Exploring the role of coastal ecosystems in mitigating tsunami waves and currents in Aotearoa New Zealand

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ABSTRACT

Aotearoa New Zealand's coastal communities are vulnerable to tsunami hazards. Hard infrastructure designed to withstand marine assaults can be costly to build and maintain. It can also cause adverse results, such as increased erosion and negatively impacts on marine life. Recognising the importance of sustainable approaches, the Aotearoa New Zealand government has recently promoted applications of Nature-based Solutions (NbS) in hazard mitigations. However, there is a lack of scientific studies in the country demonstrating the benefits of NbS in mitigating tsunami risks. This knowledge gap highlights the need for quantitative evidence to effectively communicate the benefits of ecosystems in reducing tsunami risk to stakeholders. To bridge the 'science to practice' gap, we adopted a participatory approach, engaging with potential stakeholders from 15 organisations through a workshop to help guide the research in ways that are relevant and suitable for institutions and communities. This paper presents a background to NbS, shows the participatory approach and modelling of tsunami scenarios, and demonstrates modelling capabilities to quantify the effectiveness of local NbS and hybrid systems for tsunami risk mitigation.

Keywords: tsunami hazard, Aotearoa New Zealand, nature-based solutions, coastal ecosystems, mitigation, risk, numerical modelling, sediment transport

1 INTRODUCTION

1.1 Generalities

Aotearoa New Zealand has ~15,000 km of coastline, with most of its population and critical infrastructure located in low-lying coastal areas. It is exposed to the adverse effects of coastal hazards, including tsunami, storms and sea-level rise. The New Zealand tsunami database (Downes et al., 2017) reports dozens of tsunamis of various geological and geographical origins having affected the country's shorelines during the last centuries, highlighting the risks from tsunami and the need for mitigating tsunami impacts to the community.

To counter the marine assaults, Aotearoa New Zealand traditional coastal protection structures are hard human-made structures such as seawalls or breakwaters. However, these structures have proven to be detrimental in the long-term, unrealistic at a country-large scale and have shown limitations, especially for large events such as Hurricane Katrina in 2005 and the Tōhoku, Japan, tsunami in 2011 (e.g., advantages and disadvantages of countermeasures are reviewed by Oetjen et al., 2022). It has been shown in the last decades that healthy coastal ecosystems can play a significant role in mitigating tsunami impacts acting as a bioshield. According to Mukherjee et al. (2008), the bioshield concept, which has existed already for a few decades, considers coastal vegetation structures, and by extension all natural structures, expected to protect the coast from storms, cyclones and tsunami. These so-called 'Nature-based Solutions', or NbS, can be used to provide long-term solutions to address societal challenges (e.g., climate change) by working with nature.

The present study is designed to bridge the 'science to practice' gap by providing a pathway for integrating scientific knowledge into land-use decision-making. The research has adopted a participatory approach with potential stakeholders from local, regional and national agencies to demonstrate the effectiveness of coastal ecosystems in Aotearoa New Zealand as a natural buffer against tsunami and hence support their decision making.

1.2 Background to tsunami mitigation and NbS modelling

Globally, more communities are turning to NbS to improve community resilience against natural disasters, notably following the Sustainable Development Goals part of the 2015 Sendai Framework for Disaster Risk Reduction (e.g., Acharya et al., 2020). Following the 2004 Indian Ocean tsunami in Aceh and South Java (Indonesia), coastal ecosystems have been considered, alone or as hybrid solutions of natural and human-made structures, to reduce tsunami impact (e.g., Yanagisawa et al., 2010). Coastal restoration projects, particularly those focused on mangrove forests, can effectively combine ecological restoration and disaster-risk reduction efforts (Benazir et al., 2024). As an example, after the 2011 Tōhoku earthquake and tsunami, municipal recovery plans in Futaba County now include 'building back greener' components to reduce future tsunami impacts and improve community resilience (Mabon, 2019). These natural buffers also help reduce coastal erosion, mitigate the effects of salt spray and protect human life and property (Benazir et al., 2024). Focusing on Aotearoa New Zealand, a study shows how the endemic pōhutukawa trees (*Metrosideros excelsa*; Figure 1a) could help reduce tsunami impacts (De Costa and Nandasena, 2020). However, other coastal ecosystems exist in the country, such as mangroves north of latitude ~38°S (Figure 1b) or Kelp seaweed forests (order Laminariales), which could also play a role in tsunami risk mitigation, as it was already demonstrated in storm protection (e.g., Hanley et al., 2020; Figure 1c).

Coastal ecosystems provide other services to coastal communities, such as carbon sequestration and ecotourism (e.g., Costanza et al., 1997; Hernández-Blanco et al., 2021), while also holding cultural significance for iwi (indigenous Māori tribes) and hapū (subtribes) (e.g., McCarthy et al., 2014). These ecosystems also provide nursery habitats that sustain important fish and marine invertebrates that have significant value for local communities (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005; McCarthy et al., 2014) and are therefore important to the fishing industry.

While coastal ecosystems can play an important role in safeguarding shorelines and assets from erosion, as well as buffering coastal regions from storm surges and flooding (Millennium Ecosystem Assessment, 2005), our understanding of their capacity to dampen tsunami energy remains limited. Aotearoa New Zealand in general is looking for effective, long-term, holistic solutions that enhance biodiversity to mitigate impacts from ever increasing coastal hazards to attain sustainable development (e.g., Ministry for the Environment, 2022).

Additionally, the Promoting Pacific Islands Nature-based Solutions (PPIN) project shows how NbS can be used to address environmental and societal challenges, including climate change and disaster risk. The PPIN initiative supports NbS projects in Fiji, Vanuatu and Tonga and helps these countries become more resilient to natural hazards while promoting sustainable environmental practices. Aotearoa New Zealand can adopt a similar approach. This includes protecting and restoring highly significant coastal ecosystems such as mangroves, salt marshes and kelp forests, especially for the ecosystem services that they provide. Combining multiple coastal habitats – such as reefs, seagrasses or seaweeds, and coastal forests – can offer more effective protection and improve community resilience to tsunamis.

NbS efforts should consider the eight global standards that were developed by the IUCN (2020), which emphasise integrating NbS into broader societal needs, such as land-use planning, resource management and development of long-term strategies. This means that there is a need for a collaborative approach in which stakeholders and partners consider factors such as community needs, vulnerability to tsunami risks, coastal topography and local biodiversity.

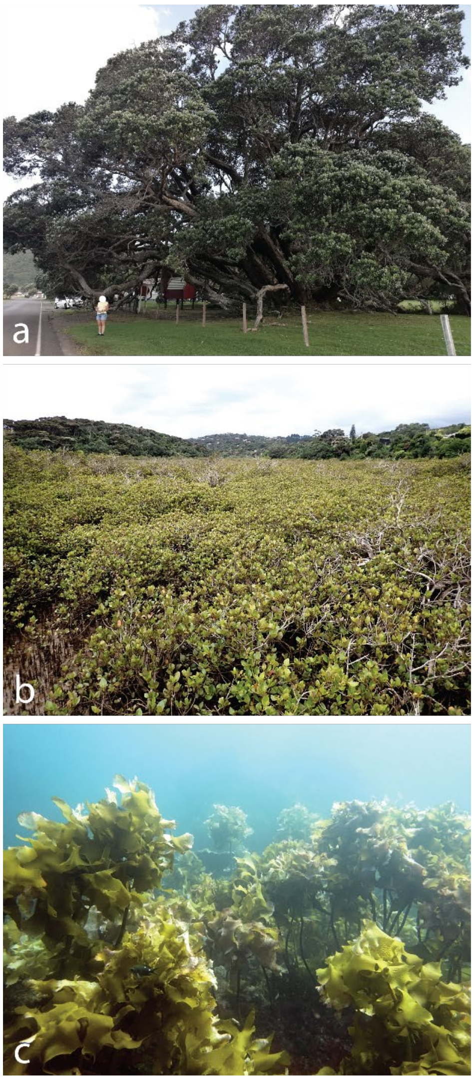

*Figure 1: Example of Aotearoa New Zealand vegetation that may be used as a bioshield against tsunami: (a) Pōhutukawa tree (*Metrosideros excelsa*, Te Waha o Rerekohu in Te Araroa); (b) mangrove (*Avicennia marina*, Waiheke Island); (c) kelp seaweed (*Ecklonia radiata*, Poor Knight Islands) (Credits: Jean Roger).*

2 DESIGNING PATHWAYS FOR STAKEHOLDER ENGAGEMENT

2.1 Research methodology

As one of the objectives of the research is to bridge the gap between science and practice, the project scope was designed to align with the needs of stakeholders. We conducted two workshops, one at the beginning of the project to determine key interests of stakeholders which helped us to design the scope of the project, and specifically, its best location; and a second one at the end of the project to receive their feedback and identify future research directions. Four study areas were identified and proposed to the stakeholders which included Napier, Gisborne, Tutukaka and Karikari Peninsula (Northland). Each area was provided with datasets (e.g., available Digital Elevation Models – DEM; key exposure assets/infrastructure like roads and ports), existing ecosystems, former or current tsunami projects, possibility of sediment-transport simulations and exposed assets.

Napier, a coastal city of ~65,000 inhabitants located in Hawke's Bay on the east coast of the North Island of Aotearoa New Zealand, was selected as the study area. Due to its location above the Hikurangi Subduction Zone, it has been already extensively studied, which means that comprehensive datasets related to tsunami scenarios are readily available. In addition, the Napier coastline already has well-established coastal ecosystems like kelp forests in place without needing to first establish or restore such ecosystems.

2.2 Findings from the engagement workshop

We present here the results of the first workshop, which was used to select the study area and vegetation to be considered in the modelling exercise. The workshop discussions helped us identify a list of key points and a case study area that were of particular interest to the stakeholders and partners. Five different categories of key points were identified (Table 1): tsunami scenarios, metrics of interest, modelling requirements, ecosystem needs and data availability.

Table 1: Key points of interest for workshop participants

Category	Key points of interest
Tsunami scenarios	• The impacts of larger tsunami, as smaller tsunami generally impact beach and marine assets rather than inland areas.
Metrics of interest	• The impact on human life is a critical metric, particularly for larger wave amplitudes. • Provide a more comprehensive overview of the extent of possible damage on human life, buildings, infrastructure and natural environments. • Identify where the risks are, e.g., harbours, major state highways and what can be done in terms of impact prevention. • Economic impact, the time needed for asset replacement and other factors such as environmental and amenity impacts, including threats to beach and marine areas. • Social cost and recovery of that particular environment.
Modelling requirements	• How different tsunami scenarios influence sediment-transport simulations. • Sediment deposition and erosion around key areas such as estuaries, ports, wharfs, jetties, marinas, bridges, piers, roads, council assets and related businesses. • Also consider hybrid solutions. • Need more data robustness; need understanding of sediment movements in the chart area. After events would also be very useful from navigation safety perspective.
Ecosystem needs	• Consider only those ecosystems that would naturally exist in a specific location. This means that NbS efforts should be suitable for the location, strategically placed and designed to support well-functioning ecosystems that can successfully meet both community and ecosystem needs. • Assess the potential for new kelp forests or other vegetation in an area and consult with ecologists to ensure suitability.
Data availability	• Workshop participants highlighted several data resources, including the councils' coastal strategy and shared sounding points and cross-sections along the coastline.

3 SCIENCE METHODOLOGY AND MODELLING FOR NAPIER

The science methodology developed in this project is divided into two interconnected simulation phases. The first phase focuses on 'standard' tsunami hazard assessment of providing information on how the tsunami hazard intensity measures, responds to different vegetation/ ecosystem coverages. The second phase focuses on sediment transport during tsunami events.

3.1 Tsunami modelling

Tsunami hazard assessment is commonly performed using numerical modelling tools, such as the Cornell Multi-grid Coupled Tsunami (COMCOT) model (Wang, 2008; Wang and Power, 2011) which was used in this study. Over a dedicated DEM of a region of interest, tsunami simulations could provide quantitative insights to the understanding of maximum tsunami amplitudes, inundation extent and tsunami currents associated to a particular tsunami scenario. In the tsunami simulations, resistance effects of natural or built environment, e.g. forests or buildings, over the topography represented by the bare-ground DEM on the tsunami waves are often approximated by applying bottom frictions through a friction model, e.g., Manning's formula, with equivalent roughness coefficient values. The roughness values could be either a constant, which is applied everywhere on the domain, or a roughness layer that shows roughness values varying with space.

The role of friction on tsunami waves has been evaluated in a few studies. These have established that, while it affects the estimates of tsunami inundations, flow speed and momentum flux, it may not have such significant impact on the inundation distance at the end, depending on the scenario and region studied (e.g., Gayer et al., 2010; Kaiser et al., 2011; Wang et al. 2017; Gibbons et al., 2022). So far, tsunami studies have almost always considered varying the roughness coefficient only on land (e.g., Kaiser et al., 2011; Amra et al., 2025). However, there is limited work and understanding how varying the roughness value of the sea floor influences the tsunami energy and subsequently coastal tsunami hazard mitigations. A few studies have considered those ecosystems in their ensemble, especially coral reefs, either as a natural hard structure (i.e. part of a DEM) having the capacity, or not, to dampen tsunami energy (e.g., Roger et al., 2014). Other studies focused on the roughness of the ecosystem itself, which adds to the roughness of its physical structure (e.g., Gelfenbaum et al., 2011; Thran et al., 2021; Lahcene et al., 2024).

The approach designed for the present study considers a 10-m-resolution DEM of Napier (built within the framework of previous projects), including both land and offshore regions, as input file for numerical simulations with COMCOT. As a pilot study, and according to the outcomes of the workshop presented in Section 2, it was decided to focus on two types of vegetation coverages: the kelp forests at sea (i.e., *Ecklonia radiata*, the dominant seaweed in Hawke's Bay), and the Aotearoa New Zealand endemic pōhutukawa trees (*Metrosideros excelsa*) on land. The first was selected because it is naturally present in front of Napier, facing the shore on both sides of the Ahuriri Estuary entrance and because kelp seabeds, like those of *Ecklonia radiata* and *Macrocystis pyrifera*, are known to dampen wave energy in certain conditions (e.g., Morris et al., 2020; Elsmore et al., 2024). The second was chosen because its potential role in mitigating tsunami impact was specifically studied by De Costa and Nandasena (2020), showing promising bioshield capabilities.

A dedicated feature has been developed in COMCOT in this project. It allows us to change the friction value in a polygon over the baseline friction layer, throughout the simulation. This allows us to vary the vegetation coverage and its corresponding roughness quickly and efficiently without having to alter the underlying simulation data. An additional feature was also implemented in COMCOT which allowed us to change the elevation of polygons over the DEM allowing us to investigate effects of engineering measures, e.g, adding a seawall somewhere in the modelled area, on tsunami mitigations.

3.2 Sediment transport modelling (tsunami context)

Not all tsunamis show large wave amplitudes. However, it is known that even small tsunamis can trigger strong currents in specific locations such as shallow bays, river estuaries, inlets, etc. (for an example, see more details in Roger and Wang [2023]). In addition to their ability to impact people and infrastructures, these currents also show the capacity to transport sediment through erosion-deposition processes. In order to assess the role of ecosystems in these processes, it was chosen to simulate sediment transport associated with tsunami waves for the same region of Napier. To this end, we use a tsunami sediment-transport model capable of simulating both suspended and bedload transport, as well as topographic changes. This model was developed in previous studies (Gusman et al., 2012; Gusman et al., 2018; Kusumoto et al., 2020). It was used to examine the effect of coastal forests on tsunami sediment movement on the Sendai Plain, Japan, during the 2011 Tōhoku tsunami through numerical simulations of sediment transport (Kusumoto et al., 2020). To account for variable roughness within the coastal forest, a composite equivalent roughness coefficient was adopted. In this previous study, it was found that the coastal forest significantly reduced the simulated mean concentration of suspended sediment, wave height, flow velocity and inundation limit.

3.3 Preliminary simulation outputs

Several simulation outputs were prepared in this project corresponding to variations of vegetation coverages and roughness values. However, these outputs cannot be used by potential users in their current form. These need to be processed in a way showing the role of the vegetation in tsunami mitigation, e.g., showing the relationship between the roughness of the vegetation and the area and volume of inundation, maximum and mean onshore flow depths and maximum onshore and offshore flow speeds.

For the first simulations, we designed four vegetation areas: (1) the present-day; as well as an extended to three different sizes, i.e., (2) extended, (3) half-extended and (4) double-extended. Figure 2 shows the locations of the four alternative vegetation extents for a kelp forest.

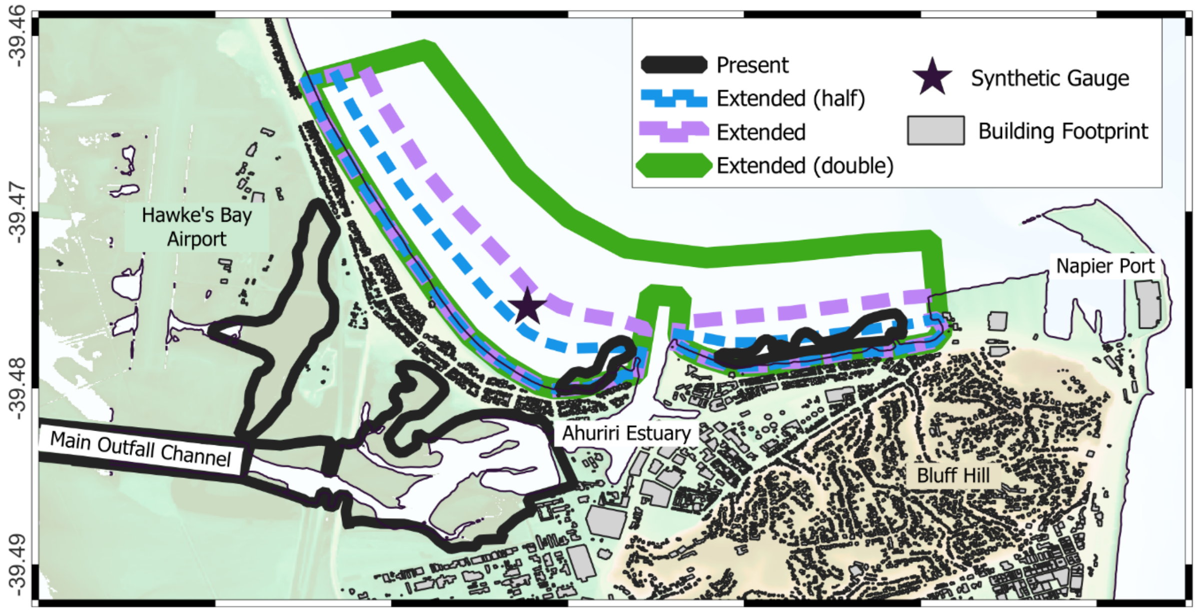

Figure 2: Map of the vegetation extents that were used in the simulations. Key locations around Ahuriri/ Napier are shown alongside the building footprints. The location of one of the synthetic tsunami gauges set up and analysed is also included (black star).

Using the four vegetation extents, we ran a series of simulations that vary the roughness of the modelled kelp forest, as the roughness value of this type of vegetation is unknown. We select 10 values of Manning's n from 0.01 to 0.06 to approximate the roughness of the kelp forest. In the simulations, the polygons outlined in Figure 2 are given a specific Manning's n and the simulations are run through to inundation. Note that all other land and marine regions of the simulation domain have usual constant roughness values set up to n = 0.025 and 0.015, respectively. For these tests, we use a scenario corresponding to a magnitude M_W 8.9 Hikurangi Subduction Margin earthquake rupture, as this event has previously been used to model inundation around Ahuriri/Napier, and the previous results showed inundation occurring to the north of

Napier city around the harbour and Ahuriri Estuary region (Moratalla et al., 2024). Each simulation was run for 10 hours of propagation time, and a set of synthetic tsunami gauges were placed across the simulation region to record time series of the tsunami data (water level and current speed variations).

From one of the synthetic gauges, we observe that, although the vegetation extent does not appear to influence the initial wave that is recorded at the gauge location, a small reduction in the amplitude of the following waves is observed when we increase the size of the vegetation extent. Figure 3 shows the synthetic recording of one of the gauges modelled using a Manning's *n* of 0.03. This pattern holds for all other gauges that were modelled.

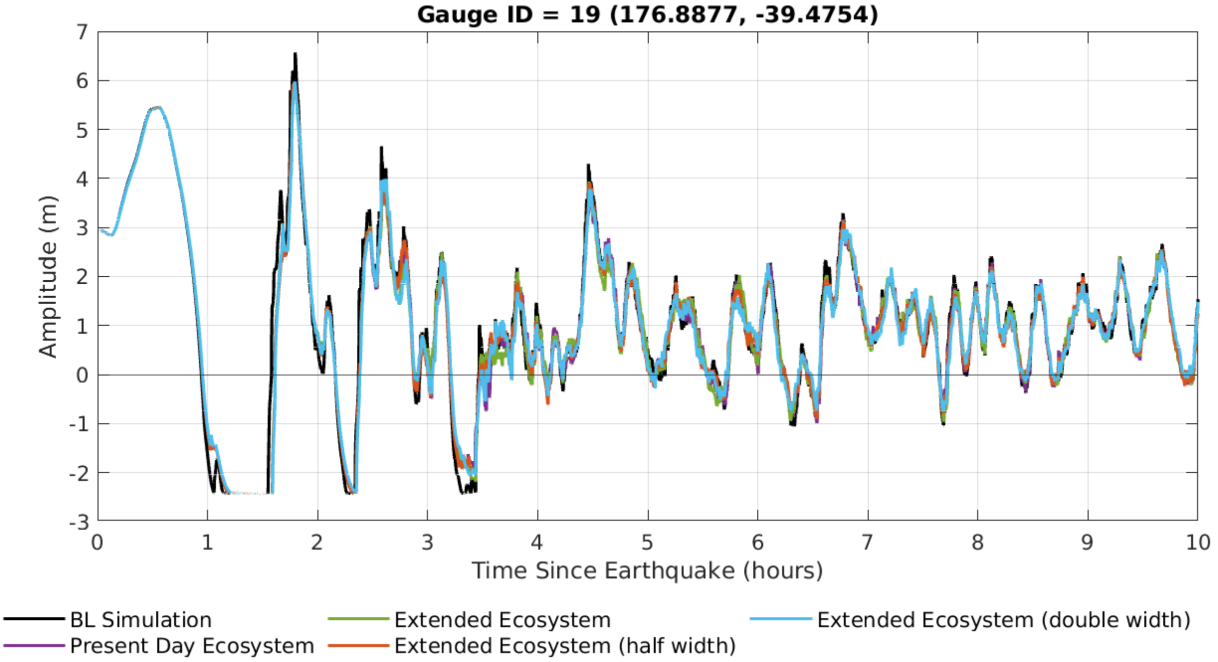

Figure 3: Synthetic tsunami gauge records showing sea-level variations with time when alternative vegetation extents are modelled. A Manning's n *of 0.03 was used for these specific simulations.*

As part of initial assessments of the preliminary results, we further examine the pattern of maximum flow velocity in more detail. Figure 4 shows the maximum flow velocities when the alternative vegetation sizes are changed and the Manning's *n* is set to 0.03.

Comparing the flow velocities of the different vegetation sizes to the 'present-day', we observe that the flow velocities decrease over the kelp area, indicating that the vegetation coverages are slowing down the waves as they reach the coast. We also see that the onshore velocities slightly decrease as well. While this represent encouraging results, a more detailed study is required to assess the overall percentage of energy reduced as a function of kelp forest coverage, and by extension to other ecosystems, with more accuracy. A special attention will be brought to the ability of the friction values to reduce the tsunami flow speed in areas such as the port or the marina, or where bridges or seawalls are located. In fact, tsunamis are known to be able to scour at the foot of these structures, fragilizing them. Thus, being able to show that bottom friction generated by the ecosystems modelled can reduce the flow speed at these locations may lead to new research opportunities.

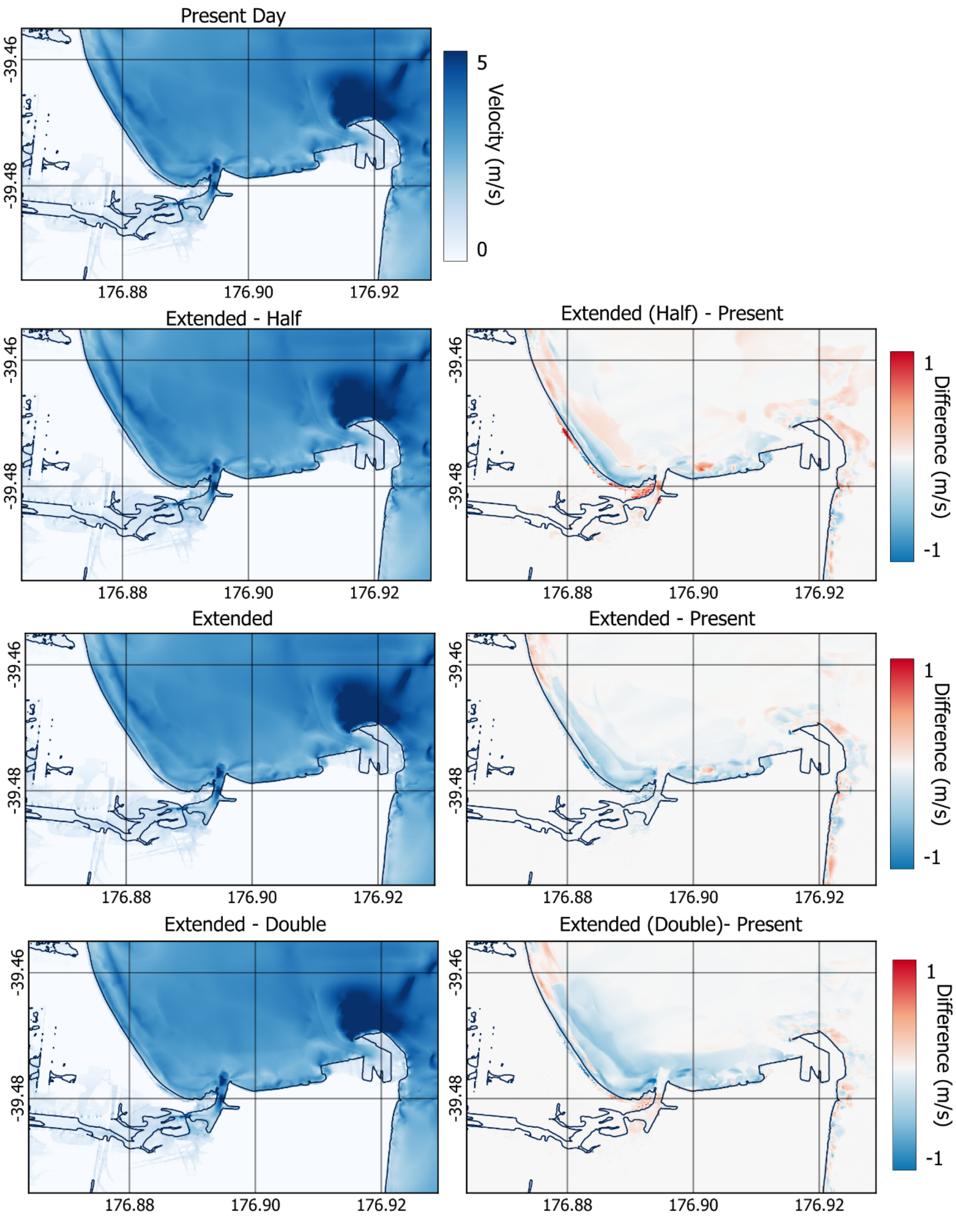

Figure 4: Maximum tsunami velocity maps for different vegetation coverages (left) and differences in the maximum velocity when different vegetation extents are modelled (right). The Manning's n *of 0.03 is used for all the cases of vegetation coverages.*

3.4 Toward risk assessment

Following the tsunami simulations, an initial exposure analysis has been carried out to understand what hazard levels elements such as buildings will be exposed to. There are over 4,600 buildings in the study area, with the majority (75%) being one-story structures. However, not all buildings in the modelled portfolio will be affected. By carrying out geospatial mapping of building and hazard layers, it was possible to obtain for each case the maximum flow depth (h_{max}) at each building location. Table 2 provides the summary of number of buildings at risk to varying levels of flow depths from inundation due to the M_W 8.9 Hikurangi Subduction Margin earthquake scenario.

Table 2: Number of buildings subjected to various flow-depth levels. All kelp areas are modelled using a Manning's n of 0.03.

Flow depth, h_{max} (m)	Kelp case			
	Present day	Extended (half)	Extended	Extended (double)
$0 < h_{max} \leq 0.25$	113	115	113	115
$0.25 < h_{max} \leq 0.5$	31	31	26	30
$0.5 < h_{max} \leq 0.75$	20	20	18	21
$0.75 < h_{max} \leq 1$	6	13	6	8
$1 < h_{max} \leq 1.5$	9	9	8	8
$1.5 < h_{max} \leq 2$	6	6	6	7
$2 < h_{max} \leq 2.5$	0	1	0	0
$2.5 < h_{max} \leq 3$	0	0	0	0
Total:	**185**	**195**	**177**	**189**

About 187 buildings on average from all of the four kelp extent cases become inundated. This is about 4% of the total number of buildings modelled in the study area. In general, damage severity can be expected to increase with increasing flow depths, especially for one-story timber buildings, which are the predominant building category for the case study. However, from comparative results shown in Table 2, no reduction in impact can be expected in the study area from extended ecosystem areas.

4 SUMMARY

This project aims to quantitatively estimate the role of some Aotearoa New Zealand native vegetation/ ecosystems in protecting coastal assets against tsunami waves, currents and associated sediment transport (erosion/deposition). We defined the main orientation of the project with the help of comments provided by potential stakeholders during a meeting held online with participants from different types of organization.

Numerical modelling of tsunami was set up for Napier City accordingly to the outcomes of the workshop, having in focus a set of critical outputs that are useful to participants. COMCOT tsunami simulation model is used to simulate tsunami generated at the Hikurangi Subduction Zone and propagating following a nested grids scheme, allowing the performance of inundation calculations on the highest-resolution grid (northern part of Napier City). To consider the ecosystems' extent and roughness, COMCOT was further developed to allow attribution of roughness values to polygons. Preliminary results showing role of vegetation/ ecosystems are shown herein but note that the project is still ongoing: several other tests of ecosystem coverage and roughness variations, including combination of land and marine vegetation and grey structures, will also be completed.

The findings of this study are expected to be helpful to a wide range of potential stakeholders, including local governments, planners, environmental agencies and decision-makers. By translating technical hazards and risk information into easily digestible and actionable data, the study will provide users with insights to support land-use planning and decision-making processes.

Maintaining ongoing engagement with potential stakeholders is important to ensure that ongoing research efforts remain relevant, accessible and easy to understand for all stakeholders and partners. This will foster continued engagement and informed decision-making.

Acknowledgements

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