Active Retreat and Infrastructure Relocation (4) and Cleanup and Land Rehabilitation / Repurposing (5). Planning and land use changes signals upcoming alterations associated with changes in the retreat phase. Table 25 and Table 26 in the national guidance [6] were used to investigate these.

As mentioned above, the Petone area was divided into different subareas using elevation and two-water asset exposure intensification as a function of SLR increments. The retreat typology, dictated the different retreat phases alongside spatial planning and land use change signals. By iterating and determining the strategy for each of the areas and accompanying it with possible portfolios (preselected), a conceptual DAPP was developed and used illustratively. The DAPP integrated the drainage system thresholds, adaptation portfolios/thresholds, subarea characteristics and retreat typology. This enabled us to illustrate and investigate the interactions between different subareas, and to identify opportunities for buying time, during which planning and preparatory work can be undertaken to underpin the active retreat phase.

3. Results

Retreat will eventually be necessary at different SLR increments for the entire study area. This is mainly due to the local topography, different elevations and opportunities for making interventions in different areas based on different adaptation thresholds. The sequence of retreat can however be different for different subareas within the study area. Other areas can also help implement retreat in the whole study area by making a spatial shift in retreat phasing within the smaller subareas, each with their unique retreat strategy.

This enabled the methodology set out in section 2 to be presented as a systematic 'routine' to be followed by water managers. For example, in this case:

- Three areas were identified using cross sections of the area in Figure 1 together with information on increased asset exposure with respect to exposure intensification as a function of SLR increments (Appendix A).

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- Subareas were defined and drainage system interactions explored based on the following parameters: asset exposure and intensification, elevation classification (DEM), pumping station exposure, coastline proximity and area opportunities.
- The coincidence and parallel implementation between the area specific options and pathways were used to enable the spatial retreat of services in a managed way.

By following these three steps we examined how area specific adaptations for all areas could be implemented using their inter-relationships to derive a cohesive managed retreat strategy.

3.2. Drainage System Thresholds

System adaptation thresholds emerged from both the exposure assessment and expert input during the stakeholder workshop, comprising 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 based on the stakeholder workshop with expert elicitation, the quantitative thresholds identified were 0.30 m, 0.50 m and 0.80 m of SLR increments, respectively, for different assets in different areas. This enabled expected pathway scenario-based lifetime and failure conditions to be generated. The 0.30 m threshold is associated with the limits of the gravity-based system and regular ponding due to increases in ground water levels. The 0.40 m and 0.50 m thresholds are associated with the wastewater pumps becoming increasingly exposed to flooding, with all of them by the time 0.50 m is reached, and a 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 from a service provider perspective. The thresholds comprise physical consequences including increasing wastewater overflows, regular ponding due to increased ground water levels and regular overflows to properties or watercourses. These can be established from community surveys and council maintenance records.

3.3. Adaptation Portfolios

Adaptation portfolios were developed in order to create pathways that could avoid AT's. Due to the complexity of the drainage system and the importance of an effective implementation of different adaptations, a range of adaptation options with individual AT's and associated signals for land use and planning changes were developed. (Pathway) Thresholds were determined for each adaptation option, based on their failure conditions. The list of possible adaptation options was simplified into portfolios of pathway actions that would, when taken together, achieve the objectives. The failure conditions are shown in Figure 4 and are based on the type of option and the system thresholds. Failure conditions were determined by portfolio, rather than by portfolio per area. However, different portfolios have pathway options with different failure conditions within each area. For example, Portfolio 5 would not be applicable in area 1 because the pump inundation at low sea levels would start to pump saltwater into the system and stop the pumps working. Increasing the pump capacity would not address this.

Adaptation options in pathway portfolios were further divided in different adaptation strategies, all aimed at maintaining service levels and avoiding an AT. Depending on the retreat thresholds for an area, these different portfolios maintain service until this threshold is reached. The inclusion of WSUD options in the portfolios was initially included to extend AT's by delaying entrance to the drainage system in the course of an extreme event, by temporarily storing or facilitating local infiltration until the system has normalized again, thereby increasing capacity. Due to the highly urbanized nature of the study area, implementation of these measures was constrained. By including these measures in the area during the repurposing phase, the increased capacity could extend the retreat threshold in adjacent areas.

During the development of two-waters adaptation portfolios, the role that statutory planning and design codes could play in signaling land use change (as options) within the retreat strategy, were added to the portfolios, in preparation for retreat phasing. These adaptation options were different for each subarea. A good example is Wellington Water's Regional Standard for Water Services, which accommodates SLR by requiring raised floor levels for new developments, based on the sea level rise increment projections in the national coastal hazards and climate change guidance (Tables 10 and 11 in [6]). This standard is serving as a signal for future sea level rise impacts. Another example is the use of Table 25 and Table 26 of the national guidelines for New Zealand [6], that illustrate possible statutory and non-statutory planning processes, methods and techniques that can be used alongside two waters retreat, to enable signaling of the retreat phases in the Olufson [44] typology. These include conditional rules and specifications for new development (1), limiting development in the retreat area by applying plan and rule changes (2), restricting development in the retreat area (in anticipation of a retreat) (3), relocating and preparing the retreat area for a new function (4) and re-zoning (5) by redeveloping the area according to the repurposing and zoning strategy developed in (4).

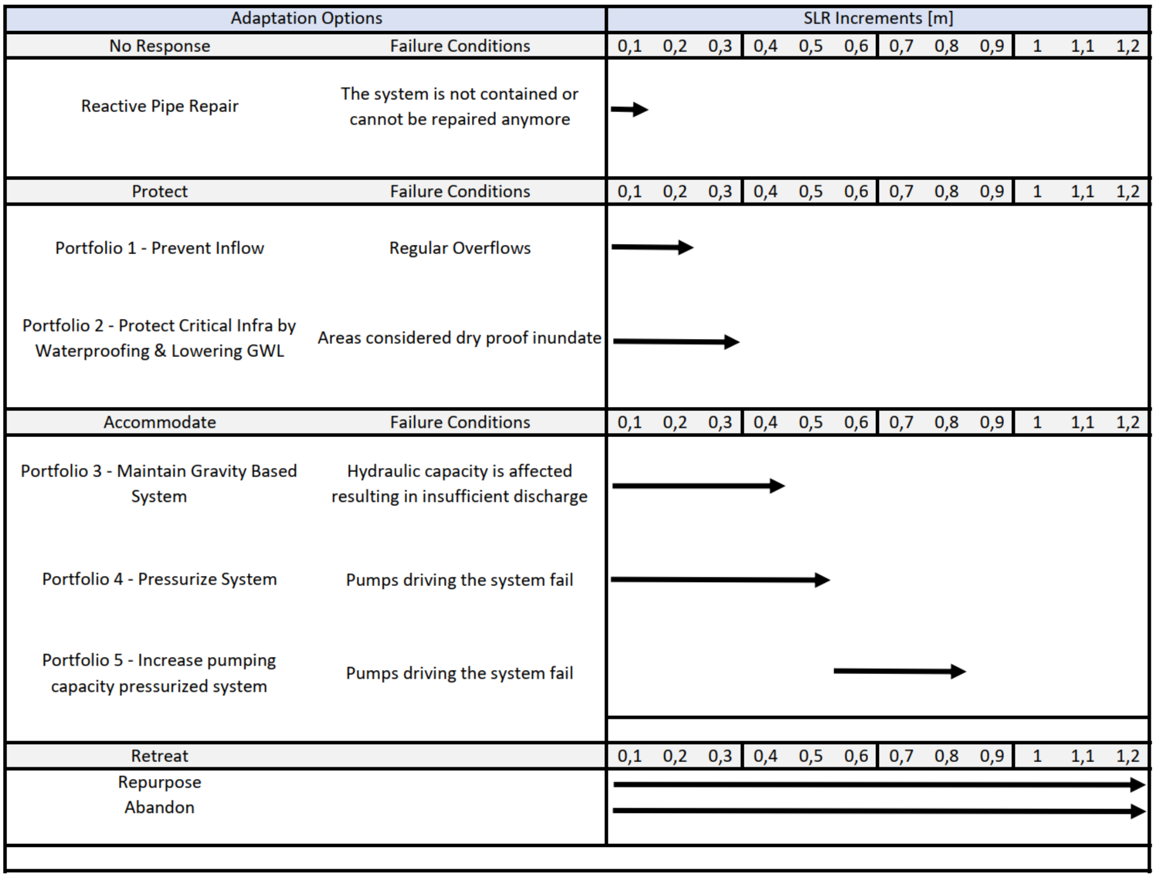

Figure 4: Adaptation Portfolios and Adaptation Thresholds in terms of SLR increments

3.4. Conceptual DAPP

After different options were developed, they were grouped in terms of costs and time needed for implementation, based on their lifetime and adaptive capacity. This was done using the managed retreat components identified in Olufson [44]. This provides a 'road map' where each pathway indicates which component of managed retreat is being initiated, and what actions should be associated with this stage of the retreat.

Figure 5 shows a schematic of our DAPP approach for illustrative purposes. Signals (warning) and triggers (decision points) were identified for each of the DAPP strategies used in the different areas. Some pathways have multiple signals on one pathway sequence. The trigger is the point where active retreat steps are initiated, and signals henceforth indicate a change in the retreat phase. Signals were defined qualitatively based on the results of the stakeholder workshop described above. Triggers are linked to a mix of quantitative and qualitative AT's established across the study area.

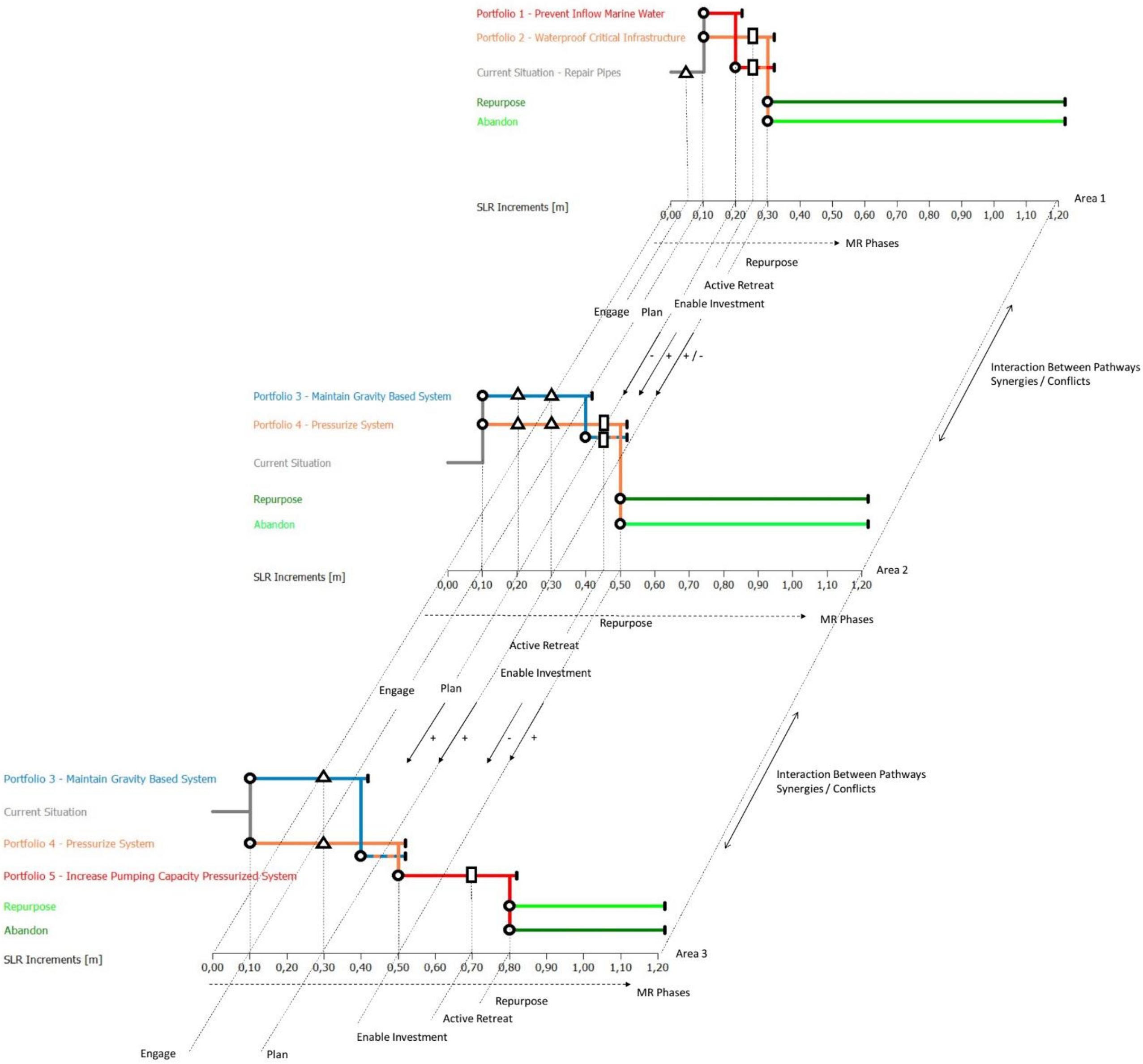

Figure 5: Conceptual DAPP for each of the subareas

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Table 1 summarizes the parameters identified for each of the subareas used in the conceptual DAPP (e.g. system retreat thresholds and considered portfolios). The retreat threshold for subarea 3 is the highest, indicating that this area is most relevant for consideration of more long-term portfolios. This is mainly due to the intensification of asset exposure only being triggered at higher SLR increments. Subarea 1 has the lowest retreat threshold and highest asset exposure over all investigated SLR increments (including critical infrastructure), which is related to both high occurrences of (critical) assets and low elevation above mean sea level. Arguably, managed retreat from this subarea could commence immediately. The intermediate subarea 2 has a high intensification of asset exposure and is located closest to the coastline. Even so, subarea 2 has a higher elevation than subarea 1 and hence an increased system retreat threshold, making it a good candidate to be considered for more transformative portfolios.

Table 1: DAPP properties for each Subarea

	Subarea 1	**Subarea 2**	**Subarea 3**
System Retreat Threshold [m]	0.30	0.50	0.80
Portfolios considered	1,2	3,4	3,4,5
Asset exposure intensification (Figure A1)	Intensification	Intensification	Intensification at higher SLR increments
Planning and Land use Signals	1) Conditional rules and specifications for new development 2) Limiting development in the retreat area 3) Restricting development in the retreat area 4) Relocating and preparing the retreat area repurposing 5) Rezoning by redeveloping the area according to the repurposing and zoning strategy		
Thresholds from New Zealand climate projections[1]			
NZ RCP 2.6 M	Ca. 2070	Ca. 2110	-
NZ RCP 4.5 M	Ca. 2060	Ca. 2090	Ca. 2140
NZ RCP 8.5 M	Ca. 2050	Ca. 2075	Ca. 2100
NZ RCP 8.5 H+	Ca. 2045	Ca. 2060	Ca. 2085

3.5. Pathway Conflicts and Synergies

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 thereby enables the system to be adjusted using a range of different adaptation strategies and to achieve a cohesive and well-managed retreat. For example, implementation strategies in the higher elevated part of the study area allow for discharge reductions in the low-lying parts. This results in lower requirements for adaptation or buys extra time before a pathway in another area has to be changed. The increased flexibility to influence one area by implementing complimentary adaptation options in different areas, is likely to be crucial for buying time across the Petone drainage system, i.e., for robust planning and costing of the adaptation options and the engineering design undertaken for the active retreat phases.

A conceptual way of illustrating the interaction between different pathways in different areas provides an overall dynamic strategy for the area (Figure 5). All areas will retreat eventually, but sequencing will be different. The synergies and conflicts between pathways in different areas are marked with the arrows showing Synergies (+) and Conflicts (-). It first starts with a DAPP for each of the subareas across the study area. 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 identified for managed retreat, retreat phases are indicated also along the x axis of the DAPP.

[1] Use the 4 Representative Concentration Pathway (RCP) scenarios in the Coastal Hazards and Climate Change Guidance [6] Figure 27 to derive thresholds

Aligning these pathways for each of the areas allows for the visualization of interaction between different areas. This also allows for illustrating positive and negative feedbacks 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 pipes in the ground, but not have the extra discharge from residential / commercial use. This in turn might offer a positive effect on the rest of the Petone drainage system. Over time, the capacity of this system will decrease, though. Hence, we assume that it will not be upgraded indefinitely, as there will be a retreat when conditions meet the trigger point, and there is little 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 could have a positive effect on the pathways implemented for the other areas.

4. Discussion

Our paper demonstrates whether and how a dedicated managed retreat strategy can be developed for two-waters infrastructure as a response to sea level rise, based on a study in New Zealand in an area affected by sea level rise. Relevant exposure and vulnerability information for developing a systematic managed retreat strategy was collected and integrated into a framework using a managed retreat typology of retreat components, and a DAPP approach to identify and assess specific options and pathways for the study area. This shows how a managed retreat strategy can be implemented over time. The results of the study can be used by the responsible agencies to facilitate engagement with the local community and to gain buy-in for planning retreat of water services that creates the least disruption to the community and the available investment streams.

Levels of Service

The duration of services, or how long two-water services can be maintained, depends on the characteristics of the retreat phase within the overall retreat strategy of the retreat area. Active retreat should be initiated before the portfolio AT is reached. This is facilitated by signals like planning provisions to warn, and condition-based triggers to decide on options and pathways ahead of the threshold. As illustrated above, this provides a conceptual DAPP that can set out portfolio-specific conditions using SLR increments, thus enabling the different portfolios to be implemented. The duration and L.o.S. depends on the area strategy that is set while developing the retreat sequencing. Not switching to alternative portfolios before an AT is reached, may 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. It is therefore important to not only monitor pathway performance but also implement timely signals and triggers that 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 of signaling these upcoming changes to the community.

During this study and particularly from the stakeholder workshop, it became clear that considerations for retreat were related to the coping capacity of the community. When the coping capacity of the community is lower than the technical threshold, (e.g. while the system is technically and design-wise able to cope with increased periodic overflows, the community impact is unacceptable and/or unsustainable) it could potentially accelerate AT's for retreat. On the other hand, it is also possible that the coping capacity of the community could extend the duration of pathways [39]. Consideration of coping capacity without direct involvement of local stakeholders could result in a loss of community support and potential legal challenges, for example, from local stakeholders having to cope with more frequent flooding, including cumulative nuisance inundation, above their tolerance limits. This stresses the centrality of stakeholder and community engagement in managed retreat planning and decision making.

Measures and pathways

In this study, adaptation options and pathways were developed based on relevant technical and scientific literature, expert elicitation, complemented by an analysis of the drainage system, including its hazard exposure. Ideally, a unique set of pathway portfolios could be developed for each of the different retreat subareas. The reason for this is that the different adaptation pathways are likely to perform differently in each subarea. Hence, dedicated portfolios are likely to yield a more accurate indication of AT's and improve the ability to quantify pathway performance. In this study, subareas were defined by a list of key parameters representing Petone/ Alicetown, rather than explicit geographic boundaries. WSUD detention and/or retention options were found to be constrained by their large spatial requirements. Since the study area is heavily urbanized and relatively densely developed, these spatial constraints limit the possibility for immediately implementing effective WSUD measures for two-waters adaptation. However, upon finishing the active retreat phase, the area could be repurposed, opening up such measures for use in the strategy. Hence, during this phase, some pathways will offer opportunities to create amenity for both the community and the two-waters drainage system depending on the pathway implemented. A water retention space in the form of a natural water body or a park could create recreational and ecosystem benefits while creating extra storage capacity for the stormwater drainage system, thus extending the initiation of the active retreat phase in adjacent areas.

The proposed approach for implementing area-dependent retreat strategies essentially 'buys time' for residents and authorities, that is, for residents to manage their own retreat and for authorities to stage their retreat budget more gradually over time. That said, this could potentially create unrealistic expectations for residents in areas that are retreated at larger AT's. Thus, the extra time might alleviate the ''pressure'' of the eventual move and create a false sense of security under current conditions. Meanwhile, property values are likely to be detrimentally affected over time, depending on how the retreat is funded [45]. There is also a reputational and legal risk for Wellington Water and the council, if they claim that water services can be provided until a defined SLR increment, and then, due to sudden disruption, this turns out to be unfeasible. At the time of this study, multiple service failures occurred nearby in Wellington City signaling vulnerability in the drainage systems regionally. Similar evidence may be drawn from the Matata case in New Zealand [46] where a community rebuilt in the same place after a debris slide some years earlier after receiving disaster funding, only to find down the track that the protection proposed was unfeasible.

Signaling planning and land use changes for the community and relevant stakeholders can enable changes in retreat phases and service levels to be anticipated. Currently, there is a signal provided by the Regional Standard for Water Services implemented by Wellington Water, which requires raised floor levels for new developments to accommodate future sea levels. 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 and adjacent properties. This in turn 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.

Sequencing and withdrawal

The retreat typology drawn from Olufson [44] is based on a signaling approach, where the community starts to withdraw as part of a planned proactive retreat strategy. Alternatively, the council could start to withdraw services. Some councils in New Zealand have signaled that service levels for infrastructure will be reduced or some services will not be provided anymore as coastal inundation becomes more frequent[2]. Following the typology outlined in Olufson [44] and the lessons learned in Lawrence [25], buy-outs or compensation could initiate house relocation or removal, before a service level change is signaled. In a post-disaster scenario, where service levels are compromised as a result of an extreme event, community retreat sometimes happens as a reactive response [47]. 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 use of repurposing options for the retreated subareas, thereby precluding the creation of recreational or ecological amenity for the community, causing disruption of retreat of adjacent subareas. This would accelerate the AT's SLR increment for retreat in those areas.

The coincidence and parallel implementation of area-specific strategies can potentially enable the spatial retreat of services in a managed way. Planning signals can also be added to the pathways, to help initiate the planning process, measures and methods. Such changes will be necessary to facilitate community retreat. The planning signals are not consequently related to different portfolios of options for each area. Rather, to the retreat phase where the portfolios are based. When used as part of our systematic 'routine', identified pathway conflicts require another iteration to either redefine pathways or create measures mitigating the effects of these conflicts. The 'routine' developed consists of the following elements outlined in Figure 6 and can be used as a decision tree.

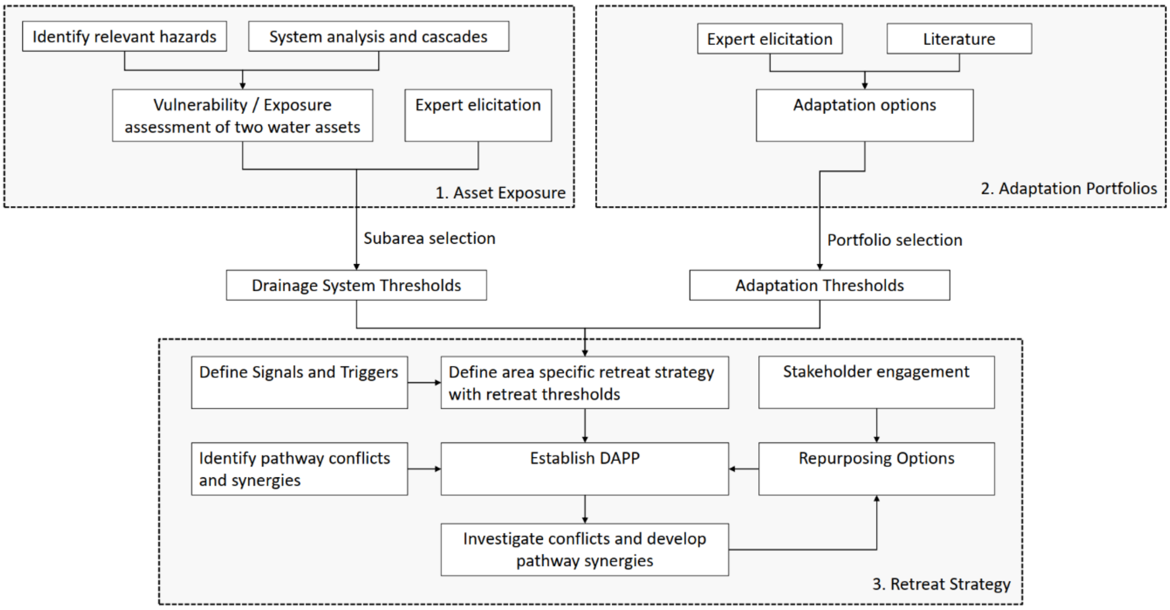

Figure 6: Decision-tree 'Routine' for managing the retreat process for network infrastructure

At all steps alongside this 'routine', it is critically important to involve relevant stakeholders for validation, to contribute to the steps taken. Local expert knowledge combined with community input would minimize chances of critical aspects being overlooked, embed community understanding and develop the much needed 'buy in' to the strategy, thus aiding implementation.

Further considerations for managed retreat strategy development

Several methodological considerations can be considered for the routine developed in this study. The first relates to the use of DAPP signals and triggers in conjunction with planning/land use measures and retreat signals and triggers. Implementing DAPP signals and triggers by developing pathway/portfolio lead times, can enable a more detailed pathways assessment to be undertaken. Quantification of service duration and L.o.S. based on full scale hydraulic analyses would enable a more detailed assessment of the conditions under which pathways have to be changed to maintain

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

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service levels for the community. This will provide a more complete basis for discussion with the community and the local council. Involving the community and other stakeholders in investigating what they currently perceive as unacceptable disruption (threshold conditions) that could inform their retreat decisions, and what their changing expectations might be in terms of L.o.S., will also aid future decision making and produce a greater consensus on the establishment of AT's.

The second, relates to the costing of the adaptation portfolios which could aid the decision-making process; by assessing the costs and benefits of the different pathway options and by showing how budgets for managed retreat can be staged over the lifetime of the different pathways. This also includes accounting for variation of cost/benefits over time. There will be an inflexion point where maintaining the system to keep up L.o.S. becomes unsustainable economically and/or with public health and safety considerations. These will influence both the retreat phasing and AT's for the retreat portfolios. Showing the staging of costs between the current reactive approach and a proactive long-term retreat approach, could enable the agencies to consider a change in strategy that allows for smoothing of budget allocations over the lifetime of the investments needed for retreat of two water infrastructure. This would reduce the disruption of sudden large costs associated with current reactive modes of decision making.

Finally, there is the matter of how a managed retreat strategy can be communicated to the community, and its involvement in the managed retreat process. As already stated, two-waters infrastructure adaptation, and its retreat is not exclusively a technical issue, it has equity, financial and political implications that are non-trivial for the community, stakeholders and agencies. Efforts have been made in this study to consider community-relevant issues by including planning and land use implications into the retreat 'routine' and by identifying the need for community engagement in developing the related signals, triggers and adaptation thresholds. Community involvement is critical for gaining support and the momentum needed to start systematically implementing the step changes over a long-term planning horizon. This will help to avoid high levels of disruption and lower the cost of addressing sea-level rise hazards after the damage has occurred.

5. Conclusions

Using a DAPP approach to frame retreat in different areas can help to address the deep uncertainties arising from SLR, when implementing a two-waters retreat strategy and to visualize how a retreat of water infrastructure could be implemented across a community. In our case, this was made possible using a combination of (1) an area specific retreat strategy, (2) area specific pathways, (3) area specific retreat phases, (4) land use change signals and (5) by identifying pathway conflicts and synergies. The systematic approach that emerged provides a suitable framework for approaching two-waters infrastructure retreat in coastal communities facing similar hazards and could help garner community understanding and 'buy in' to the managed retreat adaptation option.

By combining quantitative input parameters with expert elicitation and using network system adaptation thresholds of +0.30 m, +0.50 m and +0.80 m, pathway portfolios were developed, different suites of actions, land use planning implications and failure conditions were identified. This was found to be useful for determining pathway/portfolio changes linked to sea level rise and was combined using community-based signals and triggers. By separating the retreat phasing from the pathways enables the effects between these pathways to be visualized. Further, this approach provides the basis for a systematized 'routine' that can be used by water managers when developing managed retreat strategies.

To the authors' knowledge, this is the first study to develop a framework for preemptive two-waters infrastructure retreat where SLR is the driver. For the Petone and Alicetown area, adaptation decisions are made collectively by Wellington Water, the local council (Hutt City) and the community

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for two waters infrastructure. This includes whether to continue along the current pathway of reactive maintenance and repair 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 whether to embrace a proactive approach where adaptation to SLR is undertaken in a more cost-effective and systematic manner with less overall disruption. The DAPP provides a framework for conceptualizing and organizing how to move from reactive decision making, to a more proactive and anticipatory mode of decision making that can include managed retreat in the planning process. The DAPP can also encompass consideration of the many implementation issues such as funding and equitable compensations, planning of land use changes by signaling these early so as to minimize disruption, and enables amenity to be created by the repurposing of retreated areas.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used Conceptualization, RB, JL, RK; methodology, RK.; software, RK; validation, RK, JL; formal analysis, RK; investigation, RK; resources, RK, JL.; data curation, RK.; writing—original draft preparation, RK; writing—review and editing, RK, JL, RB, MD; visualization, RK; supervision, JL, RB, MD.; project administration, JL.; funding acquisition, JL. All authors have read and agreed to the published version of the manuscript, please turn to the CRediT taxonomy for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Appendix A

The output for a current 1percent AEP event in Figure A1 was developed using a 'heatmap' based on a Kernel Density Estimation and provides a value based on the occurrence of points in the proximity of an area. It shows 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. Although this produces non-quantifiable values, it is very effective in pinpointing a high occurrence of points, or in this case, assets. Comparing this to a 1percent AEP event +0.50 m, it becomes clear that throughout the different thresholds, intensification of asset exposure occurs in the same 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.

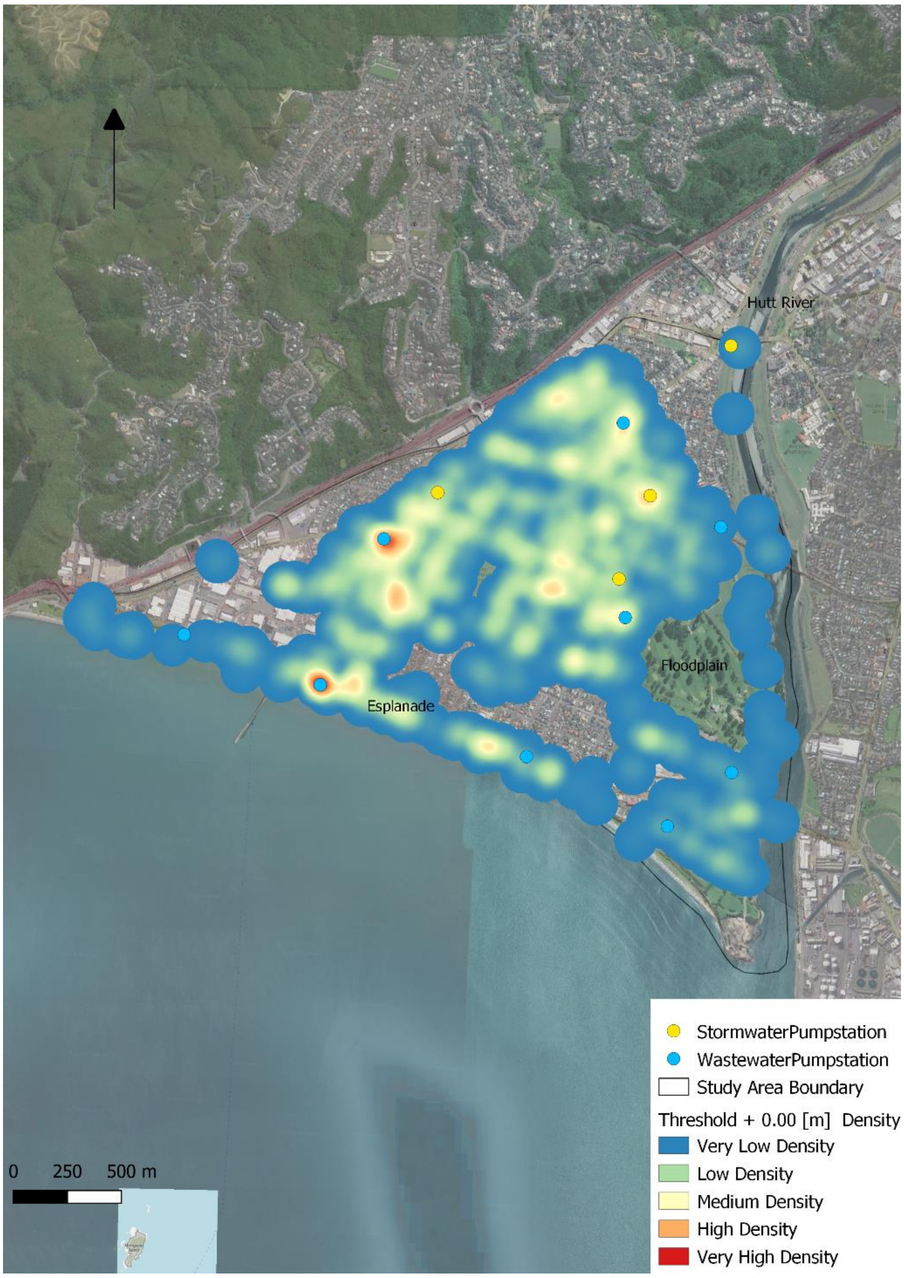

Figure A1: Location of asset exposure intensification at a current 1percent AEP event

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