NEW ZEALAND INFRASTRUCTURE COMMISSION
Te Waihanga

Invest or insure?

Preparing infrastructure for natural hazards

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New Zealand Infrastructure Commission / Te Waihanga

The New Zealand Infrastructure Commission, Te Waihanga, seeks to transform infrastructure for all New Zealanders. By doing so our goal is to lift the economic performance of Aotearoa New Zealand and improve the wellbeing of all New Zealanders.

We are an autonomous Crown entity, listed under the Crown Entities Act 2004, with an independent board. We were established by the New Zealand Infrastructure Commission/Te Waihanga Act 2019 on 25 September 2019. Information on the Commission is available at www.tewaihanga.govt.nz/

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Cut to the chase

Infrastructure is vulnerable to natural hazards

Due to our geography, New Zealand faces a high level of risk from a range of hazards, including earthquakes, flooding, volcanic eruptions, and tsunami. Our populations and infrastructure are often clustered near hazards such as fault lines, rivers, and coastlines. This means that we are highly exposed to risks from natural hazards.

Natural hazard events are relatively low frequency, but high consequence, for both private property and public infrastructure. Collectively, the infrastructure rebuild costs associated with the four largest events since 2012 is at least $10 billion.

We need to be prepared

Infrastructure providers play an important role in preparedness for, and response to, natural hazards. They provide services, such as transport and drinking water, which are critical for wellbeing. As infrastructure networks expand and climate change increases risks, we can expect the risk to infrastructure to continue to increase.

A range of different roles each need to be performed well for the country to appropriately manage its risk from natural hazards. If infrastructure providers are unable to restore services in a timely manner after an event, there can be substantial consequences, such as public health impacts and reduced economic activity. If we don't plan our communities well and build to the appropriate standard, we will be exposed to unnecessary levels of risk. If the government and other infrastructure providers are unable to pay for the damages caused by events, we will be unable to recover.

We have different choices on how to respond to risk

Natural hazards present two distinct but interrelated risks to infrastructure. First, there is the **structural risk** from the harm that occurs if infrastructure is damaged. Second, there is the **fiscal risk** associated with paying for the cost of damages if they do happen.

Infrastructure providers have three main options to proactively manage these risks. They can:

1. Reduce their structural risk by taking steps to reduce the odds of damage, e.g. by investing in resilience or moving location.
2. Reduce their fiscal risk, e.g. by purchasing insurance.
3. Defer action until after an event occurs, e.g. by having a response plan in place.

It is important for infrastructure providers to understand their risk from natural hazards and optimise their response to that risk. There can be high costs if this isn't done well. If infrastructure providers under-invest in risk reduction, this could result in a range of poor outcomes, such as unnecessary service disruptions, costly damages, and strained finances. Conversely, if providers invest in resilience improvements that aren't necessary, this could increase the costs of infrastructure services without providing net benefits to users.

While it is important that infrastructure providers manage their risk well, there is a lack of information available to support this. New Zealand lacks clear guidance for infrastructure providers on how they should manage their risk from natural hazards. There is no guidance available for infrastructure providers on when difference options to manage natural hazard risk should be used or how the different options should be evaluated. While there is a regime in place to manage the fiscal risk to private residential property from some hazards such as earthquakes, no such system is in place for infrastructure. In this context, it is unclear what the relative role of different approaches should be or how infrastructure providers should go about preparing for natural hazard events.

Assessing the costs of different options can optimise investment

We present two case study examples of how infrastructure providers can compare the relative costs of different options to respond to the risk from natural hazards. In both case studies, we compare the relative cost of three broad options: buy insurance to mitigate financial risk, invest in resilience measures, or retreat from at-risk sites.

The first case study explores natural hazard risk in the context of costs to provide infrastructure. It seeks to understand how infrastructure providers can optimise risk management approaches to minimise infrastructure costs. It can be difficult for providers to understand when it is worthwhile to invest to reduce risk because the costs and benefits may not be obvious.

The case study shows that when assets are insured, trends in insurance premiums can help to identify whether and when it is cost-effective to invest in more resilient infrastructure. This is because insurance premiums will rise when natural hazard risks are perceived to be rising and reduce when appropriate resilience investments are made. Because relative costs of different options can change over time, it is often necessary to take a multi-year or even multi-decade view of options and decision-making.

The second case study explores natural hazard risk in the context of costs to private property owners. In many cases, infrastructure can either reduce or increase risk to other parties. For example, seawalls can provide protection to nearby property owners, while the design of roads and bridges can sometimes increase flood risks to nearby property owners.

This case study seeks to understand how infrastructure providers can optimise the impact on private property owners that arises from infrastructure investment. In this case, information from insurance premiums on residential properties that might be vulnerable to flooding can help to identify whether and when to invest in infrastructure that reduces risks to those properties. However, the costs and benefits of resilience investment can be experienced by different parties. Funding approaches that allocate costs to people who experience benefits from investment can help to ensure that appropriate investments are actually made in practice.

Through the two case studies, we also explore the potential impact of uncertainty. Uncertainty can come from many sources, including a lack of complete scientific knowledge of the natural hazards themselves, uncertainty surrounding future decisions and economic conditions, and policy and moral uncertainty around what is optimal.

Because infrastructure is long lived, investment decisions made today persist well into the future. However, it is difficult to predict the future. We show that when there is more uncertainty about the future costs and benefits of risk management options, it may be difficult to choose an optimal risk management approach and identify when to implement it. We consider three sources of uncertainty: the severity of climate change impacts, future price changes for housing and infrastructure construction, and discount rates.

Our key findings

1 The 'best' approach to managing risk varies

There are many alternative approaches to managing hazard-related risks to infrastructure. Some options include fiscal risk management with insurance and structural risk reduction through actions such as strengthening resilience or managed retreat from at risk areas.

The idea of a 'silver bullet' to natural hazard risk sounds appealing. However, there is no single best approach to managing natural hazard risk to infrastructure. Instead, the optimal approach will vary depending on many factors, including likelihood and consequence of the hazard, and the relative cost of different options in different situations. For example, two buildings could have the same function and exposure to risk, but the optimal response might be different if they are made of different materials with different levels of vulnerability to damage.

2 There are barriers to managing risk well

To manage risk well, infrastructure providers need to have a good understanding of their assets and the risks to which they are exposed. They will also need the capability to assess their options and optimise their response to risks from natural hazards.

At a national level, we lack comprehensive and consistent hazard data for providers to use to assess their risk. Even when hazard data is available, there is a lack of guidance or direction on how infrastructure providers should manage this risk. A further issue is that some infrastructure providers lack good data on their assets, including condition and risk exposure data.

3 Insurance costs can guide resilience investment

From the perspective of an infrastructure asset owner facing risk from natural hazards, it may be difficult to identify the optimal risk management strategy. In a world with many risks, what risks are 'worth' investing in resilience for, and which are not?

Quantifying risk and/or pricing it through insurance premiums, can help clarify the optimal risk management approach for infrastructure assets. Optimal resilience investments should reduce risk management costs, compared to continuing to pay risk related insurance premiums. When resilience investments are more costly than insuring risk, they may not be warranted.

4 Demand for resilience is cost dependent

The costs created by natural hazards and the costs required to mitigate risk are both uncertain. Because of this uncertainty, the optimal amount of resilience investment can change over time and vary between locations.

The optimal level of resilience will depend on the relative cost of resilience investments compared to the expected cost of (and the benefits we get from) the assets being protected. We can increase the case for resilience investment by focusing on keeping infrastructure delivery costs down. Conversely, rising infrastructure delivery costs will erode the case for resilience investments. This is because the cost of buying resilience will increase relative to the benefit of buying resilience.

Case study 1: Impact of sea level rise on coastal infrastructure

Context

There is a small wooden school block located in the coastal flood zone. Coastal flooding is expected to become both more frequent and intense.

The school board is preparing its 10 Year Property Plan and needs to decide whether it should invest in resilience within the next 10 years or not.

Options

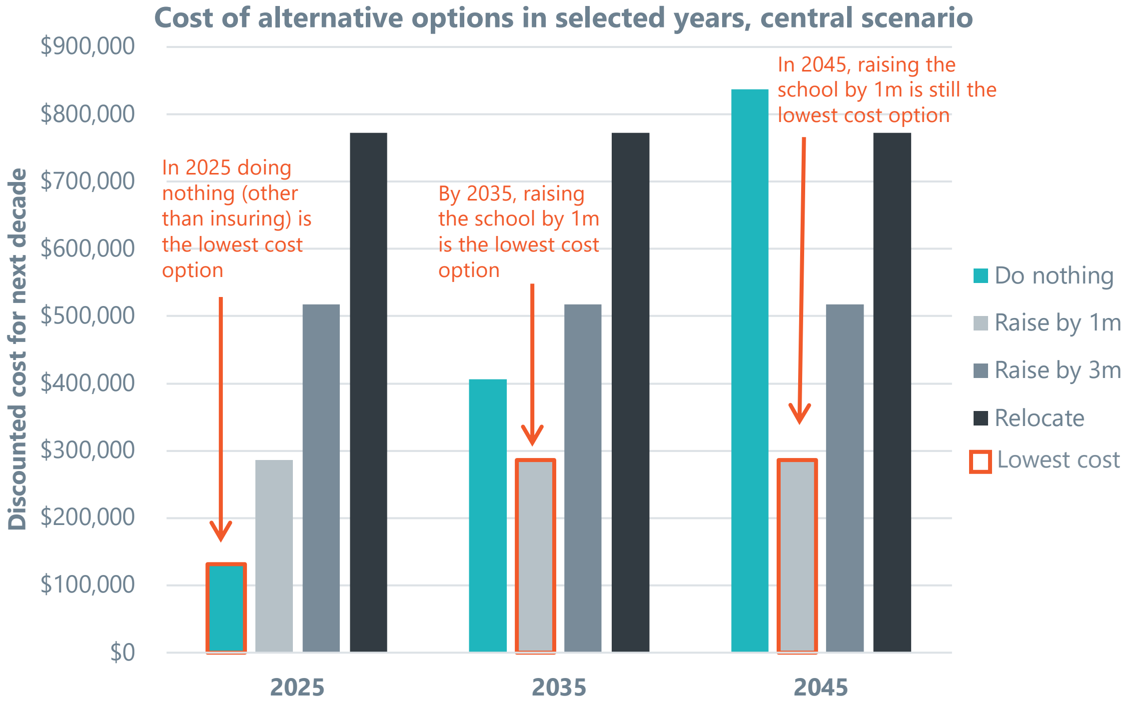
We investigate the relative costs of four different options:

1. staying at the current site and insuring the increasing risk of flooding,
2. raising the building by 1 metre,
3. raising the building by 3 metres,
4. relocating the building outside the flood zone.

We look at uncertainty surrounding future climate change impacts and try to understand if there is sufficient certainty to make an investment decision.

Key findings

- The optimal response to flood risk is not static and can change over time as the relative cost of options change.
- In this case study, insuring risk is the lowest cost option in the short term, with raising the building becoming the lowest cost option in about a decade.
- Estimating the relative cost of options over time can both minimise the overall cost of natural hazards and optimise the timing of investments.



Case study 2: Impact of price changes on optimal levels of resilience

Context

There are four residential properties that are located near a culvert that channels a stream under a local street. Because the culvert has a limited capacity, a severe weather event would result in flooding of the four surrounding properties. Climate change can be expected to exacerbate the problem.

The local council is investigating options to mitigate flood risk in the local area and needs to decide whether a resilience investment for this risk should be included in the Council's long-term plan, funded from a proposed targeted rate on nearby properties.

Options

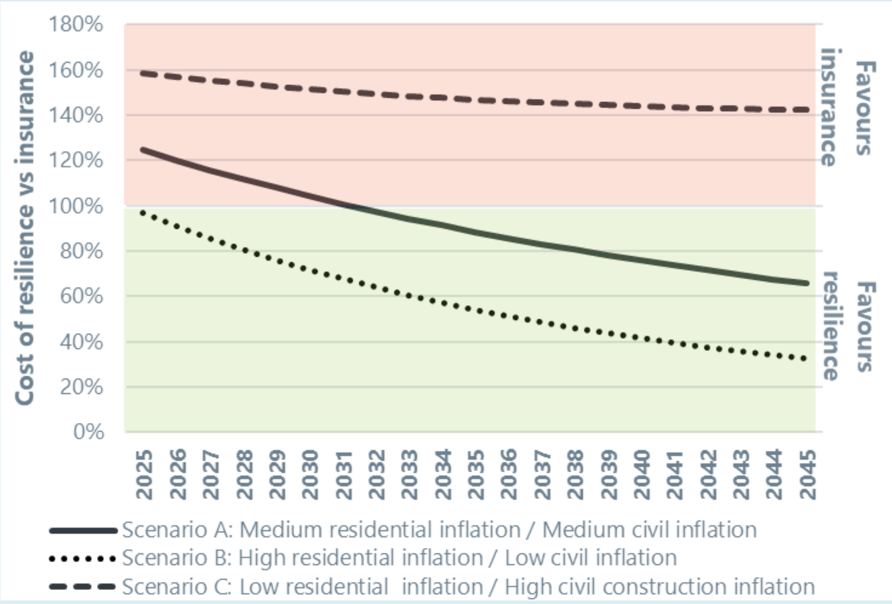
We investigate the relative costs of four different options:

1. doing nothing and expecting property owners to insure their risk,
2. building a bridge paid for by local property owners,
3. building a bridge paid for by all ratepayers, or
4. retreating from at risk properties.

We look at uncertainty about how fast residential property prices (which flow through into insurance premiums) and civil construction costs (which influence the cost of resilience) are expected to rise in the future.

Key findings

- An 'insurance cost' framework can help to think through how much to spend on resilience to avoid costs to other parties.
- The optimal response to flood risk is not static and can change over time as the relative cost of options change.
- In this case study, insuring risk is the lowest cost option in the short term, with adaptation becoming the lowest cost option in about a decade.
- This result is sensitive to expectations about future house price and infrastructure construction cost inflation, which means there may be benefits to waiting for more information before investing.



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1. Introduction

Governments play a pivotal role in the preparedness for and response to natural hazards. They provide infrastructure, such as transport and drinking water, which is critical for economic prosperity and wellbeing. If infrastructure services are disrupted by natural hazard events, there can be substantial consequences for communities, such as public health impacts and reduced economic activity. As a result, one of five strategic objectives for infrastructure in New Zealand set out by the New Zealand Infrastructure Strategy was a focus strengthening resilience to shocks and stresses (Te Waihanga, 2022).

Infrastructure is valuable, and this value can be at risk if it is exposed to risk of damage from natural hazards. In 2022, New Zealand's infrastructure assets, excluding land, were valued at $287 billion. The New Zealand government is the primary owner of this infrastructure: 45% of all infrastructure is owned by central government, 26% is owned by local government, and 29% is privately owned infrastructure and commercial assets owned by government (New Zealand Infrastructure Commission, 2024).

New Zealand's infrastructure is vulnerable to damage from natural hazards and the costs of this damage is high. Collectively, the infrastructure rebuild costs associated with the four largest events since 2012 is at least $10 billion.[1] The underlying risks are also changing. Climate change is expected to make severe weather events both more frequent and more severe. While many of the more severe impacts of climate change will not be felt until the coming decades, climate change is already starting to increase the damage felt from severe weather events.

Governments and other infrastructure providers have several options available to proactively manage the structural and financial risks associated natural hazards (Cebotari & Youssef, 2020; Kousky, 2019) They can:

- Invest in resilience to reduce exposure to physical risks,
- Manage fiscal risks e.g. through insurance or financial reserves, or
- Defer action until after an event occurs.

These options have different cost and benefit profiles over time. Investing in resilience can involve large up-front costs, while managing fiscal risks by insuring assets requires ongoing payment of insurance premiums. Both of these approaches can reduce or offset the costs of natural hazard events when they occur. Investing in resilience reduces both physical and financial risk, whereas insurance only reduces financial risk. By contrast, deferring action until an event occurs will tend to appear cheaper until an event occurs.

Ideally, governments and other infrastructure providers would choose a mix of these options to manage risk from natural hazards at the lowest whole-of-life cost. However, understanding the optimal path can be challenging because risk management decisions made today will persist well into the future – and the future is uncertain.

Uncertainty can come from many sources, including a lack of complete scientific knowledge, uncertainty surrounding future decisions and economic conditions, and policy and moral uncertainty around how to weigh up current versus future costs. Our risk management decisions need to consider the potential impact of uncertainty.

This paper seeks to address the following research questions:

- What factors influence whether it is economically preferable for infrastructure providers to insure against risks vs take proactive action to reduce risk before an event occurs?

[1] See Section 3.1 for a summary of these events.

- How can infrastructure providers assess their options for managing their risk from natural hazards?
- What is the potential impact of uncertainty on the optimal management of risk from natural hazards?

To answer these questions, this paper:

- Provides a brief overview of the broader literature on natural hazard insurance and other options that governments have to manage risks.
- Summarises what we know about New Zealand's exposure to natural hazard risks and briefly reviews current risk management settings in New Zealand.
- Presents two case studies to consider the impact of different sources of uncertainty.
  - The first case study explores the relative costs of different approaches to manage the risk of damage to infrastructure, and considers the potential impact of climate change uncertainty,
  - The second case study explores the relative costs of different approaches to manage the risk of damage to private property from infrastructure, and considers the potential impact of uncertainty about the future cost of different responses to risk,
- Concludes with a brief discussion of key lessons for infrastructure providers and decision-makers.

2. Literature review

2.1. Using insurance to manage risk

Insurance is a means of transferring a financial risk to a party that is better able to manage that risk.

Asset owners, including infrastructure providers, tend to own assets in specific locations that are exposed to certain types of risks. For instance, most homeowners have a large share of their household wealth tied up in a single home. If their home is destroyed by a natural hazard event, they are unlikely to have enough money to rebuild it.

Insurers can bear the risk of cost arising from damage to specific assets by pooling the risk across many asset owners in many locations. For instance, residential property insurers provide insurance to people living in many different cities that are exposed to different risks. As long as these risks are reasonably uncorrelated, then only a small share of people with insurance policies will submit claims for damages in any given year. In effect, insurers spread the costs of individual events across many asset owners.

The cost of insurance will depend on the likelihood of negative events and their associated costs, plus a margin. This margin will include profit for the insurer, and, potentially, insurance to cover the risk of an unusually large number of claims occurring at the same time (reinsurance). Insurance premiums will be higher for assets in riskier locations, and also higher for correlated risks that can affect a large share of insured assets.

Insurance is used to manage many types of financial risk facing households, businesses, and governments. Some common types of insurance include home insurance, health insurance, and liability insurance. However, not all risks are well-suited to insurance. **Figure 1** shows two factors that influence whether insurance is likely to be an optimal financial risk management strategy: the frequency of an event and the severity of its consequence (Cutler & Zeckhauser, 2004).

The combination of frequency and severity can be roughly divided into five broad categories:

A. **Very high severity, very low frequency events**: Insurance is generally not worthwhile to policyholders because insurance has reasonable expenses with little chance of compensation gain (Shape A in Figure 1). An example of this might be insurance against a large asteroid impact.

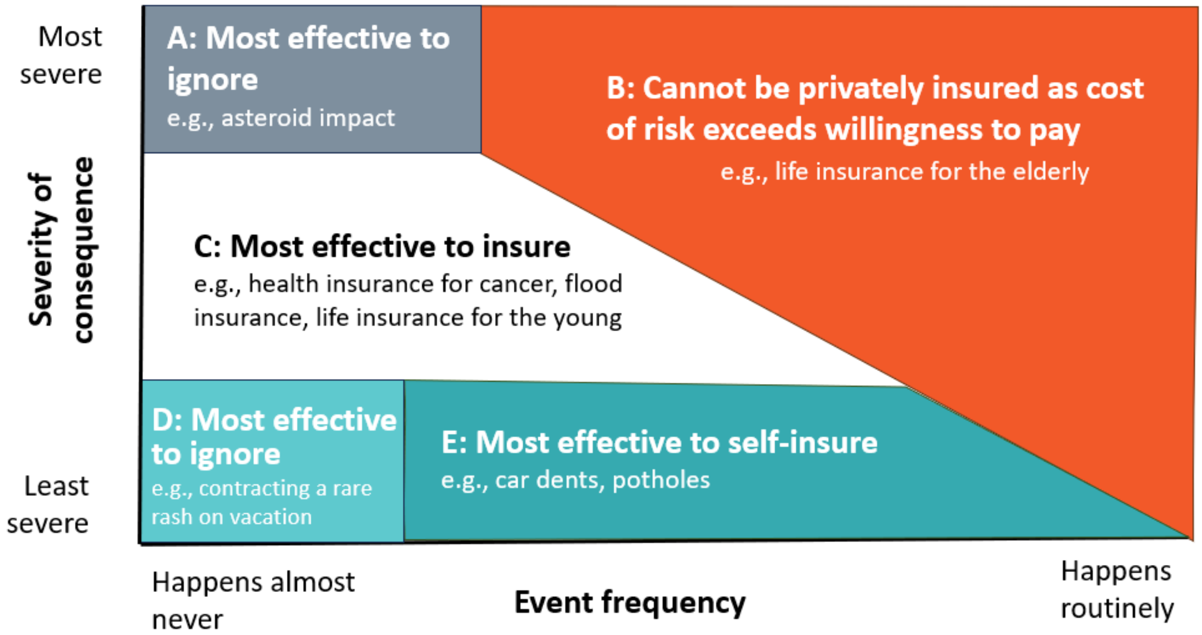
B. **High severity, higher frequency**: Risks cannot usually be privately insured as the cost of the risk is likely to exceed customers willingness to pay for, or providers willingness to offer, insurance policies (Shape B in Figure 1). Examples of this include life insurance for the elderly or motor insurance for teenagers with sports cars.

C. **Medium to high severity, medium to low frequency events**: Insurance is generally attractive for both customers and suppliers (Shape C in Figure 1). Examples of this include health insurance for cancer, flood insurance and life insurance for the young.

D. **Low severity, low frequency events**: Insurance is likely not worthwhile to policyholders because of the low expected values of policies, and high premium costs relative to risk (Shape D in Figure 1). An example of this would be insurance against contracting a rare rash on vacation.

E. **Low severity, high frequency events**: Insurance is likely not worthwhile for policyholders because it is more effective for customers to self-insure through financial reserves (Shape E in Figure 1). Examples of this would be insurance against minor dents on cars or potholes in roads.

Figure 1: Impact of event frequency and severity on the optimality of insurance



In general, natural hazards are high severity, low frequency events, which makes them well-suited to management through insurance (Davlasheridze et al., 2020; Kousky, 2019). For example, the risk of loss of the family home in a cyclone may be sufficiently likely, and the loss high enough, to justify the purchase of insurance for many households.

However, in some cases, the expected frequency of natural hazards may be too high or too low to enable effective management through insurance. On one hand, people may choose not to buy insurance against hazards that they perceive to be very low-probability, like tsunamis or major floods.[2] On the other hand, insurers may choose not to offer insurance policies against very high-probability hazards, like periodic flooding in low-lying areas (Davlasheridze et al., 2020; Kousky, 2019). It may be more cost effective for asset owners to manage risks from high-probability hazards through structural protection measures or self-insurance (Hallegatte et al., 2020).

Besides frequency and severity, there are a few other factors that influence the degree to which insurance is likely to be the most optimal, or even a viable, financial risk management strategy. Some other key factors include:

- **The correlation of risk between policyholders**: When risk is correlated rather than randomly distributed, insurance providers may no longer provide insurance coverage to everyone as it increases the systemic risk on their portfolio (Bernard et al., 2020). Many natural hazards, such as cyclones and earthquakes, tend to impact many policyholders in a single location simultaneously.
- **Adverse selection**: When insurance is optional, those who purchase it may be higher risk than those who do not. When this occurs, it increases the overall cost to providers and causes premiums to rise (Cutler & Zeckhauser, 2004). This can be present in cases such as flood insurance, where only those at higher risk buy policies, leading to the withdrawal of private insurers from markets in absence of government intervention.
- **Modelling accuracy**: If risks cannot be efficiently and accurately modelled, insurance for them cannot be accurately priced and sold (Davlasheridze et al., 2020). The modelling of risk from

[2] It is worth noting that perceptions of risk may not reflect actual risk, with people tending to increase their perception of risks for events that have occurred recently, and under-estimating their perception of risk for events that have not occurred in recent times (Botzen et al., 2009; Kousky, 2019).

floods, cyclones and earthquakes may be subject to inaccuracies and continues to evolve along with scientific advancements. Actual risk levels are changing due to climate change, reducing the accuracy of historic models.

- **Administration and transaction costs**: Even if a risk is theoretically well-suited to insurance, insurance might not be offered if the costs to administer it are too high. There can be high transaction costs, especially for coverage in remote or rural areas, and when the sum insured is relatively small. This can lead to lower than optimal provision of hazard insurance by providers (Hallegatte et al., 2020; Kousky, 2019; Kraehnert et al., 2021).

2.2. Changing risks change the cost and viability of insurance

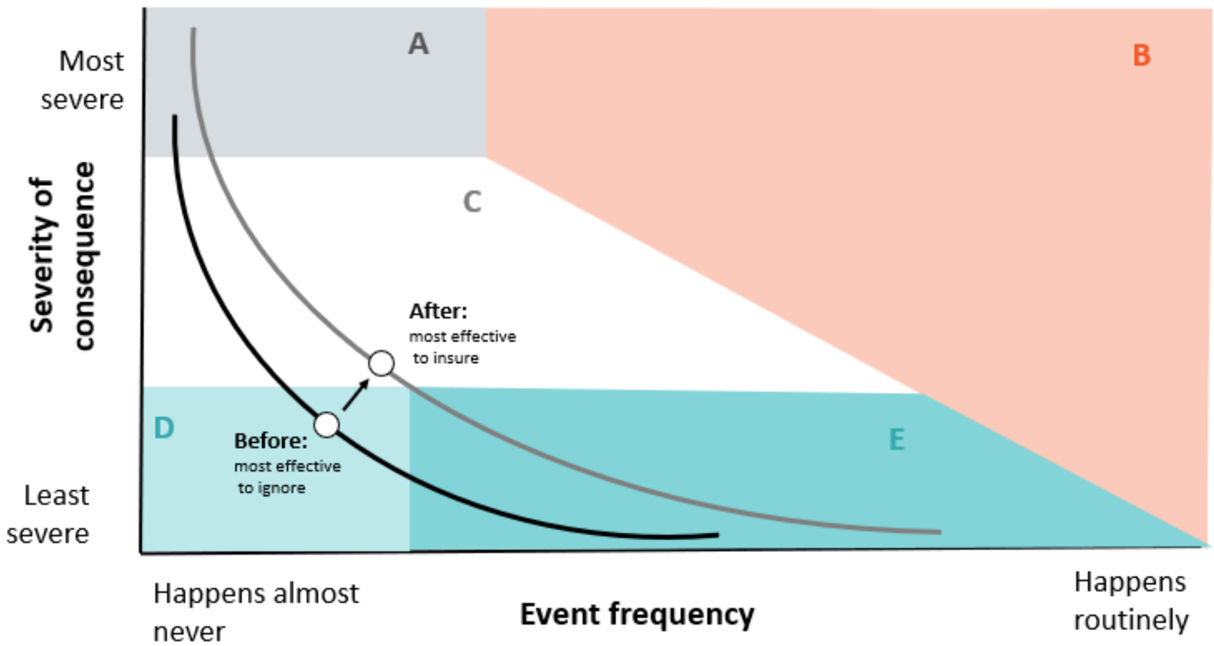
The total damage caused by natural hazard events can be viewed as a product of two factors: the probability of an event occurring and the severity of an event when it does occur.

The curved line on **Figure 2** shows a stylised depiction of the typical relationship between probability and severity. The most severe events happen infrequently, whereas the least severe events happen very frequently. For example, New Zealand experiences many small earthquakes that cause little to no damage, as well as a small number of large earthquakes that cause significant damage. The location of the curve on the chart provides an indication of the seriousness of risk: the seriousness of risk increases as curves move upward and to the right.

If natural hazard risks change over time, the cost to insure against risks and the viability of purchasing insurance may change. For example, if climate change makes flood-related damages to a property more frequent and more severe, private insurers may stop offering coverage (Storey et al., 2023).

If a natural hazard event becomes more frequent and severe, shown as an outward movement of the risk curve on **Figure 2**, the optimal risk management approach may change. For instance, a risk that was previously best to ignore (the marked point on the black curve) may become cost effective to insure (the marked point on the grey curve).

Figure 2: Changes in event frequency and severity can change the optimal risk management strategy



*Note: For a description of the regions A-E, see **Figure 1***

Because of these multiple factors, insurance can be, but is not always, an effective risk management strategy, and is more useful in some circumstances than in others.

2.3. Hazard Risk Management for Governments: What role for insurance?

In terms of natural hazard risks, governments differ from individuals and private entities in two ways.

First, governments are exposed to different types of risks from natural hazards. Whereas the financial risk that private entities face from natural hazards are somewhat well-defined, the financial risks that governments face from natural hazards can be more numerous and ambiguous.

Like private entities, governments face the need to repair their assets after a natural hazard event, or bear the cost of rebuilding them in a different location. For example, after the Canterbury earthquakes, the government incurred direct costs due to rebuilding damaged infrastructure, and indirect costs due to population redistribution to the neighbouring Waimakariri and Selwyn District Councils, which created a need for additional infrastructure in these areas.

Unlike private entities, governments also face the need to address the other social and economic impacts of a natural hazard event. These expectations may be explicit, such as contractual or legal obligations, or implicit, such as public expectations or political pressures (Polackova, 1999). For example, in 2011, the New Zealand government made the decision to implement a managed retreat from areas with severe earthquake damage, offering impacted property owners the option for full compensation for the value of their land and buildings (Noy, 2020). This decision may have created a public expectation that the New Zealand government will compensate property owners where managed retreat is implemented.

Second, governments have access to different risk management strategies than private entities.

They typically have access to more fiscal risk management strategies due to their size, risk profiles, and taxing powers (Cebotari & Youssef, 2020). This means that governments are better able to self-insure against natural hazards, for instance by establishing a sovereign wealth fund or maintaining debt capacity. They may also have more options available for transferring financial risk, such as through catastrophe bonds that pay out when a large natural hazard event occurs.[3]

Governments can also use their regulatory powers to reduce their exposure to natural hazard risks, for example by mandating private uptake of insurance or setting minimum building code standards that reduce structural risks across the country.

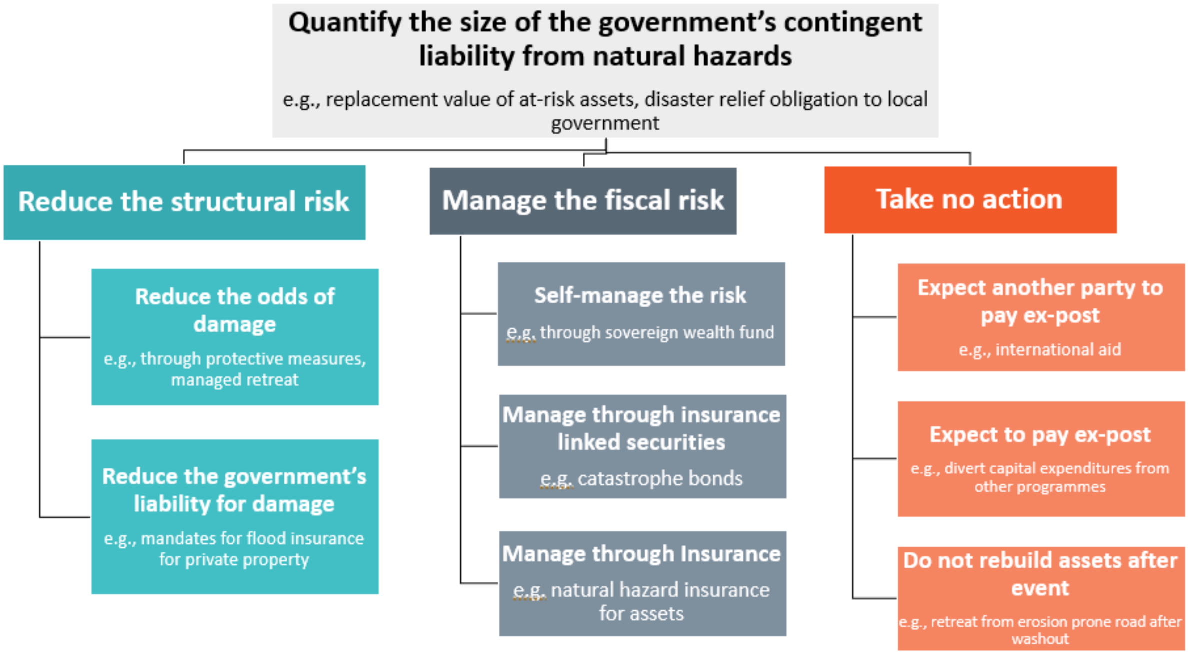
Figure 3, based on Hallegatte et al (2020), outlines the options that governments have for managing natural hazard risks before an event occurs. Hallegatte et al (2020) recommend a two-step framework that involves: 1) quantification of a government's contingent liabilities from natural hazard events; and 2) creation of a layered system for management of the contingent liabilities identified.

The first step involves development of an empirical estimate of the possible impact of events and the extent to which these may be contingent government liabilities. The second step involves an iterative process of determining what proportion of the risk should be managed through one of three alternative approaches: a) reducing the structural risk, b) managing the financial risk, or c) taking no action before an event occurs.

[3] Catastrophe bonds are a form of 'parametric' insurance (also known as index insurance), where compensation is based on predefined triggering parameters that are a proxy for actual damage (Feess et al., 2022). This distinguishes it from conventional 'indemnity' insurance, where compensation is dependent on the assessment of actual losses incurred.

Ultimately, Hallegatte et al (2020) argue that optimal risk management strategy for any government is likely to be a mix of multiple different strategies, employing a combination of resilience measures to reduce structural risk, self-management of fiscal risk, and financial risk transfer through insurance or other financial products like catastrophe bonds.

Figure 3: An outline of approaches to managing contingent liabilities for governments



In addition, governments (and other asset owners) have a range of options for reducing structural risk from natural hazards. These are summarised in the Protect, Accommodate, Retreat or Avoid (PARA) framework set out in

Figure 4. PARA has its origins in the first IPCC climate change assessment report in the context of preparing for climate change-related sea level rise (Dronkers et al., 1990). This focussed on the protect, accommodate and retreat elements, with 'avoid' being added later (Doberstein et al., 2019). The optimal approach to reducing structural approach is likely to involve a combination of these measures.

Figure 4: Example of the PARA framework to flood resilience

Protect	Accommodate	Retreat	Avoid
Sea walls, dykes	Flood construction levels	Easements	Restrictions, Zoning
Scour protection	Wet flood proofing	Land acquisition	Land acquisition
Dune building	Elevated homes	Wetland restoration	Transfer of Development Rights
Beach nourishment	Flood storage areas		

Source: Dronkers et al (2019)

2.4. Several factors influence governments' risk management strategies

There are several factors that might influence governments' choices about how to manage the financial risks arising from natural hazards. Like private entities, governments will be concerned about choosing risk management strategies that are as cost effective as possible, given the nature of the risks they face. They also need to consider factors like 1) borrowing capacity, 2) size and diversity of risk, 3) the urgency with which financial resources may be required, and 4) obligations to pay losses incurred by other parties, such as citizens or local governments.

Borrowing capacity and the size and diversity of risks facing countries can influence whether they choose to buy insurance against natural hazards or borrow money after an event to pay for recovery. Because insurance premiums tend to be higher than the expected cost of events, governments face a trade-off between the cost of insurance and the benefits of reduced fiscal risk (Cebotari & Youssef, 2020; Linnerooth-Bayer et al., 2019).[4] Cebotari & Youssef (2020) use a theoretical model to examine the optimal trade-off between the costs of the insurance and its benefits.[5] They find that insurance may be more valuable for smaller countries with less internal diversification of risk, and for countries with lower borrowing capacity, as they are less able to obtain financing to pay for repairs after an event.

Urgency and obligations to help others recover from extreme events can also influence governments' choices. Whereas private entities are typically concerned with maximising their own prosperity, governments have a primary interest in the wider wellbeing of their inhabitants. After a disaster, prompt assistance can reduce the long-term economic impact of a disaster and improve social outcomes, especially for low-income and other vulnerable populations. Governments may therefore wish to minimise recovery times by managing costs associated with immediate post-event damages through financial instruments with high liquidity, such as through financial reserves or types of insurance than can be settled quickly (Linnerooth-Bayer et al., 2019).

However, governments' obligations to support other entities' recovery from natural hazard events can cause other challenges. Goodspeed and Haughwout (2012) use a theoretical model to examine the optimal design of state-level disaster insurance in a federal government. They find that when the federal government is committed to full support of local government in the case of natural disasters, regions are incentivised to under-invest in structural protections to reduce risk, resulting in higher than optimal levels of risk exposure. There is some evidence that this theoretical finding has played out in practice, with US transport and port systems choosing to rely on federal government assistance rather than proactively managing risks (Tonn et al., 2021).

To address these misaligned incentives, Goodspeed and Haughwout (2012) propose that central government should regulate to require appropriate investment in structural protection. Alternatively, a second-best system would involve reducing transfers from federal government to regions that under-invest in protective measures. However, others have noted that this type of approach may be difficult to sustain as disaster relief is popular with voters, while ex-ante risk reduction may be less popular (Kunreuther et al., 2016).

[4] In general, private insurance exceeds the cost of self-insurance because the cost of insurance also includes the pricing of transaction, administration, and uncertainty costs.
[5] In this paper, the benefits of insurance are measured by the impact on economic growth.

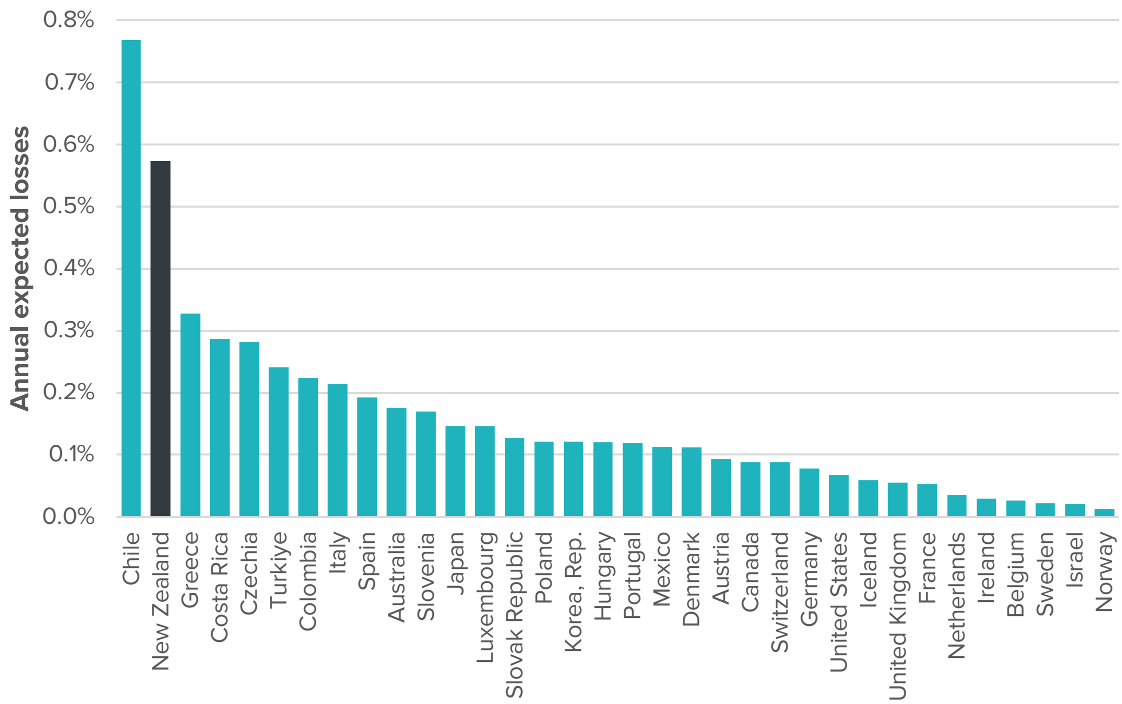
3. Practice review

3.1. The cost of natural hazards to New Zealand

New Zealand is highly exposed to natural hazards. While it is difficult to benchmark and compare natural hazard risk across countries, we have some of the highest reported damages from large natural hazard events of any OECD country. This suggests that managing natural hazard risk is more important for New Zealand than it may be for many other OECD countries.

Figure 5 shows that, in recent decades, New Zealand has experienced annual reported losses equal to almost 0.6% of gross domestic product (GDP). These losses mainly reflect damage to residential property and businesses, as well as damage to infrastructure.

Figure 5: Annual expected losses from natural hazard events in OECD countries (as a share of GDP, 1960-2022)



Source: Te Waihanga analysis of EM-DAT database and World Bank GDP data. See Appendix 1 for details of calculation.

The exact cost of damage to infrastructure from natural hazards in New Zealand is unknown. We don't know the full cost because this data is spread across many different infrastructure providers and our accounting practices do not require spending to be separated by spending purpose, making it very difficult to disentangle spending due to damages, renewal requirements, and level of service changes.

For some hazards, such as riverine and coastal flooding, we lack both national and consistent hazard maps at an appropriate resolution for identifying assets at risk (Paulik, Craig, et al., 2019). Recent studies have attempted to quantify the assets at risk to riverine and coastal flooding, although the studies have several limitations due to the availability of input data. Paulik, Craig, et al. (2019) estimate that over 19,000 kilometres of roads and over 21,000 of three waters pipelines are at risk to riverine flooding.

Paulik et al. (2019) estimate that over 1400 kilometres of roads and over 3,000 of three waters pipelines are at risk to coastal flooding.

One approach to quantifying the cost of natural hazards to infrastructure specifically is to review the costs that have been accounted for among some of the largest most recent events. Four recent events that incurred large costs are the 2011 Canterbury earthquakes, the 2016 Kaikoura Earthquake, the 2023 Auckland Anniversary weekend floods, and Cyclone Gabrielle in 2023.

A comprehensive review of the infrastructure cost of 2011 Canterbury earthquakes has not been estimated, but likely is at least $6 billion (Deloitte, 2017; Office of the Auditor-General, 2017).[6] As costs from the Canterbury earthquakes have continue to be incurred since these estimates were created, the actual costs will be higher. The cost to rebuild and strengthen the state highway and rail network after the 2016 Kaikōura earthquake was $1.25 billion (New Zealand Government, 2020), with further costs incurred by local authorities and other government departments. The central government has allocated around $3 billion to recovery from the 2023 Auckland Anniversary weekend floods and Cyclone Gabrielle, with further spending by local authorities and commercial infrastructure providers (The Treasury New Zealand, 2024).

Collectively, it will cost over $10 billion to rebuild infrastructure following these four events. This is equal to around 0.3% of New Zealand's GDP over the 2011-2023 period.

3.2. The costs of natural hazards are rising

Our understanding of both the probability and severity of natural hazards continues to improve as scientific research progresses. Improved scientific understanding sometimes results in increased estimates of risk as hazards are investigated in more detail.

For example, estimates of the likelihood and severity of earthquakes in New Zealand have increased over time as risk modelling improves. Pre-2021 modelling estimated that there was a 30% chance of a major earthquake on the Alpine Fault over the next 50 years. More recent research has estimated the probability to be much higher, with a 75% probability of occurring over the next 50 years (Howarth et al., 2021). At the national level, the 2022 update to New Zealand' national seismic hazard model resulted in an increase in New Zealand's assessed earthquake hazard by a factor of between 1.5 and 2.0 (Bora et al., 2024).

In some cases, the underlying risks are also changing as climate change is expected to make severe weather events both more frequent and more severe.

While the most severe impacts of climate change will not be felt immediately, climate change is already increasing the damage felt from severe weather events. Globally, climate change was found to be responsible for US$143 billion per year in damages from severe weather events, like heatwaves, floods, droughts, wildfires, and storms, over the past two decades (Newman & Noy, 2023). This accounts for over half (53%) of total damages from extreme weather events over this period.

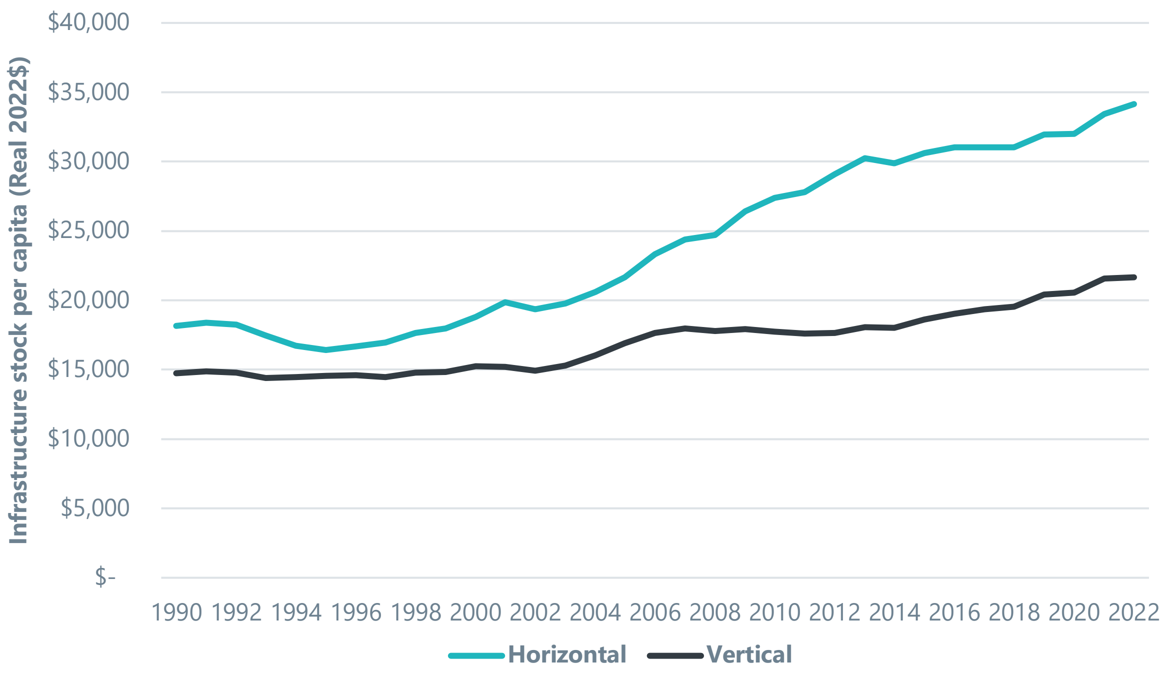
New Zealand-specific evidence also highlights that climate change is increasing both the severity and likelihood of extreme weather events. Frame et al. (2020) examined extreme rainfall events that occurred between 2007 and 2017 and found that most events showed a 40% increase in probability of occurring due to climate change. Stone et al. (2024) estimated that the total rainfall from Cyclone Gabrielle was about 10% higher due to climate change.

Finally, our exposure to risks may increase as we build more infrastructure, as we have more assets that are exposed to damage. **Figure 6** shows the infrastructure stock per capita in New Zealand from 1990 to

[6] The costs incurred by CERA were $4 billion by 2017, while the costs incurred by Christchurch City Council were $1.9 billion by 2017.

2022. The quantity of infrastructure per capita has increased by 70% since 1990, even after adjusting for inflation (New Zealand Infrastructure Commission, 2024). This increase in stock means that on average, we can expect that a similar event to one that occurred in previous decades would result in higher damage if it occurred in future.

Figure 6: Infrastructure stock per capita, 1990 to 2022



Note: Horizontal represents networks such as roads, power lines and water, while vertical is buildings such as hospitals and schools.

Source: (New Zealand Infrastructure Commission, 2024)

3.3. Current risk management settings in New Zealand

As background to our case studies, we briefly review the New Zealand government's existing framework for managing natural hazard risks to infrastructure. This includes existing legislative requirements for the management of structural and fiscal risks, and key supporting policies and guidance documents which also provide direction to government infrastructure providers.

The core legislation for the management of hazards in New Zealand is the Civil Defence Emergency Management Act (2002). The purpose of the act covers all stages of emergency management, including risk management before an event occurs, planning and preparation for emergencies, and response after an event occurs. The CDEM Act outlines requirements for three types of infrastructure providers: central government departments, local governments, and lifeline utilities.

Under the Act, these providers are required to ensure that they are "able to function to the fullest possible extent, even though this may be at a reduced level, during and after an emergency" (CDEM 2002, Part 3 s 57). However, the Act does not include any further detail regarding how infrastructure providers should meet this requirement or what actions should be taken before an event occurs.

For government owned assets, the Crown holds ultimately responsibility for the management of its risks and any financial liabilities that may arise. New Zealand's Public Finance Act (1989) provides the core legislative framework for the Government to borrow and spend public money and establishes a set of principles for responsible fiscal management for the country (The Treasury New Zealand, 2023). As such, the requirements of the Public Finance Act are the primary means by which the government manages the fiscal risk associated with natural hazards.

The Public Finance Act (1989) enables the management of fiscal risks associated with natural hazards through two key mechanisms. First, its principles of responsible fiscal management require the Government to reduce and maintain debt to prudent levels. This is intended to "provide a buffer against factors that may impact adversely on total net worth in the future" (Public Finance Act, 1989, p. 25G (a)). This requirement is intended to provide the government with borrowing headroom that can be used to respond after unexpected events, including those causes by natural hazards.

Second, the Act requires the prudent management of potential fiscal risks facing the Government through proactive fiscal forecasting that include financial statements, contingent liabilities, and fiscal risks. The requirements for reporting risks and liabilities are outlined in **Table 1**. Disclosure and accounting requirements vary according to the entity type, the size of the risk/liability, the likelihood of the event occurring, and the degree to which it can be quantified.

This process is managed by Treasury, which is required to prepare an annual statement of the specific fiscal risks of the Government. Separate to this requirement, the Treasury is also required to prepare a statement on the long-term fiscal position of the government, looking at least 40 years into the future.

The latest statement on the long-term fiscal position was published in 2021. The report explores the potential impact of major earthquakes and climate change on the government's fiscal position. The report models the potential economic and fiscal impacts of a major earthquake and finds that after such an event, debt would increase by approximately 12% of GDP. The report models the potential fiscal impact of two climate change impacts, more frequent storms and drought, and finds that severe droughts could lead to net debt being around 1% of GDP higher, and increasing storms could add almost 3% of GDP to net debt (The Treasury New Zealand, 2021).

While the Treasury has modelled the potential economic and fiscal impacts of three selected natural hazards, this is not a comprehensive assessment of the Government's risk. The cost of these risks has yet to be incorporated into the government's long-term fiscal model or disclosed as fiscal risks or contingent liabilities.

In its annual disclosure of risks, the Treasury states, "Once such an [natural disaster] event does occur, various choices arise about how to respond and when to recognise potential liabilities. Specific risks are disclosed at that point, based on the range of possible responses" (The Treasury, 2023, p. 50). While the Public Finance Act provides the structure to report fiscal risks faced by the Crown, the risk from natural hazards is not currently quantified or included within New Zealand's fiscal risk management regime.

Table 1: Reporting regime for risks and liabilities

Certainty	Who	When	What
Least certain	**Fiscal risks**		
	Who: The Treasury, in every economic and fiscal update.	**When:** Risks may have a material effect on the fiscal and economic outlook, but fiscal impact cannot be reasonably quantified, the likelihood of realisation is uncertain and/or the timing is uncertain.	**What**: All government decisions and other circumstances, to the fullest extent possible
↕	**Contingent liabilities**		
	Who: Government entities and companies. If greater than $10 million, Minister of Finance must present to the House of Representatives	**When:** The possibility is more than remote but not probable, and a reliable estimate can be made.	**What:** Any obligation for which an outflow of resources embodying economic benefits or service potential.
	Liabilities		
Most certain	**Who:** Government entities and companies	**When:** It is probable that an outflow of resources will be required to settle the obligation, and a reliable estimate can be made.	**What:** A present obligation (legal or constructive) as a result of a past event (not its possible position in the future).

Sources: (New Zealand External Reporting Board, 2014; The Treasury New Zealand, 2013, 2023)

In addition to the above approaches for disclosing and managing fiscal risks, the government can manage both fiscal and structural risks through procedures, standards, and/or expectations set for agencies through mechanisms such as cabinet circulars and guidance documents.

A core document of this type is the Cabinet Office Circular CO(23)9 on *Investment Management and Asset Performance in Departments and Other Entities* (Department of Prime Minister and Cabinet, 2023). The Circular sets out Cabinet's expectations for agencies and Crown entities regarding the management of their assets. These expectations include management of risks. Asset management planning must include consideration of whether "assets are resilient to the effects of significant risks (for example, climate change, natural disasters or demographic changes)". The Circular also states that the level of resilience required for assets should be determined by agencies and acknowledges that the optimal level of resilience may vary.

Relevant guidance is also provided by key government agencies. One example is the Ministry for the Environment's Coastal Hazards Guide (Ministry for the Environment, 2024a). This document provides guidance on expected magnitude of future relative sea-level rise under a range of scenarios out to 2150. It also outlines potential responses to sea-level rise and explains that a suite of different options could be suitable depending on different circumstances. The guide recommends using the dynamic adaptive pathways planning (DAPP) approach for developing adaptive planning strategies which allows for adjusting pathways as new information emerges. However, it does not provide specific guidance on how to assess the merits of different options or provide guidance on how decisions should be made surrounding investment in climate adaption and risk mitigation.

In the absence of an overarching framework or guidance on the management of natural hazards, different infrastructure providers have chosen to take different approaches to manage natural hazard risk. A 2013 review of insurance coverage for public assets revealed that less than half of public assets had insurance cover. At this time, many public assets had no insurance coverage, and approaches to managing risk varied widely across entities. The most commonly stated reason for not holding insurance coverage was that the entity believed that the cost of the insurance exceeded the assessed risk (Office of the Auditor-General, 2013).

The current level of insurance coverage by infrastructure providers is unknown, as the latest data is 11 years old. However, we can look to similar entities to compare their approaches to managing risk.

Both KiwiRail and NZTA are owners and operators of national transport networks that connect regions and are exposed to similar natural hazards. The national railway network is around 3,700 kilometres long, while the national state highway network is 11,000 km long.

KiwiRail has chosen an insurance-based approach to managing its risk from natural hazards. It has insurance coverage in place for loss and damage under multiple policies which cover a range of risks, which includes but is not limited to risks to infrastructure from natural hazards (KiwiRail, 2024).

NZTA has chosen a 'pay as you go' approach to managing its risk from natural hazards and does not hold insurance for its assets. Instead, it has allocated $140 million per year for emergency works to rebuild state highways after damage occurs.

Despite similar risk profiles, these entities have chosen very different approaches to managing their fiscal risks from natural hazards. It is difficult to assess whether these choices are optimal in the absence of an overarching framework or guidance on the management of natural hazards.

4. Case study 1: Impact of sea level rise on coastal infrastructure costs

The first case study explores natural hazard risk in the context of costs to provide infrastructure. It seeks to understand how infrastructure providers can optimise their management of risk to minimise infrastructure costs. We consider the possible impact of coastal flooding and sea level rise on vertical infrastructure located in the coastal flood zone. In this scenario, we imagine a four-classroom wooden single-storey school building. We assume that this individual school building is currently situated within the 1 in 100-year flood zone from coastal inundation.

We take the perspective of the school board and assume that the board is assessing the relative costs of managing the risk of coastal flooding to the school building over the next decade. We assume a 10-year analysis period as the Ministry of Education requires schools to prepare 10 Year Property Plans which prioritises and schedules property projects to be completed within a 10-year planning period (Ministry of Education, 2016)

The School Board is currently exploring four potential options to manage the financial risk associated with its vulnerability to coastal flooding. They can:

1. **Insure risk** - Keep the school building unchanged and continue to pay the insurance premiums associated with its coastal flood risk (manage the fiscal risk).[7]

2. **Raise by 1 metre** - Raise the building level by 1 metre, mitigating all potential flood damage for flooding events with a depth of up to 1 metre (reduce the structural risk).

3. **Raise by 3 metres** - Raise the building level by 3 metres, mitigating all potential flood damage for flooding events with a depth of up to 3 metres (reduce the structural risk).

4. **Relocate** - Relocate the building to elsewhere on the school grounds, which would be outside the coastal flood zone (reduce the structural risk).

We seek to address the following questions for the school Board:

- What are the relative costs of doing nothing, investing in resilience, or retreating from the site?
- If either investing in resilience or retreating from the site is likely to be cost effective compared to doing nothing, what year should an investment be made?
- Is there sufficient certainty regarding the impact of climate change on coastal flooding and discounting assumptions for the Board to have confidence in what the most cost-effective option is?

4.1. Modelling approach

For this case study, we assume that the cost of each option is the combined cost of insurance premiums for coastal flooding risk and the construction costs associated with resilience or retreat, if applicable. Insurance premiums are calculated based on the expected damages from a coastal flooding event that has a 1 in 100-year probability of occurring in 2025.

We calculate the projected impact of climate change on this coastal flooding event, considering the projected future increases in both coastal flooding frequency and severity due to climate change. For

[7] For the purposes of the case study, we assume that commercial insurance will always be available for the school.

the purposes of this illustrative case study, we consider the direct financial costs associated with each option but exclude wider or indirect costs, such as the costs of service disruption or provision of temporary schooling facilities. Options which reduce physical as well as financial risk would reduce the disruption costs associated with physical damage, whereas options that only reduce financial risk would not. In real world scenarios, it would be advantageous to account for all the substantive costs and benefits of different options.

The relative financial costs of the four options are calculated for each year from 2025 to 2050. For any given year, the projected costs are the discounted total for the next 10-year period. Relative costs are presented in this way as school boards are directed to make decisions based on a 10-year planning period.

We consider two sources of uncertainty in case study 1: future greenhouse gas concentrations and the optimal discount rate for decision-making.

We consider three greenhouse gas concentration scenarios created by the Intergovernmental Panel on Climate Change (IPCC) for their Fifth Assessment Report.[8] The Representative Concentration Pathways (RCPs) describe different pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs were developed using as input to a wide range of climate model simulations to project their consequences for the climate system. These climate projections, in turn, are used for impacts and adaptation assessment. The RCPs are consistent with the wide range of scenarios in the mitigation literature. The scenarios are used to assess the costs associated with emission reductions consistent with particular concentration pathways.

We use three of their scenarios, which relate to a wide range of future sea level rise outcome (Ministry for the Environment, 2024b).:

- RCP 2.6M: A stringent mitigation scenario, with a projected mean sea level rise of 0.5m by 2100.
- RCP 4.5M: An intermediate scenario, with a projected mean sea level rise of 0.6m by 2100.
- RCP 8.5M: A very high warming scenario, with a projected mean sea level rise of 0.9m by 2100.

The three discount rates considered are 2%, 5%, and 8%. These three discount rates are used as they represent the 2024 public sector discount rate for non-commercial proposals (2%), the 2023 public sector discount rate for non-commercial proposals (5%), and the 2024 mandatory sensitivity test for non-commercial proposals (8%) (The Treasury, 2024). These three discount rate scenarios represent a wide range of relative weighting on present vs. future costs and benefits.

We do not consider other sources of future cost changes, and other variables, such as construction costs or school rolls, remain constant. We assume that the school building will continue to be needed in all scenarios.

For a full description of the modelling approach for case study 1, see Appendix B.

[8] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp

4.2. Costs of alternative options

Figure 7 shows the modelled cost for each of the four options considered (Do nothing, raise by 1 metre, raise by 3 metres, or relocate) in the central greenhouse gas scenario (RCP 4.5M) for three years: 2025, 2035, and 2045. Costs presented are total the discounted costs for the next decade. For each of these years, the lowest cost option is outlined in orange.

Under this scenario, the lowest cost option in 2025 is to do nothing and continue to mitigate risk through insurance. At this point, the lowest-cost resilience investment (raise by 1 metre) is expected to be more than twice as costly as compared to doing nothing and insuring the risk. The benefits of raising by 1 metre and 3 metres are equivalent because flood depth is not projected to increase beyond 1 metre during the evaluation period.

However, under this scenario the optimal risk management approach would change over time. A decade later in 2035, the lowest-cost option would be to raise the building by 1 metre, which costs 30% less than doing nothing and insuring the risk. In 2045, the lowest-cost option is still to raise the building by 1 metre, which costs 66% less than doing nothing and insuring the risk.

Figure 7: Cost of options for responding to coastal sea level rise (RCP 4.5m, 2% discount rate)

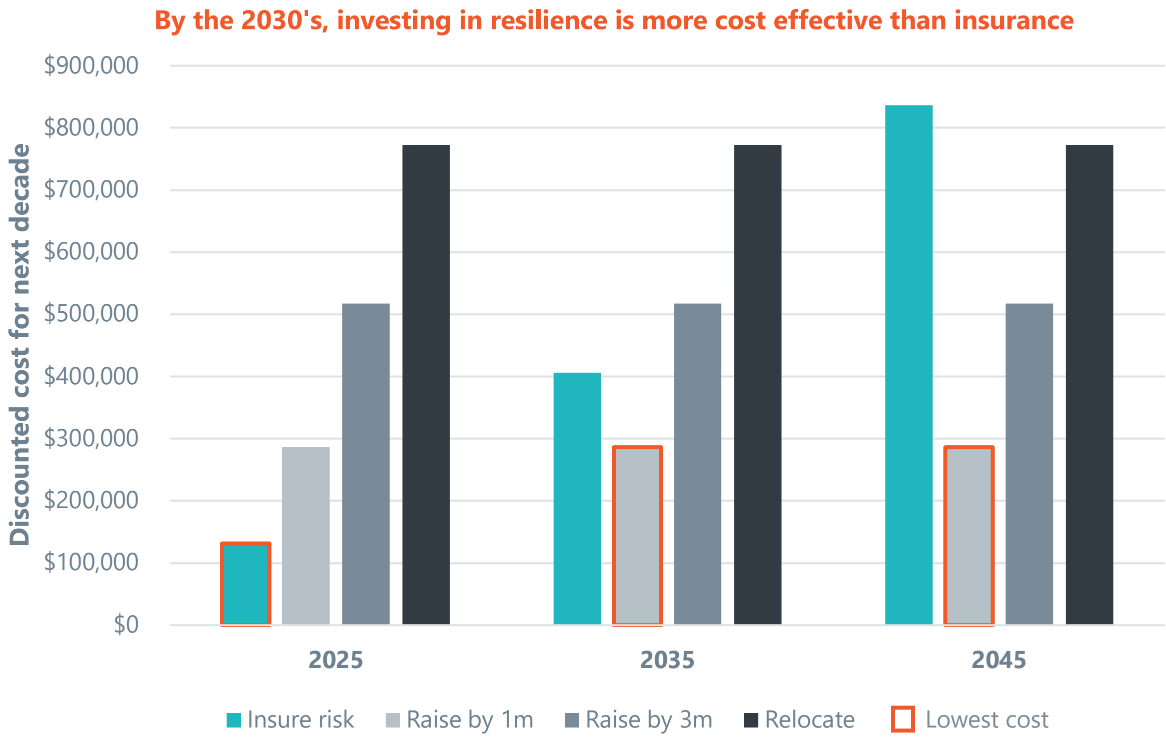


Figure 8 shows the costs of doing nothing or investing in adaptation under three climate scenarios, representing the range of potential outcomes, from stringent mitigation to very high warming scenarios. As in **Figure 7**, we see that the costs associated with coastal flooding are expected to rise over the next few decades due to increased flooding risk. As we go further out into the future, there is greater uncertainty about how large the damages may be.

Interestingly, in this case the year in which it becomes more cost-effective to invest in adaptation, rather than doing nothing, is the same for all three climate scenarios considered. However, these results are unique to the specific conditions outlined in the case study. Different locations with different levels of exposure to risk, and different buildings with different vulnerabilities to damage, would result in different results.

Figure 8: Cost of options for responding to coastal sea level rise under three climate scenarios

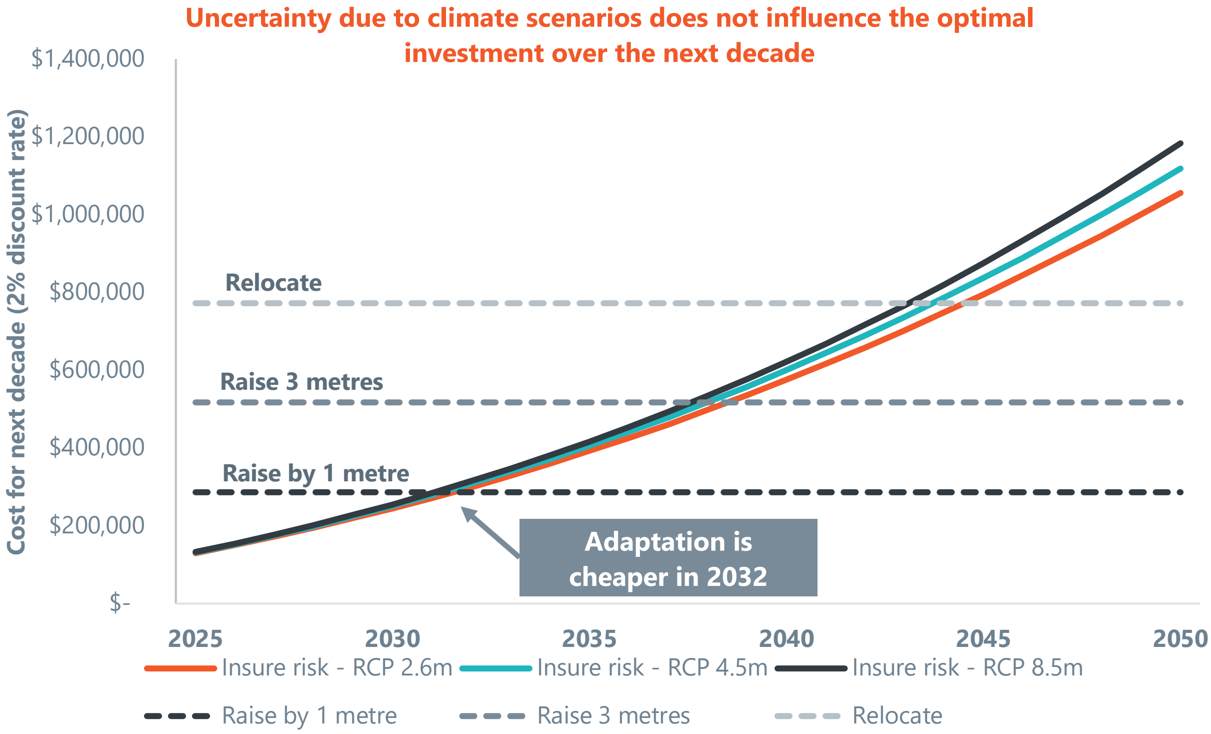
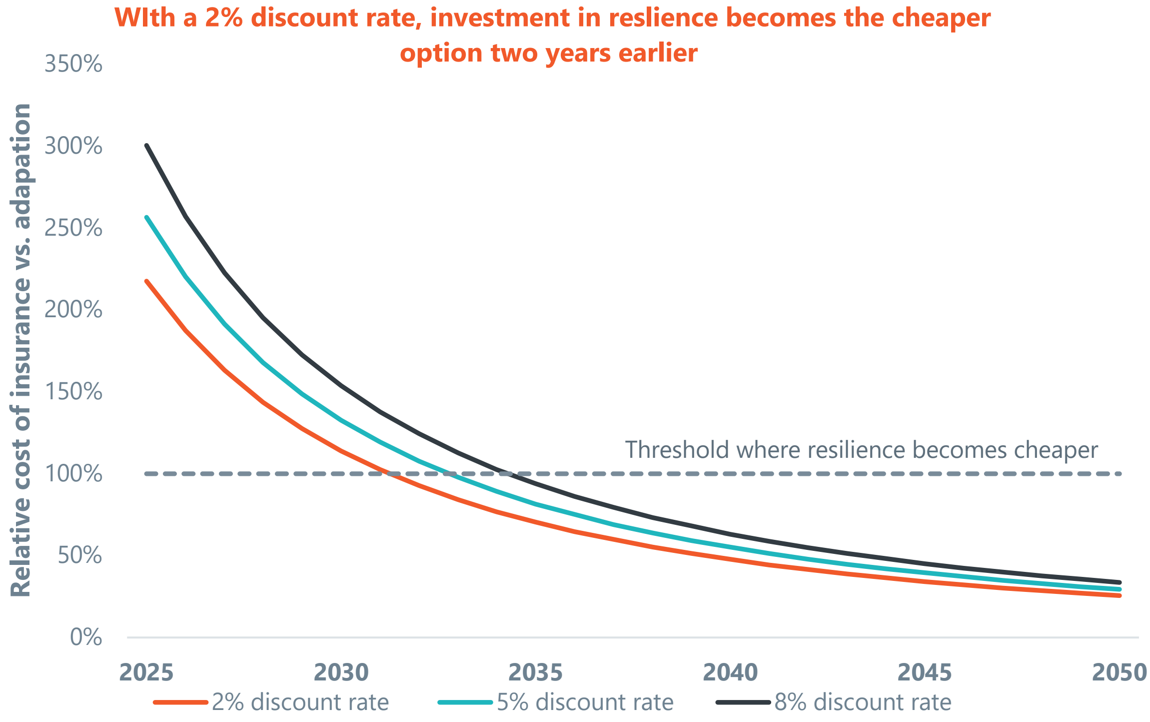


Figure 9 shows the relative cost of the do-nothing option with investing in the lowest-cost adaptation option for each year, for each of the three discount rate scenarios considered. We see that in all scenarios, the relative cost of adaptation goes down as time progresses. However, scenarios with higher discount rates see adaptation become the lowest-cost option later. With a 2% discount rate, adaptation becomes the lowest-cost option in 2032, with a 5% discount rate adaptation becomes the lowest-cost option in 2033, and with an 8% discount rate adaptation becomes the lower cost option in 2035.

This highlights that moral and political judgments about how to weigh up current and future costs, which are reflected in discount rates, and can have a significant impact on when it is considered to be optimal to change risk management strategies for public assets.

Figure 9: Impact of discount rate on optimal timing of investing in adaptation



4.3. Lessons from this case study

This case study highlights that it is possible to weigh up different risk management options, identify the most cost-effective approach given the risks facing an asset at a point in time, and identify when (and under what conditions) it may be desirable to switch to a different risk management approach. In this specific case, there is likely to sufficient information regarding the impact of climate change on coastal flooding for the Board to choose a risk management approach. This would involve mitigating longer-term flood risk to the school block by raising the building by 1 metre, and budgeting for this in the early 2030s, when the cost of the investment would be offset by reduced insurance premiums. This approach outperformed the other two investment options (raising by 3 metres or relocating the building) in all years considered.

This case study highlights a few more general lessons for managing natural hazard risk.

First, optimal management of natural hazards involves taking a multi-year view of infrastructure investment, rather than a single-year view. An understanding of how the relative costs of different options is likely to change over time can enable asset managers to incorporate resilience investments into their wider infrastructure investment programme. This can help resilience investments be integrated into wider asset management and renewal programmes.

Second, an understanding of the current and future cost to insure assets against natural hazards can help infrastructure providers understand the most cost-effective level of resilience investment.

Third, consideration of the impact of uncertainty can help infrastructure providers make informed investment decisions. When investments are less sensitive to uncertainty, it is easier to make decisions about how best to manage risks. But when there is more uncertainty, it may not be prudent to commit to a single approach. Instead, it may be better to take low-cost steps to 'future proof' the ability to invest in the future, like buying sites that could be used for future schools. Analytical methods like real options analysis or dynamic adaptive policy pathways can be used to value these future-proofing investments (New Zealand Infrastructure Commission, 2023a).

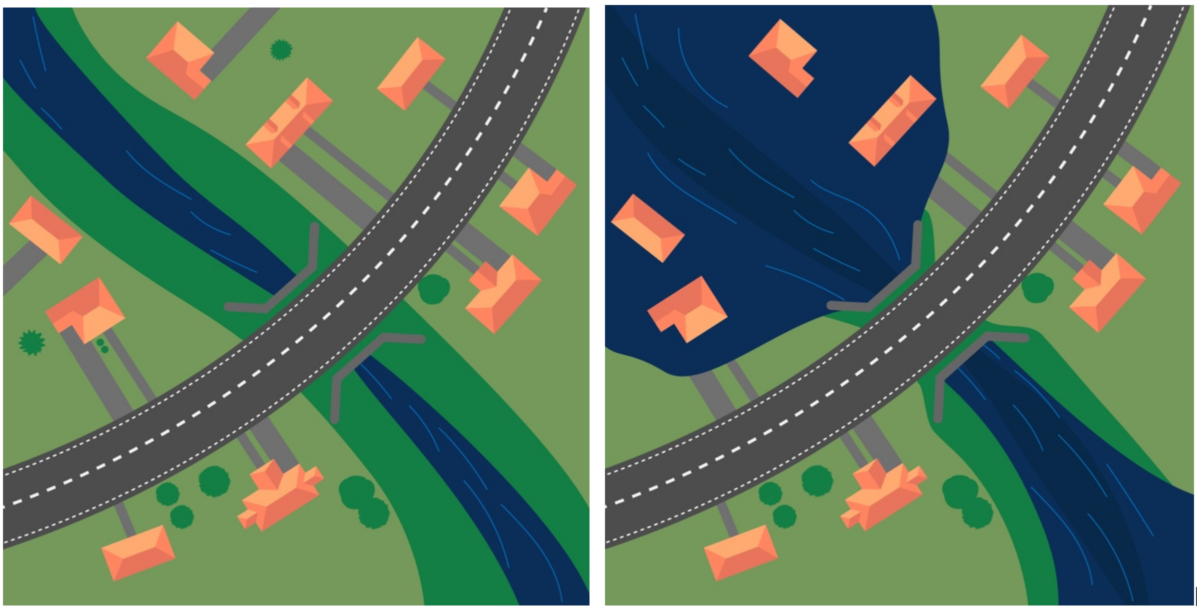
5. Case study 2: Impact of infrastructure resilience on communities

The second case study explores natural hazard risk in the context of managing costs to private property owners. In many cases, infrastructure can either reduce or increase risk to other parties. For example, seawalls can protect nearby property owners from flooding, while the design of roads and bridges can sometimes increase flood risks to nearby property owners. This case study seeks to understand how infrastructure providers can optimise the impact on private property owners that arises from infrastructure investment.

We consider the case of four residential properties that are currently at risk from riverine flooding due to the design of local infrastructure. We assume that these four properties are currently situated within the 1 in 100-year flood zone for riverine flooding, while other nearby properties are not. For these properties, flood risk arises from a nearby culvert that channels a stream under a street in a residential neighbourhood. This culvert has insufficient capacity to withstand a 1 in 100-year flood event. When a flood of this size occurs, the culvert will back up, resulting in a 1-metre-deep flood for the four properties.

This example focusses on the direct impact on the homes, rather than the value of access, and so assume for the sake of simplicity we assume that the flooding is not enough to block or wash away the road. This is shown in **Figure 10**, below.

Figure 10: Case 2 scenario, a culvert under a road in a residential area



In this example, we take the perspective of the local Council and assume that they are investigating options to mitigate flood risk in the local area. The Council can:

1. **Do nothing** – Keep the culvert unchanged and expect the local property owners to pay for the cost of any future damages, through insurance or other means (take no action / manage the fiscal risk).[9]

2. **Build a bridge -** Replace the culvert with a bridge to mitigate the flood risk to surrounding properties (reduce the structural risk).

[9] For the purposes of the case study, we assume that commercial insurance will always be available to property owners.

3. **Retreat** – The owners sell their properties to the Council, based on the most recent rating valuation. The Council removes the buildings and rezones the area from residential to recreational use only (reduce the structural risk).

We seek to address the following questions for the Council:

- What are the relative costs of doing nothing, investing in resilience, or retreating from the area?
- Is either investing in resilience or retreating from the site likely to be cost effective compared to doing nothing, and what year should an investment be made?
- Is there sufficient certainty regarding the future relative costs of options to have confidence in what the most cost-effective option is?

We analyse these choices from the perspective of overall costs and benefits to society. In doing so, we note that in this specific example, almost all of the benefits of increased flood protection are likely to accrue to property owners in the area.[10] In such a case, the best way to pay for any bridge upgrades would be to levy a targeted rate on the properties that are expected to benefit from the investment through lower insurance premiums. This will ensure that homeowners are able to obtain an adequate amount of resilience investment when (or if) it is genuinely valuable for them. We return to this point at the end of this section.

5.1. Modelling approach

For this case study, we assume that the cost of each option is the combined cost of insurance premiums for the specified riverine flooding risk and the construction cost for the resilience option, if applicable. For the retreat option, we assume that the cost is equivalent to the current rateable value of the properties.

As in the first case study, insurance premiums are calculated based on the expected damages from a flooding event that has a 1% probability of occurring in 2025. We assume that due to climate change, in 30 years' time, the same event will have a 2.2% annual probability of occurring.

For the purposes of this case study, we consider the direct financial costs associated with each option but exclude wider or indirect costs, like as the costs of closures to the road or evacuation costs for residents, as these are likely to be comparatively minor. Options which reduce physical as well as financial risk would reduce the disruption costs associated with physical damage, whereas options that only reduce financial risk would not. In some cases, including these costs may increase the value of resilience investments.

The relative costs of the four options are calculated for each year from 2025 to 2050. For any given year, the projected costs are the discounted total costs for the next 30-year period. Relative costs are presented in this way as Councils are required by the Local Government Act (2002) to make decisions based on a 30-year planning period. This would also be in alignment with a typical 30-year mortgage for residential properties.

Importantly, the cost of resilience investments, like building a new bridge, may change relative to the benefits of protecting residential property. Both infrastructure construction prices and housing prices have risen faster than prices elsewhere in the economy, but the relative pace of increase can vary over time. As relative prices change, our choices about what to invest in may also need to change.

[10] To calculate transport disruption costs, we assume that there is an average daily traffic volume of 5,000 vehicles and that if the bridge is closed, the detour route adds an additional 20 minutes of travel time for all vehicles for 48 hours. Given the cumulative probability of flooding over the 30-year analysis period, the total travel time cost associated with disruption is around $60,000, which is very small compared with the cost of flooding risk to nearby properties.

Infrastructure construction prices have risen due to rising (and volatile) input costs and comparatively slow productivity growth (New Zealand Infrastructure Commission, 2022a, 2023b). Housing prices have also risen at a rapid pace, due to the impact of tighter housing supply constraints that push up the cost to build new housing and increase its scarcity (New Zealand Infrastructure Commission, 2022b). As the value of houses increases, the cost to insure them also rises.

Looking back, there have been some periods, like the last 20 years, where residential property prices have risen much more rapidly than civil construction prices. There have also been periods, for instance the 1970s to early 1990s, when residential property prices and civil construction prices were more in line with each other. We may prefer to make different risk management decisions depending upon what we expect to happen in the future.

In this case study, we test the impact of relative price changes in civil construction, and house price indices on the relative cost of different options in different years. We consider three scenarios that reflect different expectations about what might happen to prices in the future:

A. **Central case**: Residential property inflation (driving insurance costs) and civil construction inflation (driving the cost of resilience investment) are both at average levels for the last 35 years.[11]

B. **Relatively low civil construction inflation**: Civil construction inflation is relatively low and residential property inflation is relatively high.[12]

C. **Relatively high civil construction inflation**: Civil construction inflation is relatively high and residential property inflation is relatively low.

These three price change scenarios should not be considered forecasts, but are instead a ‘what if’ analysis to understand how different expectations about future price changes might affect our views about the optimal risk management approach for the case study. For a full description of the modelling approach for this case study, see Appendix C.

5.2. Costs of alternative options

The central scenario (average price increases)

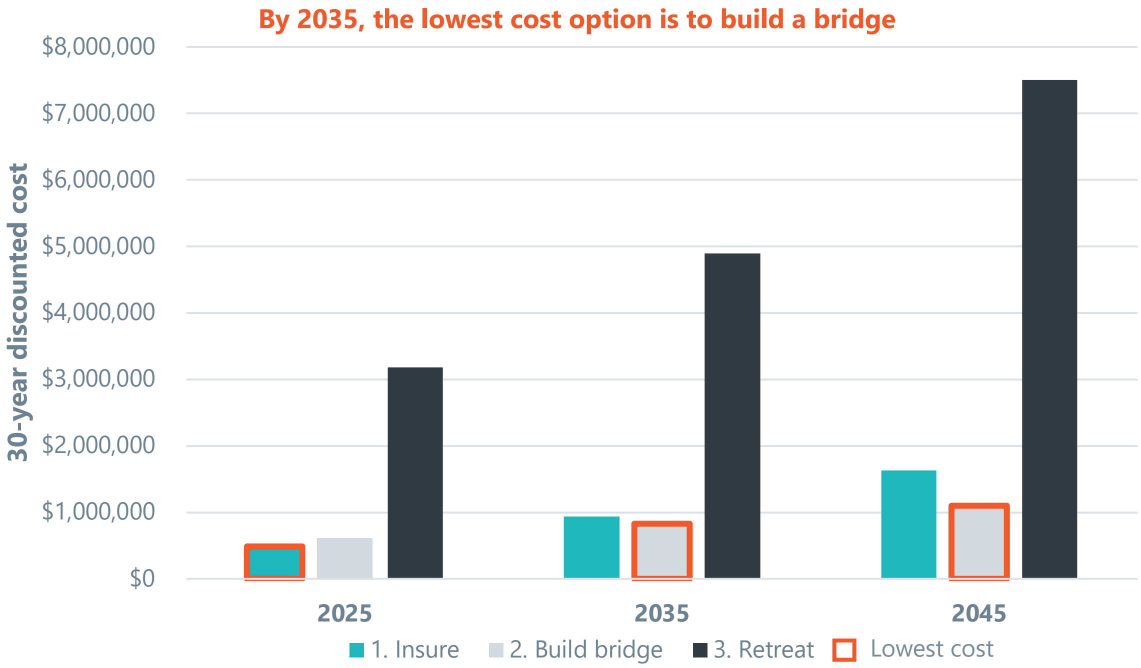
We first consider a case in which we expect residential property inflation and civil construction inflation to continue at the average rates observed over the previous three-and-a-half decades.

Figure 11 shows the modelled cost for the three options considered (do nothing, build a bridge, or retreat) in the central scenario for three years: 2025, 2035, and 2045. Costs presented are total the discounted costs for the next three decades. For each year, the lowest cost option is outlined in orange.

In this scenario, we see that in 2025, the lowest-cost option is to do nothing and continue to mitigate risk through insurance. In 2025, the insuring the risk is expected to be about 20% cheaper than investing in resilience. By 2035, the lowest-cost option would be to build a bridge, which costs slightly less than doing nothing. By 2045, the lowest-cost option would still be to build the bridge, which costs 33% less than doing nothing.

[11] ‘Average levels’ are defined as historic average annual price changes from Q1 1990 to Q1 2024. For residential property this is 4.4%. For civil construction costs, this is 3.0%. For more on this, see Appendix C.
[12] ‘Relatively low’ is defined as one half standard deviation below average (2.7% for residential building inflation and 1.6% for civil construction cost inflation., and ‘relatively high’ is defined as one half standard deviation above average (6.1%/4.4%, respectively).

Figure 11: Cost of options for responding to flood risk under a central scenario (medium residential property inflation / medium civil construction inflation)



The impact of different expectations about future costs

Figure 12, **Figure 13**, and **Figure 14** show the cost of doing nothing (i.e., insurance) or investing in the bridge in the three price change scenarios: A: the central case, B: relatively high civil construction inflation, and C: relatively low civil construction inflation. To simplify the figures, we do not include costs of retreat, as these are much larger than the other two options, as we saw in **Figure 11**, above.

The first case we consider (**Figure 12**) shows the central case where house prices and construction costs are both expected to increase at their average rates for the last three-and-a-half decades. As we saw in **Figure 11**, the costs associated with flooding are expected to rise over the next few decades due to rising property values that drive increases in insurance premiums, while the costs of building the bridge increase due to increased civil construction costs. The costs of doing nothing are expected to exceed those of building the bridge in 2032. From this point onwards the cost savings of building the bridge over insurance continue to increase.

In the case where high residential property inflation and low civil construction inflation is expected (**Figure 13**), building a bridge is already expected to be the cheaper option in 2025. The cost advantage of insurance over building diverges rapidly over time, as house prices are expected to increase faster than construction costs.

If the opposite is true, and property inflation is expected to be relatively low while bridge construction cost inflation is expected to be relatively high, the cost of building a bridge may *never* become cheaper than continuing to pay insurance premiums (as shown in **Figure 14**).

The relative cost of insuring against the risk compared to building the bridge varies dramatically across the three options. **Figure 15** shows the relative costs of resilience vs. insurance for all three scenarios.

Figure 12: Scenario A: Medium residential property inflation, medium civil construction inflation

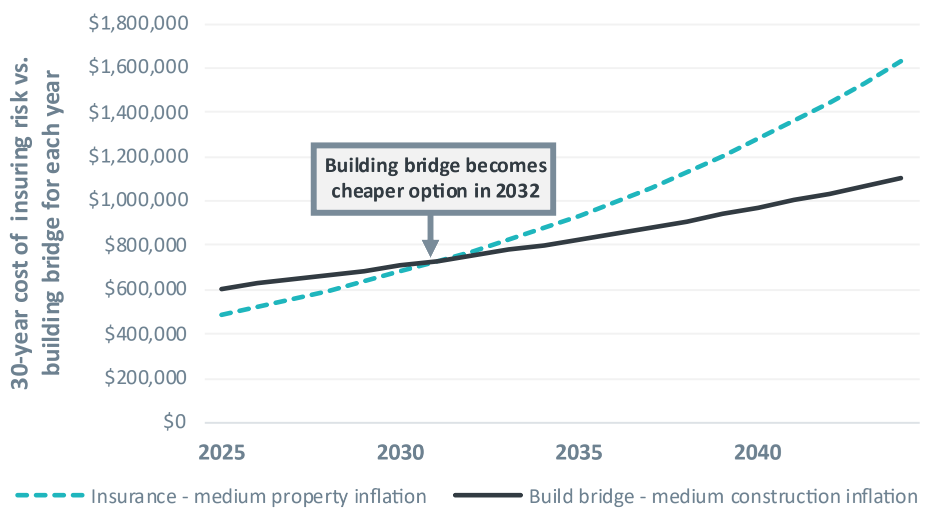


Figure 13: Scenario B: High residential property inflation, Low civil construction inflation

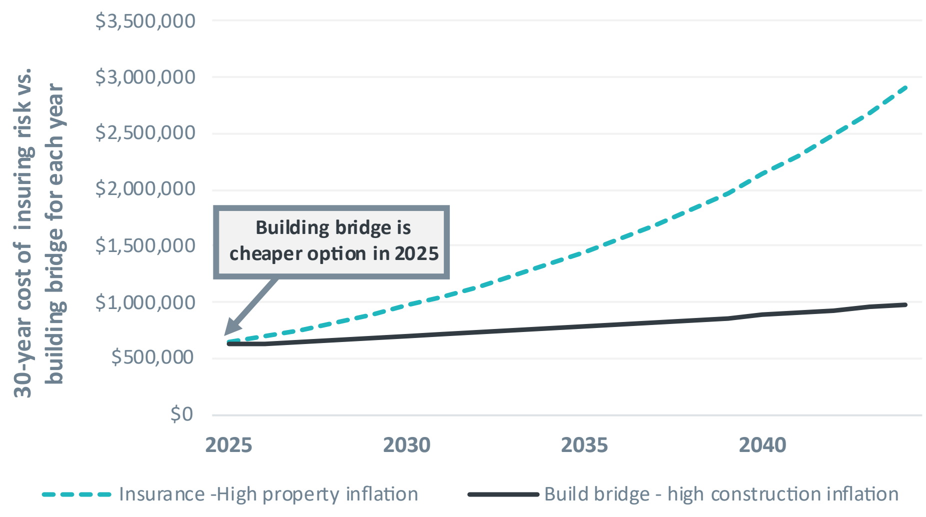


Figure 14: Scenario C: Low residential property inflation, High civil construction inflation

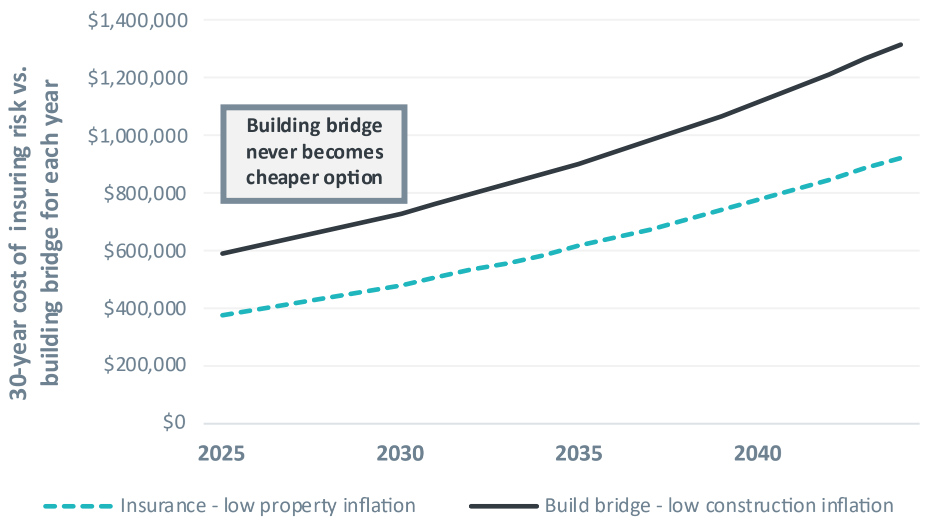
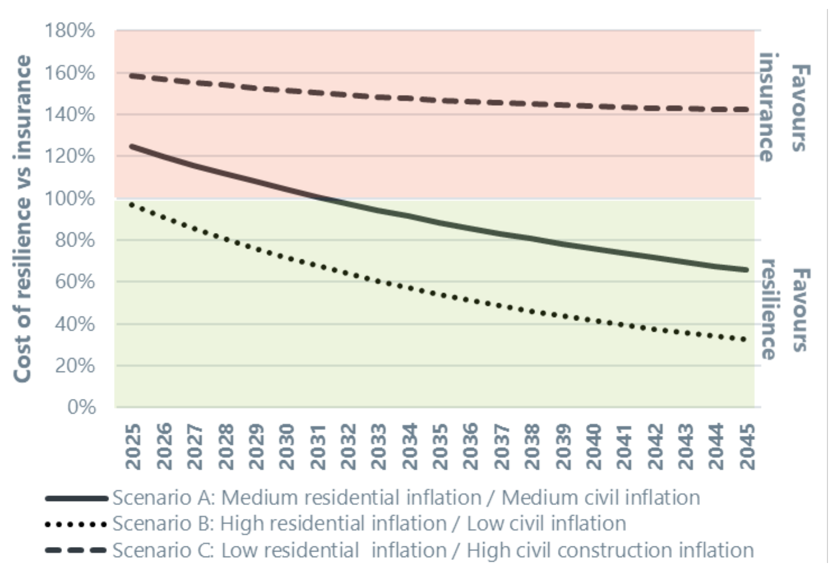


Figure 15: Cost of resilience vs. insurance in three cost scenarios



5.3. Lessons from this case study

This case study highlights that it can be important to consider other sources of uncertainty, such as how prices for different risk management options may change in the future. We find that expectations about future changes in residential property prices (which flow through into insurance premiums) and civil construction costs can have a significant impact on which risk management approach is preferred, and when different approaches are preferred.

In this specific case, results are very sensitive to assumptions about future cost changes. If decision-makers perceive significant uncertainty about future prices, then it may be preferable to wait for more information on how prices are trending before choosing. Decisions about whether and how to proceed can be reviewed periodically, for instance with periodic updates of council long-term plans.

This case study highlights a few more general lessons for managing natural hazard risk.

First, the case study shows that economic uncertainty related to expected future price changes can play an important role in determining the optimal level of resilience investment. In the context of adaptation and resilience investments, the uncertainty related to the frequency and severity of natural hazards is typically the source of uncertainty that receives attention. However, other sources of uncertainty, including future cost changes, should also be considered. This is especially important when considering risk management options that affect different types of assets, in this case bridges and residential houses, that have historically exhibited different price trends.

Second, while we do not explicitly address this in the case study, the distribution of costs, benefits, and decision-making power between different parties plays an important role in optimising natural hazard risk management decisions. Ideally, costs should be allocated between parties according to the distribution of benefits derived from the investment. When decision-making power and incentives are poorly aligned, this could lead to a sub-optimal level of investment in resilience.

In this specific case study, most benefits of resilience investment are expected to accrue to nearby property owners, rather than to the public as whole. It would therefore be appropriate to pay for the investment through a targeted rate rather than through general rates. In addition to helping to align costs and benefits of investment, this approach would also improve incentives for optimal risk management decisions. As Goodspeed and Haughwout (2012) observe, when costs are borne by third parties rather than those exposed to hazards, the parties exposed to hazards may be incentivised to under-invest in hazard reduction.

6. Summary and conclusion

6.1. Management of hazard risk starts with good data

We need to think about the natural hazard risk to infrastructure at two levels: at the infrastructure provider level and at a national level. At the local level, infrastructure providers need to be able to assess the costs of their natural hazard risk and the costs and benefits associated with actions to respond to that risk. At the national level, the government needs information on the total magnitude of risk to infrastructure so that it understands its fiscal risks and contingent liabilities, and how best to manage them.

At both the infrastructure provider and national level, better data can enable better decision-making. However, New Zealand has an incomplete picture of the hazards it faces, the risks that are created by these hazards, and how these risks are being managed. In our review of current settings, we found that there is no systematic approach in place to assessing and managing risk or tracking of the costs of natural hazards to infrastructure. We also lack clear guidance for infrastructure providers on how to manage their risk, or an understanding of how much of our risk is insured or uninsured.

6.2. The optimal approach to managing risk varies

There are many alternative approaches to managing hazard related risks to infrastructure. Some options include fiscal risk management with insurance and structural risk reduction through actions such as strengthening resilience or managed retreat from at risk areas.

In our two case studies, we presented three broad options to managing natural hazard risk: insuring the risk, investing in resilience, or retreating from at-risk areas. We found that the there is no single best approach to managing natural hazard risk to infrastructure. Instead, the optimal approach will vary depending on many factors, including likelihood, consequence, and the relative cost of different options in different situations. For example, two buildings could have the same function and exposure to risk, but the optimal response might be different if they are made of different materials with different vulnerability to damage.

This means that infrastructure providers need to have a good understanding of their assets and the risks to which they are exposed. They will also need the capability to assess their options and optimise their response to risks from natural hazards.

6.3. Pricing risk can help guide resilience investment

From the perspective of an infrastructure asset owner facing risk from natural hazards, it may be difficult to ascertain the optimal risk management strategy. In a world where there are a multitude of risks, which risks are 'worth' investing in resilience for, and which are not?

Quantifying risk and/or pricing it through insurance premiums can help clarify the optimal risk management approach for a given piece of infrastructure. For agencies who choose to purchase insurance, quantification of risk can be part of the process of seeking insurance. For agencies who choose to self-insure rather than seeking insurance, quantification of risk can help to clarify the degree of self-insurance that may be required.

Optimal resilience investments should reduce risk management costs, as compared to continuing to pay risk related insurance premiums. In cases where resilience investments are more costly than insuring risk, they may not be warranted.

6.4. Demand for resilience is cost dependent

The costs from natural hazards and the costs to mitigate risk are both uncertain. If the cost of buying resilience rises relative to the value of what is being protected, the case for resilience investment will decline. If the value of what is being protected rises relative to the cost of buying resilience, the case for resilience investment will rise. Because of uncertainty surrounding future price changes, the optimal amount of resilience investment is not set in stone.

Instead, the optimal level of resilience will depend on the relative cost of resilience investments compared to the cost of (and the benefits we get from) the assets being protected. We can increase the case for resilience investment by focusing on keeping infrastructure costs down. Conversely, increasing infrastructure costs relative to other costs will erode the case for resilience investments.

It may not be possible to predict future price changes with a high level of accuracy. However, it is possible to forecast the bounds of uncertainty surrounding future price changes. Assessment of the value for money of resilience investments under a range of different scenarios can help to provide confidence that they are robust to uncertainty and likely to provide value for money under a range of possible futures.

6.5. Good asset management can optimise the timing of resilience investment

Sound asset management planning involves understanding one's assets and taking a long-term view of maintenance, renewal, and improvement needs. Our underlying risks are changing, and this means the optimal risk management strategy will change as well. Good asset management planning can help us understand the optimal timing of resilience and adaptation investments to make the most of our infrastructure investments.

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Appendix A: Cross-country comparisons of natural hazard damage costs

This appendix explains how we derived some broad cross-country comparisons of natural hazard damage costs.

A large share of the costs of natural hazards relate to low-probability, high-impact events, like major earthquakes or tsunamis. Because these events are infrequent, data on costs incurred in a single year (or a short time frame) can provide a misleading estimate of relative risk. Ideally, natural hazard risk models would be used to benchmark and compare between countries. In practice, however, different countries model risks in different ways, making these types of comparisons difficult.

As a result, we construct a broad cross-country comparative measure of natural hazard costs using an approach applied by Lloyd's insurance to compare risk and under-insurance across countries (Centre for Economics and Business Research, 2012)

6.6. Overview of methodology

Lloyd's approach uses data on the reported economic costs of major events over a multi-decade period, from the EM-DAT database (Centre for Research on the Epidemiology of Disasters, 2023). The advantage of this approach is that it takes a longer-term perspective on risk, although some types of hazards may not occur, even over a multi-decade period. EM-DAT includes data on events that occurred from 1900 to 2022, although coverage of events is better in recent decades.

EM-DAT includes information on damages and economic losses that are directly or indirectly related to a given natural disaster. Reported damages are broader than damage to infrastructure assets and include damage to homes and businesses. In some cases, damage to infrastructure assets may not be fully reported, for instance if countries do not consistently measure and report all of these costs. A further consideration is that damage costs are missing for some events in the database – we discuss this further below.

The key steps in this approach are:

- First, for each event with reported damage costs, we calculate damage costs as a share of national GDP, using current-price GDP data from the World Bank.
- Second, within each country, we identify the ten costliest events, ranked by share of GDP. Note that some countries have fewer than ten events with reported damage costs.
- Third, within each country, we identify the earliest and latest year of these events and use this to estimate the probability (p_i) of a costly event occurring in that country in a given year.
- Fourth, within each country, we calculate the average cost of a costly event as a share of GDP (c_i), when it occurs.
- Fifth, we multiply the probability of a costly event by the average cost of that event to estimate the expected annual losses from natural hazard events ($e_i = p_i * c_i$).

This is intended to be a broad cross-country comparison, rather than a comprehensive analysis of natural hazard costs or a forecast of future costs. To test robustness, we chose different thresholds for event size (top 5 events or top 15 events, all events with a cost over 0.1% or 0.01% of GDP, or all events with reported economic losses), and restricted the natural hazard event data to a shorter time window (1990-2022, rather than the full period included in EM-DAT).

6.7. Overview of the EM-DAT database

While the EM-DAT database includes events from 1900 onwards, we restricted our analysis to the 1960-2022 period, as World Bank GDP data is only available for 1960 onwards. We also restricted our analysis to the 38 current OECD members, and to natural hazard events (as opposed to 'technological' hazards like industrial accidents or transport crashes).

After these restrictions, we are left with 4189 event records in all 38 OECD countries. However, the EM-DAT database only includes information on economic losses for 1963 of these events – slightly less than half of the total. **Table 2** shows that coverage is similar for climatological, geophysical, hydrological, and meteorological events, but much lower for biological events (like epidemics and infestations). Moreover, the quality of data on economic losses is likely to vary over time and between countries.

It is likely that large events are more likely to have recorded economic losses than small events. For instance, events that affected more people or killed more people are more likely to have recorded economic losses.

Lastly, recording of economic losses appears to vary between countries, even after controlling for type of events. Non-OECD countries tend to have much lower reporting of economic losses, but there are also some meaningful variations within OECD countries. For example, 52% of natural hazard events in New Zealand had recorded economic losses, compared with 68% in Australia and 31% in Greece.

Table 2: Share of EM-DAT recorded natural hazard events with recorded economic losses in OECD countries, 1960-2022

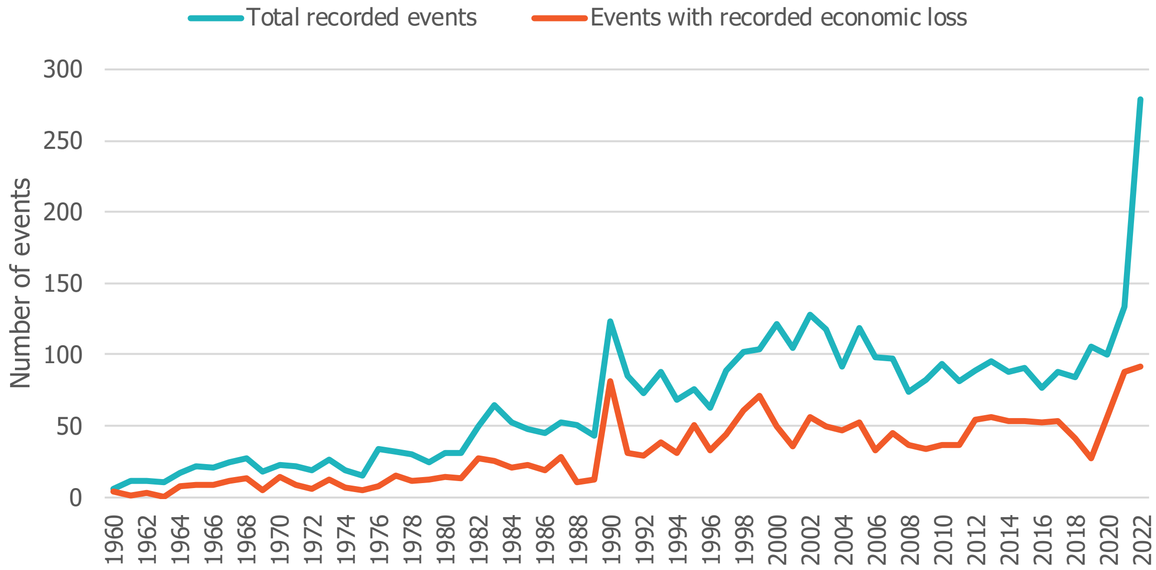
Disaster Subgroup	Total recorded events	Events with recorded economic losses	Share with recorded economic losses
Biological	66	2	3%
Climatological	375	191	51%
Geophysical	411	207	50%
Hydrological	1314	548	42%
Meteorological	2023	1015	50%
Total	4189	1963	47%

Source: Te Waihanga analysis of EM-DAT data

Figure 16 shows that the number of recorded events in OECD countries, and the number of events with recorded damages, has gradually risen over time, with a sharp increase around 1990. This is likely to reflect better data collection in recent years, although the frequency of events may be shifting as well.

The share of recorded events with reported economic losses has risen slightly over time. Between 1960 and 1989, 40% of events had recorded economic losses. From 1990 to 2022, 49% of events had recorded economic losses.

Figure 16: Total recorded natural hazard events and events with recorded economic losses in OECD countries, 1960-2022



Source: Te Waihanga analysis of EM-DAT data

6.8. Summary of results

Table 3 summarises our key results for 34 OECD countries where we had sufficient data to calculate annual expected losses. The five countries with the highest annual expected losses are highlighted. New Zealand is the second-ranked country on this metric, after Chile.

New Zealand experienced its ten largest natural hazard events between 1987 and 2022. Over this period, the annual probability of a large event occurring was roughly 28% (10 large events in 36 years), and the mean cost of an event, when it occurred, was over 2% of GDP. This leads to an expected annual cost of 0.6% of GDP.

Variations between countries reflect different estimated annual probabilities or different mean costs of large events. For example, France experienced its ten largest natural hazard events between 1983 and 2021. Large events had an annual probability of 26% (10 large events in 39 years), but a much lower mean cost of 0.2% of GDP. This leads to an expected annual cost that is less than one-tenth as high as New Zealand.

Table 3: Cross-country comparisons of annual expected losses from natural hazard events, 1960-2022

Country	Year of earliest event	Year of latest event	Probability of large event occurring (pi)	Mean cost of a large event (ci, % GDP)	Annual expected loss (ei, % GDP)
Australia	1967	2022	18%	0.98%	0.18%
Austria	1990	2013	42%	0.22%	0.09%
Belgium	1983	2021	26%	0.10%	0.03%
Canada	1977	2021	22%	0.40%	0.09%
Chile	1960	2015	18%	4.30%	0.77%
Colombia	1970	2011	24%	0.94%	0.22%
Costa Rica	1968	2009	24%	1.20%	0.29%
Czechia	1997	2021	40%	0.71%	0.28%
Denmark	1981	2007	30%	0.38%	0.11%
France	1983	2021	26%	0.21%	0.05%
Germany	1990	2022	30%	0.26%	0.08%
Greece	1978	2007	33%	0.98%	0.33%
Hungary	1992	2010	53%	0.23%	0.12%
Iceland	1973	2022	14%	0.43%	0.06%
Ireland	1990	2011	45%	0.06%	0.03%
Israel	1995	2020	27%	0.08%	0.02%
Italy	1966	2022	18%	1.22%	0.21%
Japan	1960	2022	16%	0.92%	0.15%
Korea, Rep.	1965	2003	26%	0.47%	0.12%
Luxembourg	1990	2010	43%	0.34%	0.15%
Mexico	1967	2022	18%	0.63%	0.11%
Netherlands	1990	2022	30%	0.12%	0.04%
New Zealand	1987	2022	28%	2.06%	0.57%
Norway	1990	2020	19%	0.06%	0.01%
Poland	1990	2017	36%	0.34%	0.12%
Portugal	1979	2017	26%	0.47%	0.12%
Slovak Republic	1997	2010	57%	0.22%	0.13%
Slovenia	2003	2012	60%	0.28%	0.17%
Spain	1962	1999	26%	0.73%	0.19%
Sweden	1977	2021	20%	0.11%	0.02%
Switzerland	1987	2009	43%	0.20%	0.09%
Türkiye	1966	2022	18%	1.37%	0.24%
United Kingdom	1987	2013	37%	0.15%	0.06%
United States	1965	2022	17%	0.39%	0.07%

Note: Te Waihanga calculations based on EM-DAT data and World Bank GDP data. Estonia, Finland, Latvia, and Lithuania are excluded from this table as the number of natural hazard events with recorded damages was too small to enable calculations. In addition, some of the countries in the table above have fewer than ten natural hazard events with recorded damages. We have adjusted for this when estimating the annual probability of an event.

6.9. Robustness tests

Table 4 reports a set of robustness tests based on different thresholds for event size (top 5 events or top 15 events, all events with a cost over 0.1% or 0.01% of GDP, or all events with reported economic losses) and restricting the natural hazard event data to a shorter time window (1990-2022, rather than the full period included in EM-DAT). The five countries with the highest annual expected losses in each test scenario are highlighted. New Zealand is ranked in the top three countries under all robustness tests. Moreover, overall country rankings are reasonably stable under all robustness tests. Correlation coefficients between the baseline ranking and rankings under the six robustness tests range from 0.85 to 0.98.

Table 4: Robustness tests on annual expected loss calculations

Country	Baseline: Top 10 events over 1960-2022 period	Top 5 events over 1960-2022 period	Top 15 events over 1960-2022 period	Top 10 events over 1990-2022 period	All events with cost over 0.1% of GDP	All events with cost over 0.01% of GDP	All events with reported damage
Australia	0.18%	0.18%	0.20%	0.10%	0.23%	0.28%	0.28%
Austria	0.09%	0.15%	0.09%	0.09%	0.17%	0.09%	0.09%
Belgium	0.03%	0.03%	0.03%	0.03%	0.02%	0.03%	0.03%
Canada	0.09%	0.08%	0.10%	0.05%	0.10%	0.11%	0.10%
Chile	0.77%	0.78%	0.71%	0.54%	0.74%	0.75%	0.75%
Colombia	0.22%	0.20%	0.19%	0.13%	0.22%	0.18%	0.17%
Costa Rica	0.29%	0.33%	0.27%	0.28%	0.27%	0.28%	0.28%
Czechia	0.28%	0.27%	0.28%	0.28%	0.27%	0.28%	0.28%
Denmark	0.11%	0.12%	0.11%	0.15%	0.11%	0.11%	0.11%
France	0.05%	0.04%	0.06%	0.06%	0.05%	0.05%	0.06%
Germany	0.08%	0.10%	0.09%	0.08%	0.11%	0.10%	0.10%
Greece	0.33%	0.34%	0.20%	0.21%	0.20%	0.20%	0.20%
Hungary	0.12%	0.11%	0.12%	0.12%	0.11%	0.12%	0.12%
Iceland	0.06%	0.06%	0.06%	0.03%	0.06%	0.06%	0.06%
Ireland	0.03%	0.02%	0.03%	0.03%	0.02%	0.03%	0.03%
Israel	0.02%	0.02%	0.02%	0.02%	0.04%	0.02%	0.02%
Italy	0.21%	0.22%	0.23%	0.12%	0.24%	0.26%	0.26%
Japan	0.15%	0.14%	0.16%	0.26%	0.18%	0.21%	0.21%
Korea, Rep.	0.12%	0.09%	0.09%	0.07%	0.12%	0.11%	0.11%
Luxembourg	0.15%	0.72%	0.15%	0.15%	2.82%	0.15%	0.15%
Mexico	0.11%	0.08%	0.13%	0.14%	0.15%	0.17%	0.17%
Netherlands	0.04%	0.03%	0.04%	0.04%	0.03%	0.04%	0.04%
New Zealand	0.57%	1.41%	0.54%	0.70%	0.58%	0.40%	0.40%
Norway	0.01%	0.01%	0.01%	0.01%	0.05%	0.01%	0.01%
Poland	0.12%	0.12%	0.12%	0.12%	0.23%	0.12%	0.12%
Portugal	0.12%	0.13%	0.10%	0.17%	0.12%	0.10%	0.10%
Slovak Republic	0.13%	0.22%	0.13%	0.13%	0.22%	0.13%	0.13%
Slovenia	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%	0.17%
Spain	0.19%	0.46%	0.13%	0.07%	0.14%	0.15%	0.15%
Sweden	0.02%	0.02%	0.02%	0.03%	0.03%	0.02%	0.02%
Switzerland	0.09%	0.09%	0.08%	0.12%	0.11%	0.08%	0.07%
Türkiye	0.24%	0.41%	0.25%	0.41%	0.24%	0.25%	0.25%
United Kingdom	0.06%	0.05%	0.06%	0.06%	0.05%	0.05%	0.04%
United States	0.07%	0.09%	0.08%	0.13%	0.09%	0.17%	0.19%

Note: Te Waihanga calculations based on EM-DAT data and World Bank GDP data.

Appendix B: Modelling approach for Case Study 1

Scenario and options considered

For case study 1, we consider the case of vertical infrastructure (a school building) that is at risk from coastal flooding due to its location and design. We seek to estimate the lowest cost option to respond to coastal flooding from event *Y* for a building sitting a coastal flood zone. Event *Y* is defined as a flooding even with a 1 in 100-year annual exceedance probability (1% AEP) in 2025. This threshold was chosen as a flooding event with a 1% AEP is the threshold for flooding that amounts to inundation in the New Zealand Building Code and is the likelihood that is typically used for flooding risk assessment in New Zealand.[13]

We consider the costs for the school associated with four alternative options:

1. **Insure** - Keep the school building unchanged and continue to pay the insurance premiums associated with its coastal flood risk.
2. **Raise by 1 metre** - Raise the building level by 1 metre, mitigating all potential flood damage for flooding events with a depth of up to 1 metre.
3. **Raise by 3 metres** - Raise the building level by 3 metres, mitigating all potential flood damage for flooding events with a depth of up to 3 metres.
4. **Relocate** - Relocate the building to elsewhere on the school grounds, which would be outside the flood zone.

Step 1: Calculate annual insurance costs

To compare the costs associated with each of the four potential options outlined above, we calculate the annual expected hazard specific insurance cost (*CI*) for event *Y* associated with each option *j*. Costs are calculated for each individual year *t* in the analysis period, which starts in 2025 and ends in 2075, as follows:

$$CI_{jt} = LF \times AEP_{jt} \times d_{jt}$$

Where:

- *LF* is the assumed loading factor, a parameter for the administrative costs and profit margin for the insurer,
- *AEP* is the expected annual exceedance probability of coastal flooding inundation, and
- *d* the expected damage given the assumed hazard event *Y*.

The parameter *AEP* varies by year based on projected change in coastal flooding frequency due to climate change.

Parameter *d* is a function derived based on expected damage event *Y* in year *t* as follows:

[13] For example, risk assessments used for the preparation of district and regional planning documents typically use a 1% AEP, such as Bay of Plenty Regional Council's regional policy statement (2014).

$$d_{jt} = (FD + SLR_t) \times dr_{jt} \times v$$

Where:

- *FD* is the flood depth in year 0,
- SLR_t is the projected sea level rise in year *t*
- *dr* is the damage ratio for the building for the anticipated flood depth in year *t, and*
- *v* is the building's estimated value, which is kept constant.

The damage ratio (*dr*) is calculated using the flood fragility curve for a single-storey timber building subjected to a given flooding inundation depth, from Reese and Ramsay (2010). Flooding inundation depths are derived by adding together the flood depth in year 1 for event *Y* and the projected mean sea level rise in year *t*. Mean sea level rise for each year is considered under three different climate change scenarios: RCP 2.6m, RCP 4.5m, and RCP 8.5m.

Step 2: Calculate net present value of options

We then calculate the net present value of projected costs for the next 10 years for any given year (NPV_{jt}), as follows:

$$NPV_{jt} = \sum_{t=1}^{10} \frac{(CI_{jt})}{(1+r)^t} + U_j$$

Where:

- *r* is the discount rate, and
- *U* is the cost of the resilience upgrade in option j (no cost for doing nothing, the cost to raise by 1 metre, raise by 3 metres, or relocate the building).

This process is then repeated for all years in the evaluation period. For each individual year, we compare the relative costs of each of the four options: do nothing, raise by 1 metre, raise by 3 metres, or relocate the building.

Step 3: Consider impacts of uncertainty

We consider two sources of uncertainty in case study 1: future greenhouse gas concentrations and the optimal discount rate for decision-making. For each of these sources of uncertainty, a low, medium, and high parameter value was identified, which are outlined in **Table 5**.

The three greenhouse gas concentration scenarios considered are a stringent mitigation scenario (RCP 2.6M), an intermediate scenario (RCP 4.5m), and a very high warming scenario (RCP 8.5m) (Ministry for the Environment, 2024b). These three concentration scenarios are used as they represent a wide range of potential future sea level rise outcomes.

The three discount rates considered are 2%, 5%, and 8%. These three discount rates are used as they represent the 2024 public sector discount rate for non-commercial proposals (2%), the 2023 public sector discount rate for non-commercial proposals (5%), and the 2024 mandatory sensitivity test for non-commercial proposals (8%) (The Treasury, 2024).

We do not consider other sources of future cost changes, and other variables, such as construction costs or school rolls, remain constant.

Table 5: Key parameter assumptions for Case Study 1

Parameter	Parameter value	Rationale	Source
Scenario assumptions			
Discount rate (*d*)	Base case 2% Sensitivity test 1 – 5% Sensitivity test 2 – 8%	Public sector discount rates required by the New Zealand Treasury, previous public sector discount rate required by Treasury	(The Treasury, 2024)
Analysis period	10 years	10 years is the planning period for school property plans.	(Ministry of Education, 2016)
Flood depth in year 1	0.1m	Assumed flood level at baseline.	N/A
Insurance cost assumptions			
Projected mean sea level rise (SLR) by 2100	Low – 0.5m Medium – 0.6m High – 0.9m	Recommended sea level rise projections for New Zealand	(Ministry for the Environment, 2024a)
Loading Factor (*LF*)	130%	As the actual value used by insurers is unknown due to commercial sensitivity, a sensible assumption must be made.	(Hudson, 2018)
Building fragility curve (used with FD to calculate ***dr)***	$-0.0522x^2 + 0.3839x + 0.1149$, where x = flood depth in m	Value for timber one storey constructed pre-1970	(Reese & Ramsay, 2010)
Change in AEP from sea level rise	$0.02297x^2 - 0.005935x + 1.1746$, where x = SLR in cm	Estimated minimum impact of SLR on AEP for Christchurch port. Christchurch port was used as a hypothetical example as it was a central example, of the four cities included in the referenced study.	(Storey et al., 2023)
Resilience cost assumptions			
Cost to Raise by 1 metre	$237,000	Central cost estimate. Provided by quantity surveying firm.	(Morden, 2024)
Cost to raise by 3 metres	$468,000	Central cost estimate, including addition of lift. Provided by quantity surveying firm.	(Morden, 2024)
Cost to relocate building	$723,000	Central cost estimate, including land acquisition cost. Provided by quantity surveying firm.	(Morden, 2024)

Appendix C: Modelling Approach for Case Study 2

Scenario and options considered

For case study 2, we consider the case of four private residential properties that are at risk from riverine flooding. We assume that the four properties are located near a culvert that channels water under a residential road. During certain flooding events, the culvert's capacity will be exceeded, resulting in flooding for the four residential properties. We seek to estimate the lowest cost option to respond to the flood risk event *Y* for the four buildings sitting in the identified flood zone. Event *Y* is defined as a flooding even with a 1 in 100-year annual exceedance probability (1% AEP) in 2025.

We take the perspective of the local Council and assume that the Council is investigating options to mitigate flood risk in the local area. They can:

1. **Do nothing** – Keep the culvert unchanged and expect the local property owners to pay for the cost of any future damages, through insurance or other means.
2. **Build a bridge -** Replace the culvert with a bridge to mitigate the flood risk to surrounding properties. This bridge could either be paid for by a targeted rate levied on the four surrounding properties or paid for by general rates paid by all ratepayers in the Council area.
3. **Retreat** – The owners sell their properties to the Council, based on the most recent rating valuation. The Council removes the buildings and rezones the area from residential to recreational use only.

The costs associated with each of these options could potentially be paid for by several different parties, including the property owners, the local Council, or the central government. In the first instance, the analysis is concerned with the distribution of benefits between different parties, and what implications this may have for the potential distribution of costs.

Step 1: Calculate annual insurance costs

To compare the costs associated with each of the four potential options outlined above, we calculate the annual expected hazard specific insurance cost (*CI*) for event *Y* associated with each option *j*. Costs are calculated for each individual year *t* in the analysis period, which starts in 2025 and ends in 2075, as follows:

$$CI_{jt} = LF \times AEP_{jt} \times d_{jt}$$

Where:

- *LF* is the assumed loading factor, a parameter for the administrative costs and profit margin for the insurer,
- *AEP* is the expected annual exceedance probability of riverine flooding inundation, and
- *d* the expected damage given the assumed hazard event *Y*.

The parameter *AEP* is kept constant.

The parameter *AEP* varies by year based on projected change in riverine flooding frequency due to climate change.

Parameter *d* is a function derived based on expected damage event *Y* in year *t* as follows:

$$d_{jt} = (FD \ \times dr_{jt} \ \times v$$

Where:

- *dr* is the damage ratio for the building for the anticipated flood depth in year *t, and*
- *v* is the combined estimated value of the four properties.

The damage ratio (*dr*) is calculated using the flood fragility curve for a single-storey timber building subjected to a given flooding inundation depth, from Reese and Ramsay (2010). Flooding inundation depths are assumed to be constant over the analysis period.

The estimated value of the properties *(v*) is calculated using historic average annual changes to the house price index, from Q1 1990 to Q1 2024.

Step 2: Calculate net present value of options

We then calculate the net present value of projected costs for the next 30 years for any given year (NPV_{jt}), as follows:

$$NPV_{jt} = \sum_{t=1}^{30} \frac{(CI_{jt})}{(1+r)^t} + U_j$$

Where:

- *r* is the discount rate, and
- *U* is the cost of the resilience upgrade in option j (no cost for doing nothing, the cost to build a bridge, or the cost to retreat).

This process is then repeated for all years in the evaluation period. For each individual year, we compare the relative costs of each of the three options: do nothing, build a bridge, or retreat.

Step 3: Consider impacts of uncertainty

We consider two sources of uncertainty in case study 2: future changes in property values and infrastructure construction costs. For each of these sources of uncertainty, a low, medium, and high parameter value was identified, which are outlined in Table 6.

The importance of productivity growth is demonstrated by William Baumol's unbalanced growth model, which shows the link between industry-level productivity growth and structural changes to the composition of the economy. Under this model, aggregate productivity growth of the economy slows down because industries with relatively low productivity growth become a higher proportion of the economy (Baumol, 1967). While this model does not shed light on why some industries have faster productivity growth than others, it sheds light on the wider consequences. Uneven productivity growth results in changes in the sectoral composition of the economy (Nordhaus, 2008). Consumers respond to changes in relative prices by substituting away from goods (or industries) with higher relative prices, towards goods (or industries) with relatively higher prices (Duernecker et al., 2024; Moulton, 2018).

In the current case study, the relative cost of insuring against risk or investing in resilience to mitigate risk will be influenced by future changes in the relative cost of residential property, which at least partly influences insurance costs and civil construction costs, which drives future bridge construction costs.

Figure 17 shows a box and whisker plot of the distribution of three indices from 1990 to 2024: residential building construction, civil construction, and house prices. We see that across the three indices, the house price index has the highest average annual growth rate, and the highest variability, while civil construction has the lowest average annual growth rate and the lowest variability.

Figure 17: Distribution of annual index changes, 1990-2023

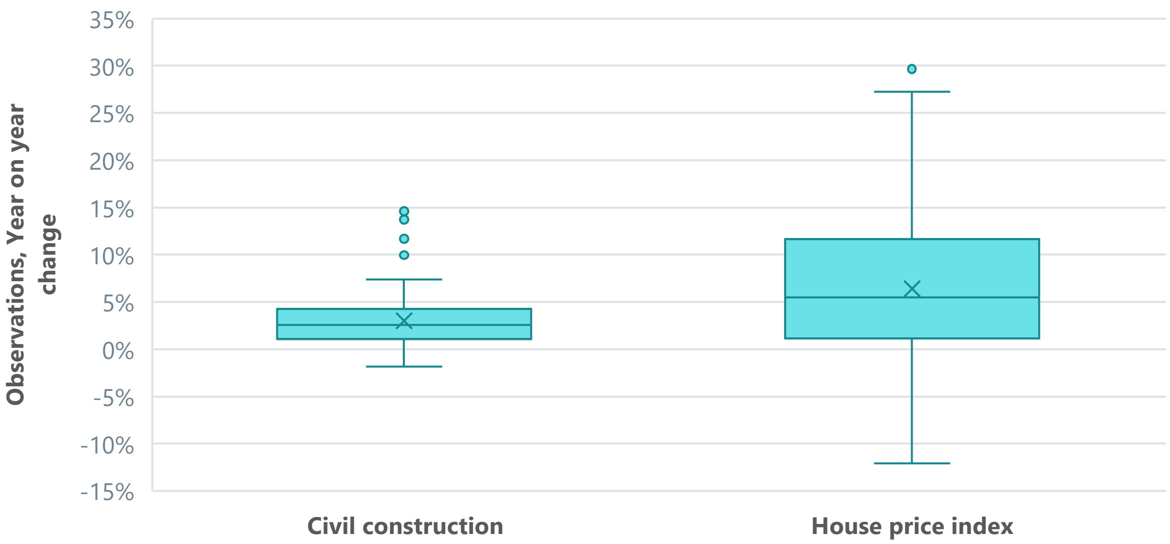
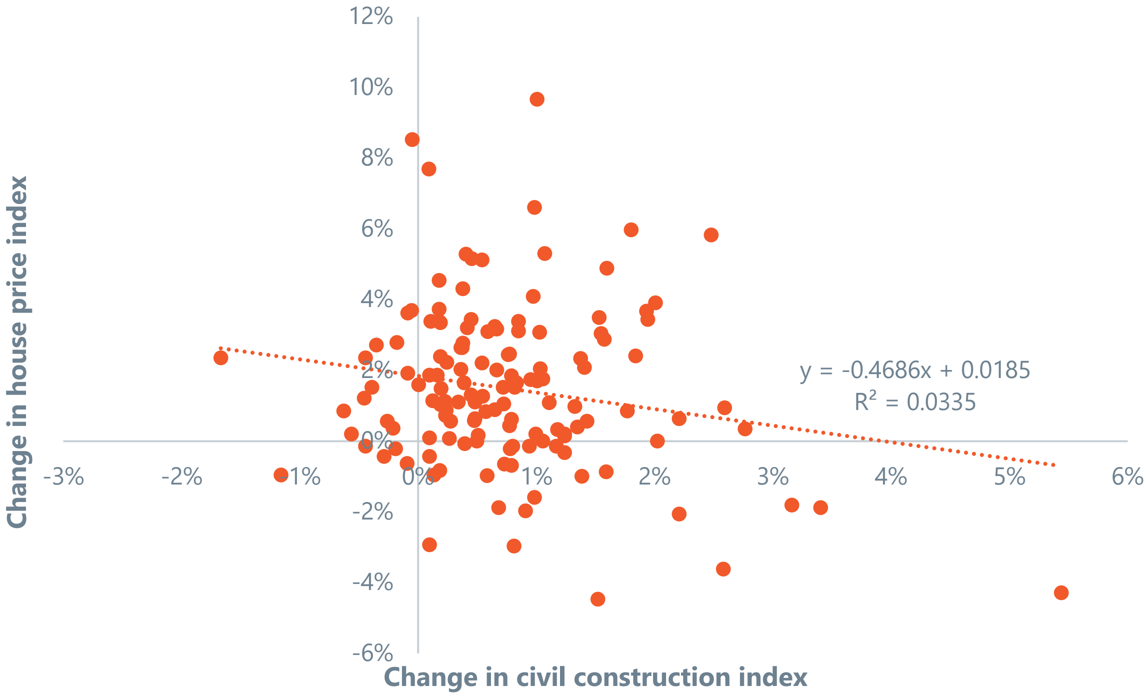


Figure 18 shows a scatterplot of quarter-to-quarter changes in civil construction inflation index vs. the house price index from 1990 to 2024. We see that quarterly changes to these indices are not correlated with each other (R^2 = 0.03).

Figure 18: Quarter to quarter change, civil construction inflation vs house price index



The three price change scenarios considered are:

A. **Central case**: Residential property inflation and civil construction inflation are both at average levels, defined as historic average annual price changes from Q1 1990 to Q1 2024.

B. **Relatively low civil construction inflation**: Civil construction inflation is relatively low (one half standard deviation below average), and residential property inflation is relatively high (one half standard deviation above average).

C. **Relatively high civil construction inflation**: Civil construction inflation is relatively high (one half standard deviation above average), and residential property inflation is relatively low (one half standard deviation below average).

These three price change scenarios should not be considered forecasts but are instead a 'what if' analysis or sensitivity tests to understand the impact of relative price changes on the optimal investment decision for the case study.

We do not consider other sources of future cost changes, and other variables, such as flooding probability and severity, remain constant.

Table 6: Key parameter assumptions for Case Study 2

Parameter	Parameter value	Rationale	Source
Scenario assumptions			
Discount rate (*d*)	2%	Public sector discount rates required by the New Zealand Treasury	(The Treasury, 2024)
Analysis period	30 years	30 years is the planning period for local government long-term plans. It is also the typical mortgage length for a residential property.	(LGA 2002)
Flood depth – all years	1.5m	Assumed flood level at baseline.	N/A
Insurance cost assumptions			
Loading Factor (*LF*)	130%	As the actual value used by insurers is unknown due to commercial sensitivity, a sensible assumption must be made.	(Hudson, 2018)
Building fragility curve	$-0.0522x^2 + 0.3839x + 0.1149$, where x = flood depth in m	Value for timber one storey constructed pre-1970	(Reese & Ramsay, 2010)
Annual change, residential building value	Central – 4.4% High – 6.1% Low – 2.7%	Central – Average, Q1 1990- Q1 2024 High – 0.5 std deviation above average Low – 0.5 std deviation below average	Te Waihanga analysis of (Reserve Bank of New Zealand Te Putea Matua, 2024)
Annual change, civil construction cost	Central – 3.0% High – 4.4% Low – 1.6%	Central – Average, Q1 1990- Q1 2024 High – 0.5 std deviation above average Low – 0.5 std deviation below average	Te Waihanga analysis of (Statistics New Zealand, 2024)
Change in AEP from climate change	1% AEP in Year 1, 3% AEP in Year 50.	Paulik, Craig et al. estimate that a 1% AEP event could increase in frequency to become a 3% AEP event by . This should be taken as an illustrative example as the impact of climate change to riverine flooding is highly variable.	(Paulik, Craig, et al., 2019)
Resilience cost assumptions			
Cost to build bridge in Year 1	$545,000	Central cost estimate. Based on assumed 8m long, two lane bridge	Benchmarking against similar projects
Cost to relocate buildings in Year 1	$4,730,000	2021 Capital value for four selected residential properties located near a culvert.	(Wellington City Council, 2021)