Value for money Resilience: Nature-Based Solutions for New Zealand's Urban Transport Networks

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Abstract

Coastal urban environments are increasingly vulnerable to the impacts of flooding, driven by both climatic factors—such as sea-level rise and extreme rainfall—and anthropogenic influences, including land use changes and urban densification. In New Zealand, floods are the most frequent and second most costly natural disaster, following earthquakes. Global projections estimate that flood-related economic losses will continue to rise unless adaptive strategies are implemented. Nature-Based Solutions (NBS) have emerged as a promising umbrella framework for addressing both environmental and societal challenges using naturally occurring systems and processes. Within the urban water management context, sub-frameworks such as Water-Sensitive Urban Design (WSUD), Green-Blue Infrastructure (GBI), Low Impact Development (LID), and Sustainable Urban Drainage Systems (SUDS) offer practical strategies to mitigate flood risks while delivering co-benefits for communities.

Keywords: Nature-based solutions, transport resilience, flooding, green infrastructure, Petone

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3.1 Background

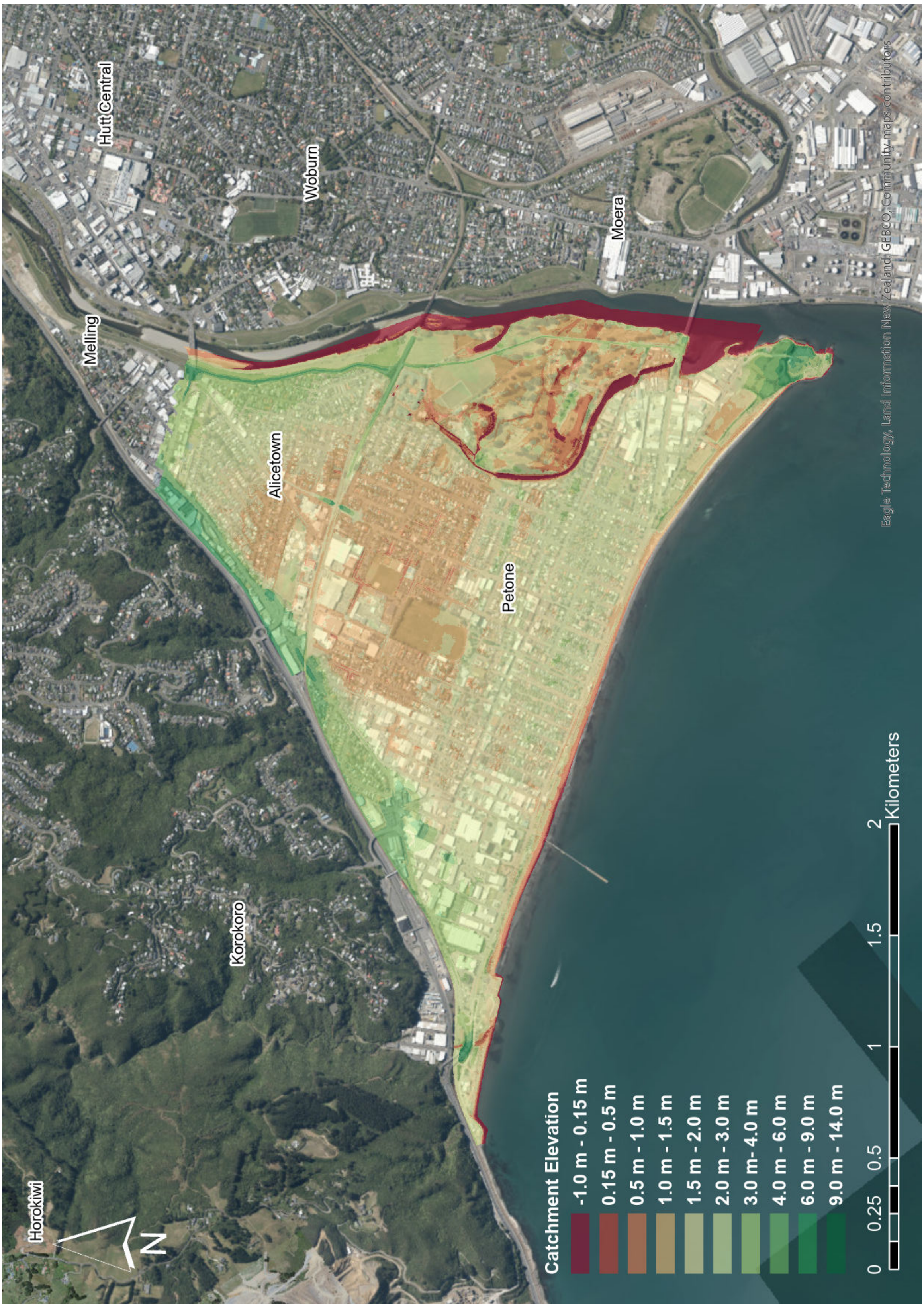

Figure 1

Elevation of Petone

3.1.1 Case Study Area

3.2 Research Question

3.2.1 Research Objectives

- To identify which critical transport assets within the Petone-Alicetown catchment are vulnerable to flooding (coastal inundation, pluvial, fluvial) under current and future sea-level rise and climate scenarios as identified in the IPCC sixth assessment report and downscaled by NIWA (Andrews, 2023).

- To design and evaluate the technical feasibility of selected adaptation scenarios which highlight the use of NbS for addressing both coastal inundation and flooding from extreme rainfall compared to traditional grey infrastructure approaches, and to consider their role in a longer-term retreat strategy for Petone.

- To examine the cost-effectiveness of the selected adaptation options given the regulatory, financial, and governance barriers to their implementation within Hutt City's existing urban transport system.

- To consider how the implementation of larger proposed transport projects (Cross Valley Link, River Link, Petone to Grenada) may:

  - Alter the adaptation needs for the Petone-Alicetown catchment, and

  - Be integrated with NbS adaptation options.

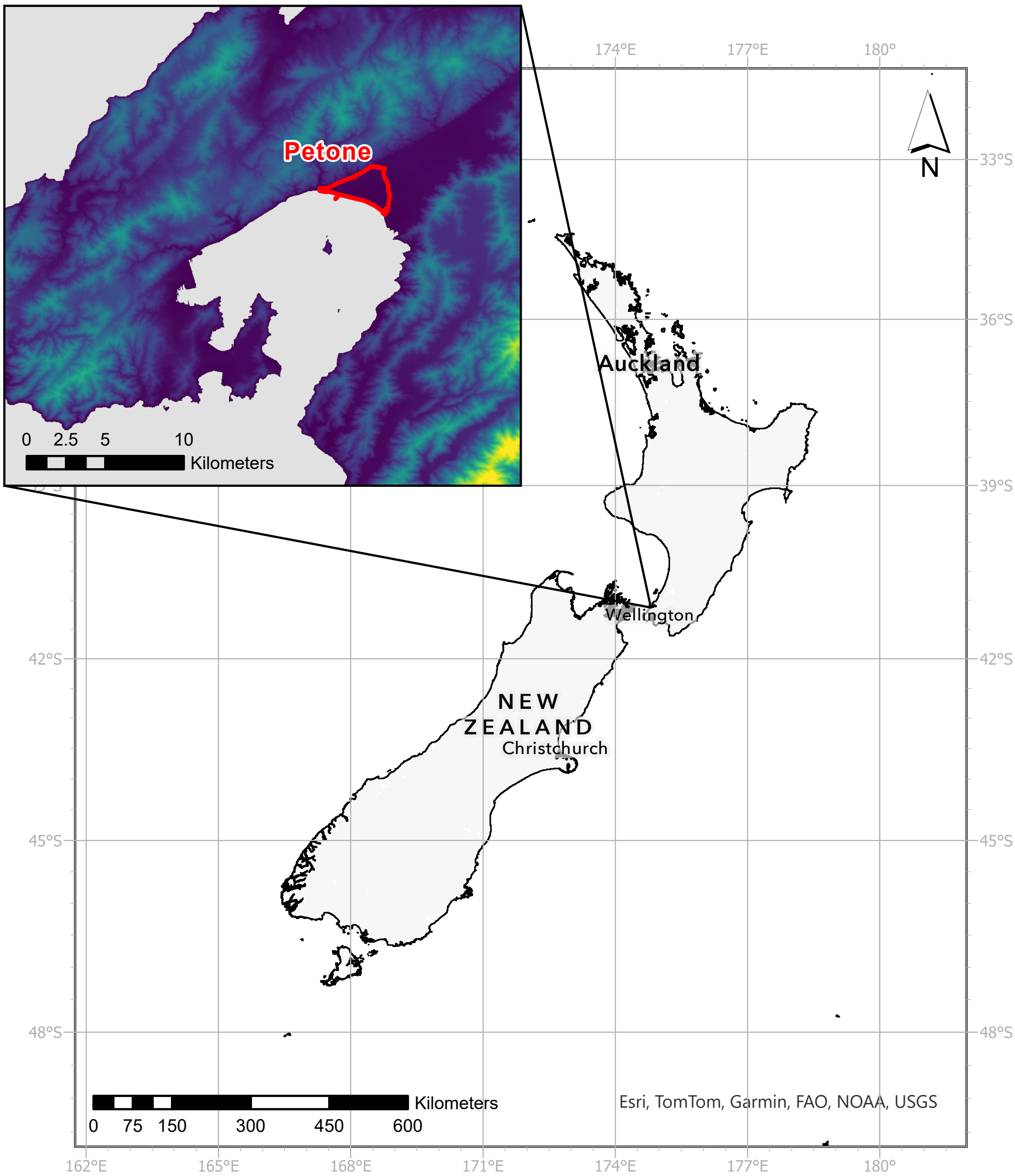

Figure 2

Caption

3.3 Thesis Outline

4 Literature Review

4.1 Flood Risk

Flooding is one of the world's most pervasive natural hazards, with approximately 1.47 billion people, or 19 percent of the world's population, directly exposed to significant risks during 1-in-100-year flood events (IPCC, 2023). The strategic benefits of settling near the coast, including the ease of trade, access to food and other resources, and simply its unique sense of place has meant that globally approximately 896 million people live in low-lying coastal areas. However, accelerating urbanisation rates in areas predisposed to flood risks combined with a changing climate means that major coastal cities, including New York, Jakarta, Dhaka, and Amsterdam, are experiencing increased flood vulnerability (Caljouw et al., 2009; Haque et al., 2010; Kim & Newman, 2019; Madajewicz, 2020). Even with significant advances in flood management technology, it is claimed that humanity is more exposed to flood risk today than ever before (White, 2013).

This trend of growing exposure is no different in New Zealand, where a major flood occurs every four months on average, each resulting in average damage costs of $2 million NZD, for the last 40 years (Crawford-Flett et al., 2022). Paulik et al. (2023) estimated that 441,384 residential buildings are exposed to flood hazards in New Zealand, with a replacement value of approximately NZD $218 billion, a figure that continues to grow despite increasing knowledge of the exposure to flood risk throughout the country (Hughes & Sharman, 2015; Levy et al., 2023; Naish, Levy et al., 2024; Paulik et al., 2023). As sea levels rise and the severity of extreme rainfall events increases (for the Environment & NZ, 2023), coastal developments are increasingly exposed to more frequent and severe natural hazards, including inundation, erosion and shoreline recession (Storey et al., 2024).

Strategies to manage this growing risk in New Zealand are becoming more integrated into policy and decision-making practices (Schneider et al., 2020; Storey et al., 2024, 2025), however the reality of responding to flood risk in existing coastal urban areas is that a highly complex and nuanced approach is required to ensure an equitable transition to a resilient future (Hughes & Sharman, 2015; T. M. Logan & Guikema, 2020)

This chapter evaluates the existing research identifying flooding as a core threat to the function of urban communities situated in the coastal zone (Fu et al., 2023; Kool et al., 2020; Pennington, 2025; Schneider et al., 2020; White, 2013). It begins by defining flooding, its sources, and its primary climatic and anthropogenic drivers, then focuses on the hazard terminology used to describe flood risk in the context of community resilience. The distinctive patterns and processes which contribute to flood risk in New Zealand's coastal settlements will then be discussed. It also examines how floods are predicted and how the uncertainty associated with these predictions is managed. Finally, the emerging paradigm shift from technocentric flood management towards resilient, nature-based approaches is introduced (White, 2013). A clear understanding of the risk which flooding poses to communities allows for the development of adaptive management practices for coastal urban areas like Petone.

4.1.1 Defining Flooding

The first challenge of responding to flooding in urban areas is understanding the subjective nature of the phenomenon. As Pennington (2025) explains, the phrase 'fixing flooding' can refer to addressing minor nuisance flooding on a private property, or much more convoluted strategies, such as the relocation of Indonesia's entire capital city from the subsiding, flood-prone Jakarta to Nusantara (Perwira et al., 2024). Ultimately, how flooding is defined shapes the design of flood adaptation policies (Schneider et al., 2020), placing importance on clearly identifying the nature and severity of flood risk present in a given area, such as the Petone-Alicetown catchment.

Assessing and responding to floods is the domain of multiple disciplines, including hydrology, sociology, economics, geography, and environmental science (Solin & Skubinčan, 2013). Differing priorities of each discipline have resulted in varying definitions of the term ‘flood’ within the literature (Fu et al., 2023; Organization, 2011; Pennington, 2025; Ward, 1978; White, 2013). However, a practical definition of flooding used in hydrology, concerned with the study of the volume, storage, and movement of water within the earth’s system (Salas et al., 2014) (see figure 3), is given by the World Meteorological Organisation: ‘the, usually brief, rise in water level of a stream or water body to a peak from which the water level recedes at a slower rate.’ (Organization, 2011). This simplistic definition recognises that flooding is periodical in its nature and can be considered a naturally occurring state of a water body, akin to drought conditions (White, 2013). The lack of a single quantitative value also emphasises that flood levels are catchment specific (Pennington, 2025). Although this definition is helpful to contextualise flooding within the hydrological cycle, a different framing of the concept is required to understand its impacts on people and society.

The European Parliament and Council (2007) addresses this issue by providing a helpful distinction between ’flood’ and ’flood risk’. Here, a flood is defined as ’a temporary cover of land by water’, while ’flood risk’ is ’the combination of the probability of a flood event and the possible adverse consequences for human health, the environment, cultural heritage and economic activity.’ This recognition that there is a connection between social systems and the natural environment highlights the human responsibility to find appropriate ways to manage flood risk. Wang et al. (2022) also provide a description of flood risk, which shifts the perspective of floods as an ’act of god’ to the idea that the risk is constructed by societal choices to develop urban environments in flood-prone areas.

This definition also uses the concept of probability to describe flood risk. Probabil-

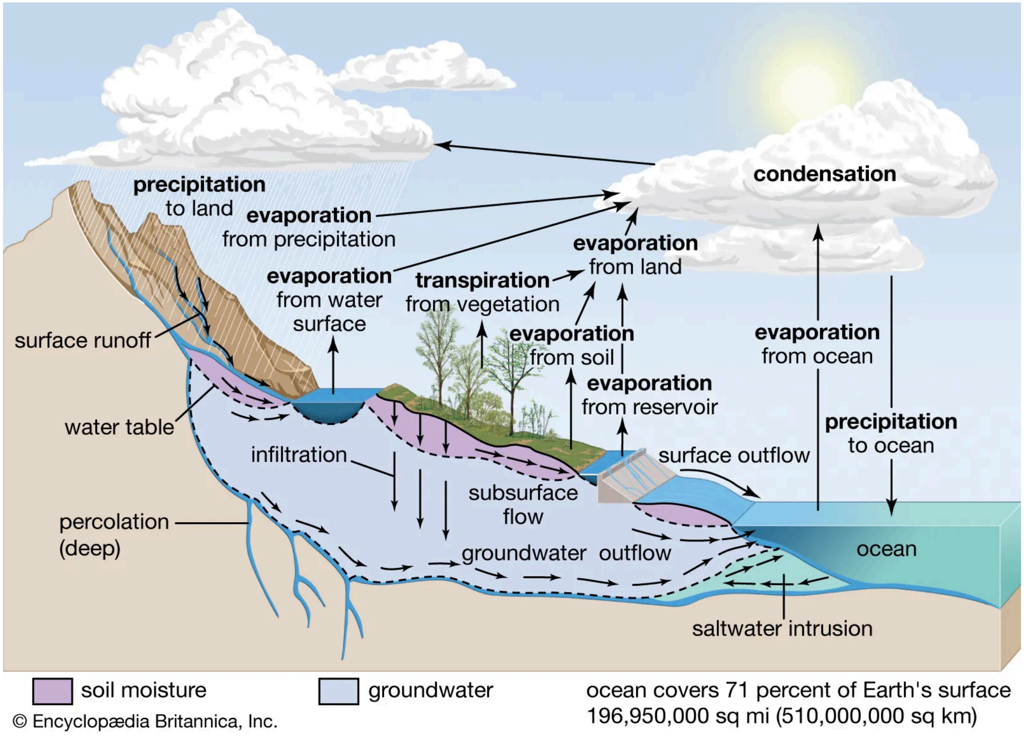

Figure 3

Graphical description of the transfer of water within the hydrological cycle

ity is a key part of flood frequency analysis (FFA), which is concerned with predicting the likelihood of flood events of varying severity (Dalrymple, 1960). Two key statistics used in FFA are Average Return Intervals (ARIs), which describe how often a flood of a certain magnitude will occur within a certain timeframe, and its inverse, Annual Exceedance Probability (AEP) which gives the percentage chance of a flood of such a magnitude occurring in any given year (Morrill & Becker, 2018). Constructed using historical, catchment-specific rainfall-runoff data, this mathematical framing of risk is beneficial for engineering design and residual risk management purposes. However, given that change to climatic and land-use condition can affect the relevance of past flooding as a predictor of future flooding, the use of AEP as a reliable flood severity metric has been questioned (Machado et al., 2015). AEP is used as a descriptive statistic throughout this thesis, with the recognition that the metric can be misinterpreted within the public sphere. Methods for managing this misinterpretation are explained later in the literature review. AEP provides a baseline for comparing flood scenarios and developing adaptation choices.

The intention of this thesis is to address Petone's growing exposure to moderate flood events due to rising relative sea levels and increased storminess (for the Environment & NZ, 2023). This is to be achieved by improving infrastructure resilience, particularly through adjustments to the transport network, while considering that a degree of residual flood risk is likely to remain even with these improvements. To guide this goal, this thesis adopts a working definition of flooding as follows: 'An excess of water that surpasses the capacity of the urban stormwater system, leading to unwanted inundation that challenges a community's ability to maintain essential urban functions and adapt to changing conditions over time.' This definition allows for flexibility and innovation in the approaches used to manage flooding.

4.1.2 Sources of Flooding

It is evident from past flood events that any flood of sufficient severity has the potential to damage interdependent infrastructure systems within urban environments. However, several scholars have noted that making a distinction between the source of flooding within a catchment area is critical (**Pozo2023**; Chormanski et al., 2011; White, 2013). These distinctions influence the design of flood defences, land-use planning, stormwater infrastructure, and emergency response protocols.

Ward (1978) gives attention to the physical catchment properties, including soil type, topography, land use, and catchment size, that shape both the causes and intensity of flooding (see figure 4). White (2013) identifies four primary types of flooding: (1) flooding from watercourses, (2) surface water and drains, (3) coasts and estuaries, and

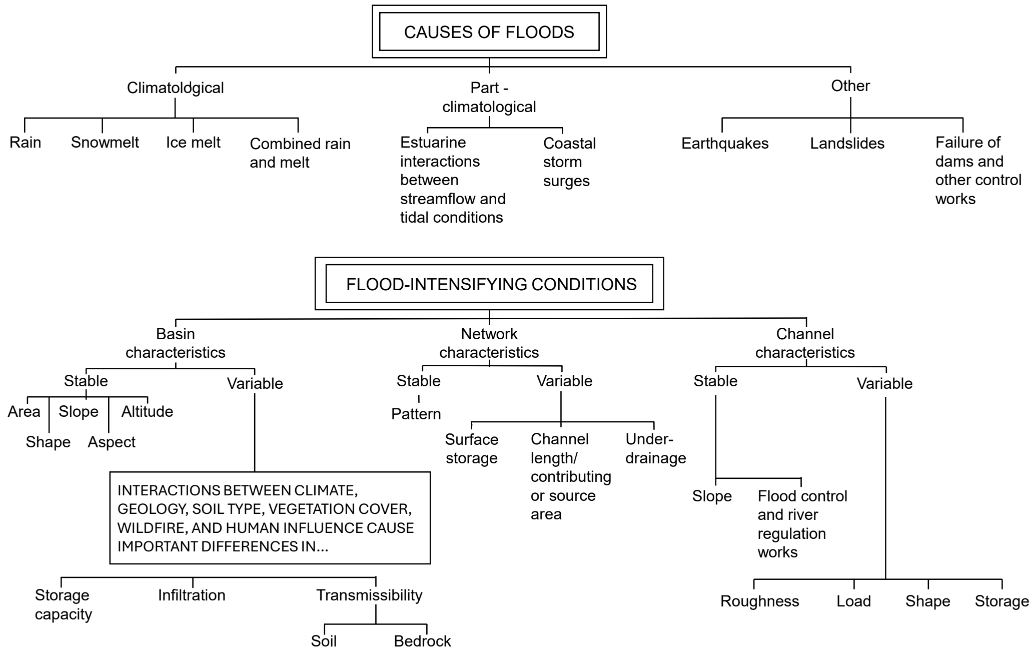

Figure 4

Causes of floods and flood-intensifying conditions as described by Ward (1978)

(4) groundwater. These categories will be used to characterise the flood risk landscape of the Petone-Alicetown catchment, which is exposed to multiple, often interacting, flood hazards.

4.1.2.1 Flooding from Watercourses

Watercourse, or fluvial flooding, occurs when water levels in rivers or streams exceed the channel's capacity, causing the overtopping of riverbanks and the flow of flood waters into adjacent land (Craig et al., 2021). This phenomenon can occur rapidly after intense rainfall, or more gradually due to prolonged wet weather (**smart2010**). Watercourses may be natural stream paths or artificially constructed channels (**Harding2015**), but both are influenced by upstream rainfall, land use, channel morphology, and modifications to riverbanks or floodplains (**liu2022**).

Figure 5

Caption

Fluvial flood risks are a major component of New Zealand's flood risk exposure, in both urban and rural areas (Fu et al., 2023; Hanna et al., 2025). In Petone, the largest source of watercourse flood risk is from the Hutt River which has a history of overtopping its banks, with particularly notable fluvial floods which resulted in damage to residential properties and infrastructure occurring in 1898, 2009, and 2015 (**atapattu2015**; Ballinger et al., 2011). The Korokoro stream, which crosses state highway 2, also has the potential to inundate a major transport corridor under intense rainfall. This occurred in 1978 (see figure 5) and in 2015, illustrating that even minor watercourses compromise major transportation infrastructure systems.

In response to fluvial flooding, strategies such as 'Room for the River' and managed retreat management options have been proposed within urban planning schools of thought (Brierley et al., 2023; Lawrence et al., 2020). However, social and political complexity means that it is not yet known exactly how these strategies can be executed in densely populated urban floodplains in an equitable manner (Hanna et al., 2022; Pawson & Blakie, 2025).

4.1.2.2 Flooding from Surface Water

Surface water flooding, or pluvial flooding, typically occurs when high-intensity rainfall overwhelms the urban stormwater system, leading to ponding or sheet flow across impermeable surfaces (**Seybert2007**; **li2020**). This is distinct from river flooding in that it may occur in locations with no existing waterways and can affect areas not traditionally mapped as flood-prone (**Pozo2023**; **Smart2010**).

This type of flooding is increasingly recognised as a major urban challenge due to the prevalence of impermeable surfaces. Severe surface water flooding can damage property and endanger people, but even shallow surface flooding of can interfere with the day-to-day function of urban systems. Pregnolato et al. (2017) finds that surface flood depths of 30 cm can critically impact transport functioning, causing passenger vehicles to float. This highlights the importance of finding ways to improve infiltration rates of flood waters within urban areas. In Petone, surface water risk is exacerbated by low permeability in roads and industrial areas, where runoff accumulates rapidly during storms.

To assess these impacts, researchers have promoted the use of depth-disruption functions that link flood depth with levels of infrastructure disruption (Kalantari et al., 2014; Paulik et al., 2025). Effective management requires increasing infiltration and slowing runoff. While new construction on greenfield sites can incorporate swales or permeable pavements, retrofitting older urban areas like Petone is more complex and costly (**WWL2022**; Shafique & Kim, 2017), requiring targeted drainage upgrades and the integ-

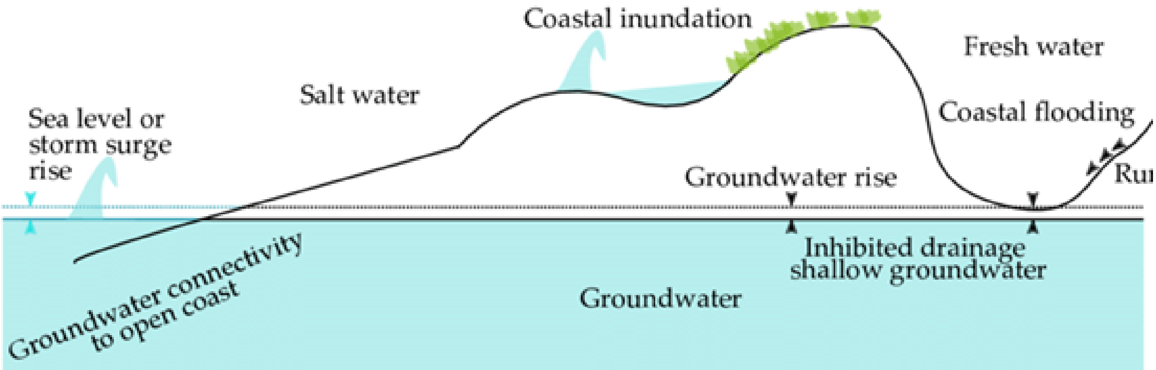

Figure 6

Caption

ration of green infrastructure where space allows.

4.1.2.3 Coastal Inundation

Coastal inundation occurs because of several, often combined meteorological and astronomical processes which elevate sea levels to a point where low-lying coastal margins become inundated with seawater (**NIWA2023**). Changes in mean sea level (MSL), astronomical tides, storm surge, wave setup and runup, and the effects of climate change all influence this phenomenon (see figure 6. The interaction of these drivers is non-linear and spatially variable, meaning inundation potential differs significantly along New Zealand's coastlines.

New Zealand has a highly varied coastline with different levels of exposure to coastal inundation. **hume2016<empty citation>** define 11 coastal hydrosystem categories, which help to characterise local susceptibility to coastal flooding (see table **??**). Among the most at-risk environments are low-lying floodplains where rivers meet the sea, such as the Hutt Valley, where rising sea levels affect a greater land area and amplify inland flooding risks.

Table 1

*Coastal hydrosystem classification for New Zealand's coastline (***Hume2016***)*

Geomorphic Class	**Subclass Description**
1. Damp sand plain lake	
2. Waituna-type lagoon	A. Coastal plain depression; B. valley basin.
3. Hāpua-type lagoon	A. Large hāpua-type lagoons; B. medium hāpua-type lagoons; C. small hāpua-type lagoons; D. intermittent hāpua-type lagoons.
4. Beach stream	A. Hillside stream; B. damp-sand plain stream; C. stream with pond; D. stream with ribbon lagoon; E. intermittent stream with ribbon lagoon.
5. Freshwater river mouth	A. Unrestricted; B. deltaic; C. barrier beach enclosed.
6. Tidal river mouth	**A. Unrestricted;** B. spit enclosed; C. barrier beach enclosed; D. intermittent with ribbon lagoon; E. deltaic.
7. Tidal lagoon	A. Permanently open; B. intermittently closed.
8. Shallow drowned valley	
9. Deep drowned valley	
10. Fjord	
11. Coastal embayment	

The Petone foreshore experiences [relatively low tidal variation], but during prolonged southerly winds, which are characteristic of Wellington's climate, it is exposed to significant wind-driven swells with inundation potential (**OPUS2010**). Even small increases in relative sea level will intensify the magnitude and frequency of these events, reducing the return period of storm tides that are currently considered rare.

Management strategies for coastal inundation include the construction of seawalls, elevating infrastructure, dune restoration, and managed retreat (Schneider et al., 2020). However, these approaches are not without challenges. Coastal zones are valued for their amenity and ecological function, and proposals for structural interventions often encounter public opposition (Azevedo de Almeida & Mostafavi, 2016; Woodruff et al., 2018). Additionally, some scholars argue that certain adaptive infrastructure projects can lead to maladaptation by encouraging further development in hazard-prone areas, thereby increasing exposure and asset value in places that remain fundamentally at risk (T. Logan et al., 2018; Macintosh, 2013).

4.1.2.4 Groundwater Flooding

Groundwater flooding occurs when the water table rises to or above the surface, causing inundation from below. Understanding the extent of groundwater flooding, especially within urban areas (**macdonald2011**), is notoriously difficult within the discipline of hydrology (Abboud et al., 2018; Bosserelle et al., 2022). Key restrictions on the accurate prediction of groundwater flood risk include a lack of monitoring locations, unsolved hydrological complexities, and uncertain subsurface conditions (Condon et al., 2021).

In low-lying coastal areas like Petone, this risk is elevated due to naturally high groundwater tables and poorly draining soils (Naish, Lawrence et al., 2024). As sea levels rise, the infiltration capacity of soils is reduced, increasing the frequency and persistence of groundwater flooding (**liu2020**). Groundwater flooding may not appear as damaging as other sources of flood waters, but it can cause significant damage to sub-surface infrastructure systems and compromise the quality of road surfaces and building foundations (Bosserelle et al., 2022; Mourot et al., 2022).

A high groundwater table also impedes the function of traditional gravity-based stormwater systems (Kool et al., 2020), requiring the installation of expensive pump-based drainage systems (**WWL2022**; Lawrence et al., 2020). Strategies for managing groundwater flooding in Petone will need to be implemented over a long time scale

4.1.2.5 High Impact, Low Probability Events

4.1.2.6 Compound Flooding

4.1.3 The Changing Nature of Flood Risk Drivers

A major factor increasing the difficulty of flood management in urban areas is the dynamic, changing nature of the system, both in terms of environmental and anthropogenic change (O'Donnell & Thorne, 2020; Randhir & Tsvetkova, 2011). Between 1980 and 2024, the economic damage caused by flooding disasters has increased significantly year over year, with a total cost reported in 2023 of 33.49 billion NZD (see figure 7). Some may assume that this is a direct result of increased flood events, however the majority of researchers consider the drivers of this increase figure to be much more complex (Ward, 1978; White, 2013). White (2013) discusses the four aspects of the changing world that may be contributing to an increase in natural disasters being reported: (1) there is a rise in severity of natural weather patterns, (2) societies may play a role in amplifying the hazard, (3) people are increasingly exposed to risks from extreme events, and (4) people are more vulnerable to experiencing the effects.

4.1.3.1 Climatic and Environmental Drivers

Table 2

Excerpt of Table 1 in O'Donnell (2018). S = Source, P = Pathway, R = Receptor. [a] = Recent additions to Evans et al. (2008)

Driver Group	Driver	Explanation
Climate change (S)	Precipitation	changes in short-duration precipitation—amount, intensity, duration, location, seasonality and clustering
	Temperature	influence of temperature on soil moisture and hence runoff.

Driver Group	Driver	Explanation
	Relative sea-level rise	Rising relative sea level due to climate change-induced melting of icecaps and thermal expansion in conjunction with land subsidence or uplift. Makes coastal flooding more frequent.
	Waves	increases in the height and direction of coastal waves will transmit more wave energy to the shoreline at some locations and less energy at others, increasing the risks that waves will breach and overtop coastal defences.
	Storm surges	increases in surge levels are expected due to climate change-induced increases in storminess. Stronger surges mean that higher extreme water levels with more energy reach the shoreline, increasing risks of breaching or overtopping of coastal defences.
Catchment runoff (P)	Urbanisation	a change in land management with green field and previous surfaces covered by less pervious materials (buildings and infrastructure) and associated new conveyance systems.
Groundwater systems and processes (P)	Groundwater flooding	groundwater flooding occurs when the water table reaches the elevation of the land surface (waterlogging) or by the emergence of water originating from subsurface permeable strata.
Fluvial systems and processes (P)	River morphology and sediment supply	changes in river channel morphology (size and shape) and sediment supply that alter attributes of the river channel and floodplain to influence flood conveyance, routing and storage.
Urban systems and processes (P)	loss of floodable urban spaces[a]	loss of urban spaces that previously helped reduce flood risk through infiltration, attenuation or storage. Includes the loss of urban green space and brownfield land (to buildings and infrastructure) and changes in the types of urban green space that affect its rainfall-runoff reduction potential.
Coastal processes (P)	Coastal morphology and sediment supply	changes in the near shore sea-bed, shoreline and adjacent coastal land, coastal inlets and estuaries will in the short term affect the wave and surge energies that affect the shoreline.

Driver Group	Driver	Explanation
Human behaviour (P)	Stakeholder behaviour	the behaviour of individuals, groups and institutions will influence flood risk. Different mechanisms will accommodate different stakeholders' interests.
Socio-economics (R)	Infrastructure Impacts	the relationship between flood risks and the array of networks and nodes that deliver physical services including gas, water, electricity, transport, telecoms, etc.
	Indirect economic impacts[a]	the indirect impacts of flood events including losses from capital and labour productivity disruptions, e.g. flooded roads interrupting transportation and consequentially disrupting economic activities

4.1.3.2 Climate and Environmental Drivers

The nature and occurrence of a flood is highly dependent on environmental conditions. textciteWard1978 separates the relevant flood drivers into 'causes of floods' and 'flood-intensifying conditions'. Enviornmental factors are a direct cause of flooding, Coastal environments are particularly susceptible to a range of environmental hazards including relative sea level rise, Coastal environments are uniquely exposed to a multitude of environmental phenomena, including The key phenomena discussed below, including increasing atmospheric moisture,

4.1.3.3 Anthropogenic Drivers

Anthropogenic drivers are undoubtedly impacting the climate, and hence the environmental drivers of flooding, but

- Urbanisation - Upstream Land Use Change - Population Growth and Land Pressure - Infrastructure Development

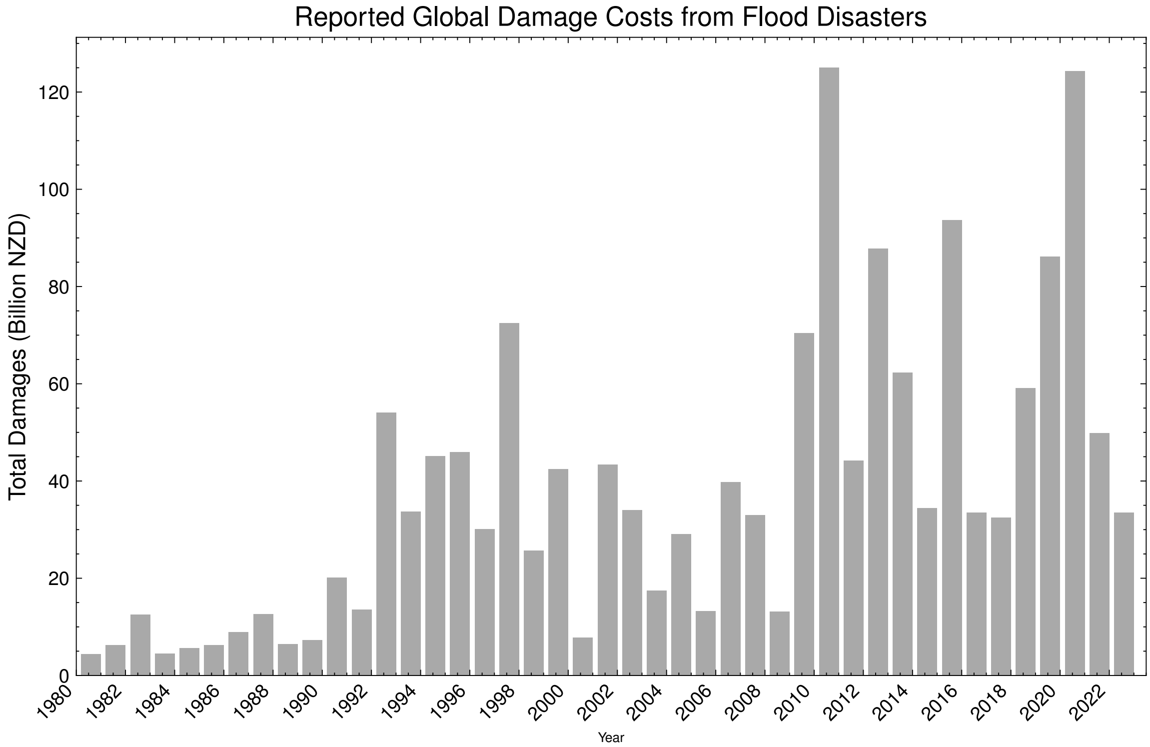

Figure 7

An increase in the global reported costs of damage resulting from flooding over the last 35 years.

4.1.4 Modelling Floods

4.2 Building Resilience to Floods

4.2.1 Defining Resilience

4.2.2 Structural Interventions

4.2.2.1 Critical Infrastructure

4.2.2.2 Transport Infrastructure

4.2.2.3 Implementing Resilient Infrastructure

4.2.3 Non-Structural Interventions

4.3 Nature-based Solutions for Urban Flood Resilience

4.3.1 Defining Nature-based Solutions

4.3.2 Achieving Urban Flood Resilience with NBS

4.3.3 NBS Design Typologies

4.3.3.1 Rain Gardens

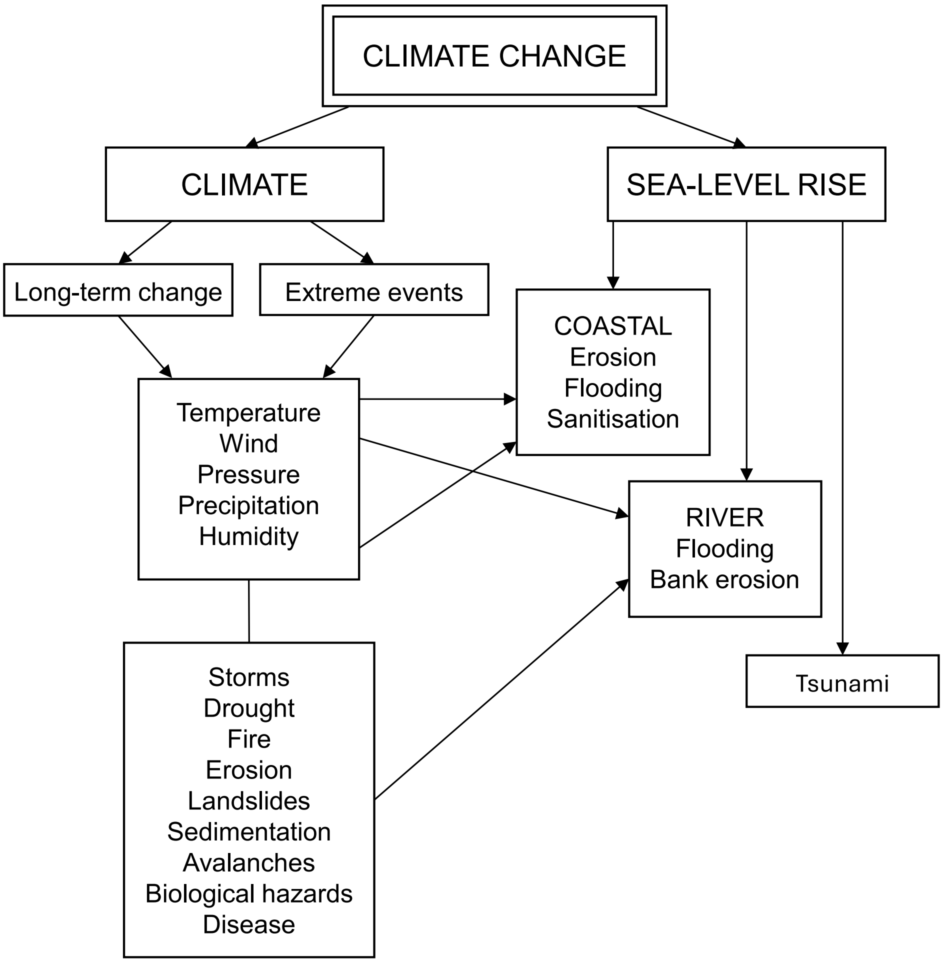

Figure 8

Overview of increased hazards due to climate change, adapted from Pickering and Owen, 1997 (p.149)

Figure 9

Natural disasters include: cyclones, extreme weather, flooding, fires, landslides.

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