Infrastructure disruption from coastal flooding

Project Summary

National SCIENCE Challenges

THE DEEP SOUTH

Te Kōmata o Te Tonga

This research investigated coastal flooding and sea-level rise impacts on urban infrastructure in New Zealand. Coastal flooding was mapped nationally and applied in local (Christchurch and South Dunedin) and national analyses (road network and interdependent infrastructure networks) case studies to analyse infrastructure vulnerabilities and interdependencies.

This document provides a summary of research methods and results with links to new information sources on coastal flooding and sea-level rise impacts to critical infrastructure.

Key findings

The research on coastal flooding and sea-level rise impacts to urban infrastructure shows:

- Significant infrastructure network service disruption to customers occurs beyond areas directly affected by coastal flooding.
- Beyond 20cm of sea level rise, the expected annual exposure to coastal flooding increases significantly for several infrastructure networks.
- Local road networks could bear the brunt of direct economic losses.A case study of South Dunedin identified a critical "tipping point" at a 0.6-metre SLR (which could be reached within 60 to 90 years), where the impacts of coastal flooding begin to significantly disrupt essential services.
- A case study of Christchurch simulates the significant risk currently faced by Christchurch communities: for a 10-year recurrence interval flood event with no sea-level rise, about 9% of total end users would lose at least one utility, with the majority of these disruptions resulting from cascading failures rather than direct flooding.
- At the national scale, for the first 20 cm of sea-level rise, direct, rather than indirect disruption dominates, indicating that infrastructure owners should generally focus more on directing adaptation and/or resilience building initiatives towards their own exposed assets in the near term rather than a focus on redundancies across all assets such as backup power supplies.

Who will use the research products and supporting information?

These findings will be of use to entities planning to manage the potential future flood impact to different infrastructure networks at national to local scales. New insights on infrastructure interdependencies and the geographic distribution of service disruption will be of use to emergency response and recovery agencies who manage the direct and indirect effects of coastal flooding events.

Background

Climate change poses significant risks to critical infrastructure networks globally, particularly in coastal regions. As sea levels rise and the frequency of extreme weather events increases, we need to better understand and quantify the impacts to our population and the inherent damage costs that we will need to account for in defining how we adapt to future coastal flooding.

The interconnected or 'interdependent' nature of our infrastructure systems also mean that asset failures in one network can cascade and propagate to other networks, potentially disrupting communities far from the initiating hazard event. In our context of coastal flooding, communities can be isolated with the flooding of a single-access road, or an inundated electricity substation may not only lead to a power cut, but a wide range of outages across assets reliant on electricity to function, such as water or wastewater pumpstations. It is this wider view of indirect impacts that are not well recognised in our current understanding of infrastructure asset exposure across New Zealand networks.

This overview synthesizes the findings from the Deep South National Science Challenge project '*Infrastructure disruption from coastal flooding*', providing insights into the vulnerabilities and interdependencies of urban infrastructure in New Zealand. By examining both local case studies (Christchurch and South Dunedin) and national-scale analyses (road network and interdependent infrastructure networks), this briefing document reports on the current state of knowledge to enhance resilience and preparedness. The five journal papers produced under this project are all open-access and are linked at the end of the document. Refer to these for further information and a better understanding of the modelling and assumptions in generating these results.

Research Methods

Mapping Coastal Flood Hazards

Updated coastal flooding hazard maps appropriate for national-scale analyses were made for New Zealand using the latest LiDAR elevation data [1,2], allowing for greater precision around urban areas where infrastructure assets are more concentrated. The steps taken were:

1. **Calculating Extreme Sea Levels (ESL)**: ESL heights for Annual Recurrence Intervals (ARI) across 2-, 5-, 10-, 20-, 50-, 100, 200-, 500-, and 1000-years were calculated based on components such as mean sea level, storm tide, storm surge, and waves.

2. **Developing Composite Topographical Dataset**: A composite topographical dataset, combining Airborne Light Detection and Ranging (LIDAR) and bias-corrected Shuttle Radar Topography Mission (SRTM) data, was created to represent land elevation. Higher resolutions were available for urban areas and modifications made to account for flood mitigation structures that act as barriers to flooding.

3. **Executing a Scalable Model**: A model was employed to translate the ESLs to map land inundation areas for any incremental relative sea-level rise scenarios, providing flexibility to account for future uncertainties such as differing rates of sea-level rise (SLR) and vertical land movement.

The 100-year ESL flooding maps can be viewed and downloaded from the online portal[2], with additional ESL maps available through data access agreements with NIWA.

Network Modelling

Across our studies[3,4,5,6], we represent each of the studied infrastructure assets as a network of nodes and edges to capture the flow of services. Using water supply as an example, nodes represent point assets such as raw water intakes, treatment plants, pump stations, and reservoirs. These are connected by edges, representing pipes that connect to end users and complete the structure of the network. Under different flooding and relative sea-level rise scenarios, our models check for a connectivity path between a source (i.e. potable water source) and the end users. A disruption is registered when there is no connectivity path available or reduced level-of-service is apparent. This is what we define as a 'direct disruption', those disruptions which are constrained within the same network and a single infrastructure owner/operator has complete oversight.

Each of these networks are interdependent, such that assets which have a reliance on another network are connected to them and required for normal operation. For example, each water pumpstation requires electricity and is therefore connected to the nearest electricity network component at an appropriate voltage. Should electricity connectivity be lost and no other alternative routing of electricity is available, then the water pumpstation is what we define as 'indirectly disrupted' given the initiating disruption originated from elsewhere and is a result of a cascading outage. Assessing these direct and indirect disruptions together allow us to identify our most critical assets and both quantify and spatially map the impact increased flood protection or alternative redundancies (such as backup generators) can have on a given network.

Local Scale Case Studies

South Dunedin[3]

This case study addressed the impact of future coastal flooding scenarios in South Dunedin, a low-lying and densely populated area that is known to be highly vulnerable to future flooding. Interdependent infrastructure networks modelled include electricity (grid exit point, distribution zone substations; buried cables, and overhead lines), wired telecommunications (exchanges; cabinets; and cables), potable water (pumpstations and pipes), wastewater (pipes, pumpstations, and treatment plants), and road networks.

The study identified a critical "tipping point" at a 0.6-metre SLR, where the impacts of coastal flooding begin to significantly disrupt essential services. At this threshold, a 100-year average recurrence interval event would lead to widespread direct loss of road access and electricity services. This, in turn, causes indirect failures, particularly affecting telecommunication services and the functionality of the critical wastewater pumpstation in the area. The research found that approximately 80,000 residents outside South Dunedin would also be impacted by the failure of the wastewater infrastructure. Furthermore, a secondary critical point occurs at 0.9-metres SLR, where additional substations fail, exacerbating the indirect impacts on the dependent networks.

These tipping points could be reached within 60 to 90 years based on current sea-level rise projections (SSP2-4.5 and SSP5-8.5 scenarios). This timeframe aligns with long-term infrastructure planning cycles, emphasising the need for a proactive adaptation measures and strategies for future plans of key assets in the area amidst uncertainty.

Christchurch[4]

This case study focuses on the effects of coastal flooding in Christchurch, focusing on selected ARI's (10-, 100-, and 1000-year) and SLR scenarios out to +3.0 m. The infrastructure networks of interest were selected based on proximity to flooding and included: electricity (grid exit points, distribution zone substations, local transformers), potable water supply (intakes, reservoirs, pumpstations), and wastewater (pump stations, treatment plants) networks.

Through simulating these high-resolution networks, we see the current day (0 cm SLR) 10-year recurrence interval event is still a major threat to the local population. About 9% of total end users lost at least one utility, with the majority of these disruptions resulting from cascading failures rather than direct flooding. This indicates that the interconnected nature of infrastructure systems amplifies the extent of service disruptions. For instance, in the same scenario, indirect impacts caused a 71% increase in electricity network disruptions, a 129% increase in water network disruptions, and a 131% increase in wastewater network disruptions compared to direct impacts alone. Looking far into the future, these results are fairly consistent until > 1.0 m of relative sea-level rise, at which point direct exposure to flooding becomes the main contributor to disruptions across the study area.

As with the South Dunedin case study [3], the importance of high-resolution spatial data is imperative to get a complete picture of local-scale adaptation options and the importance of recognising infrastructure interdependencies in nearer-term risk assessments. With the significant populations that could be expected to be without multiple infrastructure services following a (relatively) frequent 10-year flooding event, the findings of this case study further highlight the issues of evacuation and both targeted back-up equipment and relocation of residents for extended periods should key assets be out of service for an extended period.

National Scale Case Studies

National Interdependent Infrastructure Networks[5]

This study used the same network-based approach to model infrastructure exposure and disruptions due to coastal hazards, but this time upscaled to the entire country. Relying on openly available datasets, network representations were created for: electricity transmission (173 power stations, 185 transmission substations, 38,600 transmission network towers, and 11,000 km of overhead lines and buried cables), electricity distribution (777 substations, 402,000 power poles, 42,000 km of lower voltage overhead lines and buried cables), water supply (3600 intakes/treatment plants/pumpstations/reservoirs, and 13,000 km of pipes), wastewater (1136 treatment plants/pumpstations, and 1,600 km of critical pipes), and fuel supply (11 bulk supply points, 1400 petrol stations) which is routed via 65,000 km of road network. Each infrastructure component as modelled as a topological network-with the exception of electricity transmission which utilised a more accurate DC-power-flow approximation given the sensitivity of the entire country to concurrent outages in the national grid.

Focused on annualised exposure (the assets and populations that could be expected to be impacted on an annal basis), we observed that within the first 20 cm of SLR, changes in asset exposure and population disruptions are relatively minor and gradual. However, beyond this threshold, expected annual exposure increases significantly. Compared to the case studies above, this study highlights a predominance of direct disruptions over indirect ones when looking at the national resolution. This indicates that infrastructure owners should generally focus more on directing adaptation and/or resilience building initiatives towards their own exposed assets in the near term rather than a focus on redundancies across all assets such as backup power supplies. An exception and challenge is the fuel supply distribution system, which is highly dependent on the road network for conveying fuel to retain pump stations and therefore has fewer options for spending on redundancies given the significant exposure of roads and ports to coastal flooding.

In the scaling up of the local case studies to a national scale, we further confirm that disruptions are mainly confined to coastal areas without cascading over significant spatial extents. This differs to other natural hazards, such as earthquake and fluvial/pluvial flooding which have shown a propensity for much wider spatial extents. This containment is attributed to network redundancies, initial planning and siting of critical assets that have considered coastal hazards in the near-term SLR scenarios, and potentially lower populations in the most exposed areas. Despite the value of broad national studies, localized case studies remain crucial for precise adaptation planning. The study also underscores the necessity for improved spatial data quality and quantity, including a wide range of key asset attributes to assess damage and prioritise adaptation measures effectively.

Road Networks[6]

Given the importance of the road network identified in the national interdependent networks study[5], we further explored and quantified the spatiotemporal economic risk of our entire road infrastructure to coastal flooding and relative sea-level rise between 2020 and 2120. Using RiskScape software, the research quantified direct monetary losses, measured by expected exceedance probability loss and average annual loss, under various relative sea-level rise scenarios. It found that downward vertical land motion[1] could cause projected economic losses by 2100 to occur 10 to 20 years earlier. By 2100, the expected annual economic losses could range from NZD $86 million to $138 million, depending on the scenario. Regional differences were significant, with Auckland, Waikato, Hawkes Bay, and Canterbury contributing to over half of the national losses. Secondary and access roads were most vulnerable, while national and high-volume roads saw lower absolute and proportional losses.

The findings highlight the urgent need for adaptation strategies to enhance the resilience of New Zealand's road network to future relative sea-level rise changes and coastal flooding. Prioritising structural adaptations, such as elevating roads and improving drainage systems in vulnerable regions, especially in Auckland, Waikato, and Canterbury, could mitigate significant future losses. Additionally, non-structural measures like updated zoning laws and land-use planning that consider projected relative sea-level rise changes could further protect road infrastructure. The study raises the importance of incorporating local vertical land movement data in planning and policy decisions to ensure timely and effective adaptation measures.

Concluding Remarks

The studies presented here reveal that traditional risk assessments, which predominantly focus on direct impacts, fall short in capturing the full extent of outages and disruptions. By incorporating both direct damage and resulting indirect disruptions, a more comprehensive understanding of the vulnerability of key infrastructure networks is achieved.

Furthermore, while national-scale studies offer valuable overarching insights, they do not replace the necessity for localised assessments. These are crucial for detailed and actionable adaptation planning, particularly when higher resolution data is available, enabling better representation of physical processes within infrastructure networks.

The presented research advocates for a move away from developing resilience/adaptation strategies in isolation for different natural hazards. Instead, we call for integrated, multi-hazard approaches to prevent maladaptation and resource misallocation. This requires a better representation and damage prediction model of each of our most critical exposed infrastructure assets to better understand their vulnerability to various hazards. Further, incorporating dynamic levels of service across infrastructures is required to capture the complexities of cascading failures more accurately and aid prioritisation in infrastructure recovery. Finally, for more confidence in our long-term simulations, direction is needed in the potential impacts of emerging and disruptive technologies, such as widespread electrification and decentralized infrastructure systems. Simulating changes in network structure and demands in response to non-stationary climates, erosion, and vertical land movement is essential to better align to timescales we are considering with the longer-term relative sea-level rise and climate scenarios.

Further Information

For further information and access to coastal flood maps for Aotearoa New Zealand, please refer to the following open-access resources:

1. Paulik, R., Wild, A., Stephens, S., Welsh, R., & Wadhwa, S. (2023). National Assessment of Extreme Sea-Level Driven Inundation under Rising Sea Levels. *Frontiers in Environmental Science, 10*. 10.3389/fenvs.2022.1045743 [Open Access]
2. Extreme coastal flood maps for Aotearoa New Zealand: https://niwa.co.nz/coastal-hazards/extreme-coastal-flood-maps-aotearoa-new-zealand
3. Lan, C., Wild, A., Paulik, R., Wotherspoon, L., & Zorn, C. (2023). Assessing Indirect Impacts of Extreme Sea Level Flooding on Critical Infrastructure. *Journal of Marine Science and Engineering, 11*(7), 1420. 10.3390/jmse11071420 [Open Access]
4. Brunner, L., Peer, R., Zorn, C., Paulik, R., & Logan, T. (2024). Understanding cascading risks through real-world interdependent urban infrastructure. *Reliability Engineering & System Safety, 241*, 109653. 10.1016/j.ress.2023.109653 [Open Access]
5. Zorn, C., Paulik, R., Thacker, S., & Wotherspoon, L. (in review). Enhancing the Systemic Resilience of Infrastructure to Coastal Flooding and Sea-Level Rise. *Civil Engineering and Environmental Systems*. 10.13140/RG.2.2.35856.01288 [Open Access]
6. Paulik, R., Powell, J., Wild, A., Zorn, C., & Wotherspoon, L. (under consideration). Spatiotemporal economic risk of a national road network to episodic coastal flooding and sea level rise. *Climatic Change*. DOI TBC [Open Access]

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