Towards a Real Options Analysis of Adaptation to Sea Level Rise around the Lower Kaituna River

Report to NIWA

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Infometrics

Economics put simply

Authorship

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Cover photograph: Wainui Repo Whenua saltmarsh restoration project, Bay of Plenty Regional Council.

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Glossary

Abbreviation	Explanation
AEP	Annual exceedance probability. For example AEP=100 denotes a 1 in 100 year event. Statistically this means that over a period of 100 years there is a 63.2% probability of at least one such event and a 36.8% probability of no such event.
Beta distribution	A statistical distribution with a fatter tail than a Normal distribution. It provides scope to constrain the distribution outcomes within plausible bounds and allows skewed distributions.
CBA	Cost benefit analysis: a standard technique used to value streams of costs and benefits of different investment strategies over time using discounting – see Appendix C.
CEA	Cost effectiveness analysis: the same as CBA except that the benefits are the same across all alternative strategies, so they do not need to be measured in monetary values.
Cut-off probability	The risk-neutral probability at which the statistically expected cost from over-investing (spending more or sooner than is required to avoid an adverse outcome) is the same as the statistically expected cost of damage from under-investing or delaying investment to avoid adverse outcome.
ROA	Real options analysis: essentially the same as CBA except that a value is estimated for the option of delaying an investment if delaying could provide more information about likely outcomes. An option value could be negative.

1. Introduction & Summary

This report contributes to NIWA's *Future Coasts Aotearoa* research project, financed by the Endeavour Fund of the Ministry of Business, Innovation and Employment. The full programme title is *Transforming coastal lowland systems threatened by sea-level-rise into prosperous communities*. The overarching aim of the project is to enhance the evidence base for relative sea level rise risks (exposure, consequences, evolving environmental states, adaptation thresholds, positive/negative feedbacks) by building evaluation tools that are fit for purpose – and incorporating them into a decision-making framework.

Our contribution is to apply Real Options Analysis (ROA, an extended form of cost benefit analysis) to various broadly defined strategies for pro-active adaptation to address the increasing severity of inundation events with an Annual Exceedance Probability of 1% in the context of future sea level rise in the lower Kaituna river region in the Bay of Plenty. We do not analyse adaptation strategies to address existing or unchanged risk.

Also excluded is the effect of slowly rising groundwater, although the effect of sea level rise on flood levels is included.

We look at three active adaptation strategies requested by the project team:

1. Recognition of the monetised value of ecosystem services from restored wetlands.
2. Maintain and enhance as necessary the existing stopbank and drainage system.
3. Managed retreat.

Comprehensive and robust input data for modelling is scarce, but with extensive sensitivity testing our analysis suggests that:

- If the estimates of the monetised value of ecosystem services delivered by restored wetlands are correct, letting the stopbanks and the drainage system deteriorate and thereby rewetting dried wetlands, may be the least cost adaption strategy.
- Maintaining and enhancing the stopbank and drainage system to protect against increasing AEP=1% events is also a viable strategy, but likely requires more certainty about future sea level rise and climate change to be preferable to doing nothing. Delaying such action could be worthwhile.
- Managed retreat is not economically sensible at this stage, although we caution this may change over time and if viable alternative locations are identified.

There are many more combinations of strategies, their implementation dates and sea level rise scenarios than could be examined here. However, in this preliminary application of ROA we do not have the detailed data to constrain the number of combinations to something that is both manageable and based on consultation with the community.

Finally we stress that our analysis is based purely on economic costs and avoided losses. Other than including the monetised value of wetland benefits it does not consider the social, cultural or environmental aspects of adverse extreme events associated with climate change and rising sea levels. A multicriteria approach could be a useful contribution to assessing such non-monetised benefits, including distributional effects.

2. A Guide to ROA

The emphasis in economic evaluation is on the efficient allocation of resources to meet some desirable social objective. In the context of adaptation to climate change effects that means analysing the cost of protecting the services provided by natural assets and built capital assets such as dwellings and infrastructure (e.g. roads and pipes), as well as agricultural and forestry operations. In essence the issue is whether the net benefit of protecting an asset exceeds the net benefit of either relocating it, providing some other means to deliver the services it provides, or letting it fail.

Real Options Analysis (ROA), frequently in combination with Dynamic Adaptive Pathways Planning (DAPP) can reveal how robust adaptation strategies are to changes in the timing and severity of risks posed by a climate change hazard such as sea level rise (SLR).

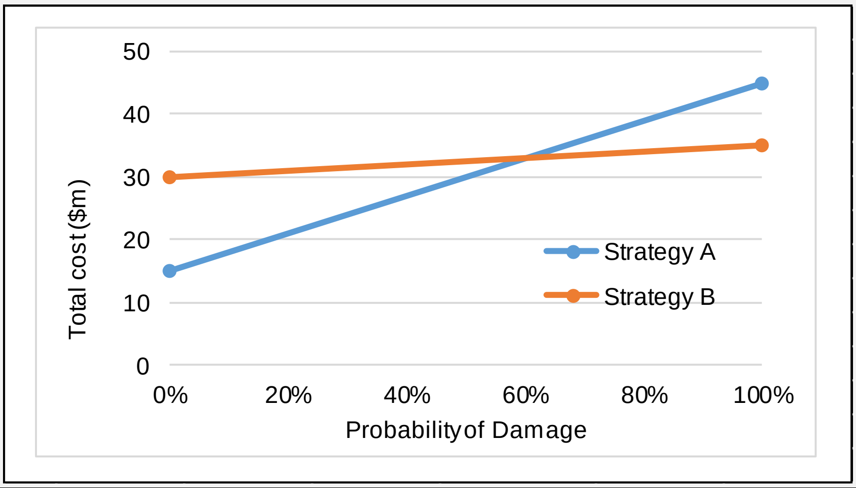
The trade-off is between spending too much too soon (if the hazard turns out to be less serious than initially anticipated) and potentially incurring economic loss if the hazard emerges sooner or more intensely than anticipated. This gives rise to a concept called the cut-off probability – see box below.

The 'Cut-off' probability

In many applications of ROA the analyst is required to stipulate the probability of different future outcomes, with ROA then producing the adaptation strategy with the highest expected net benefit. We reverse the question and ask at what probability do two (or more) investment strategies yield the same expected net benefit? That probability is termed the cut-off probability.

The cut-off probability is not an estimate of the probability of a particular climate change or sea level rise scenario. It is the risk-neutral probability at which the statistically expected cost from over-investing in protection (spending more or sooner than is required for the desired degree of protection) is the same as the statistically expected cost of damage from under-investing or delaying investment in protection.

The following simplified example illustrates the concept. If Strategy A is undertaken and the damage scenario does not eventuate, the expected discounted cost is $15m, whereas under Strategy B the cost is $30m - twice as much as is required to provide the desired degree of protection. If, however, the damage scenario does occur, Strategy A is more costly than Strategy B which provides more protection. At a probability of 60% the statistically expected costs are equal. That is the cut-off probability. It is likely to change with different climate change scenarios.



DAPP provides a strategy to reduce the under/over risk by identifying flexible pathways along which short term protective actions (including adaptation) do not compromise further actions in the future. ROA can quantify those pathways by assessing the option value of waiting for more information that could lead to a better decision, frequently relative to a Do-Nothing strategy.

Among the costs and benefits that are needed as inputs into ROA/DAPP are the following:

- The economic life of an existing asset, encompassing its current value and operating costs.
- The costs involved in prolonging its economic life.
- The capital and operating costs of adaptation measures (e.g. stopbanks and pumps).
- The costs of relocating built assets elsewhere (managed retreat).
- The capital and operating costs, and benefits of changing how its services are delivered (e.g. replacing some reticulated water with rainwater tanks).

However, the question is more complicated than just collecting the above data. The complication is uncertainty, not so much with regard to estimating costs and benefits (though these are not straightforward), but rather with regard to the timing of SLR and thus the timing of investment in adaptation measures. This is why the techniques of DAPP and ROA, rather than just traditional cost benefit analysis (CBA) are required.

The definition of assets may be broad, encompassing natural assets such as wetlands, salt marshes and other riparian vegetation. Restoration or enlargement of these non-built assets could appear on the benefit side of the equation if land currently used for agriculture or buildings becomes unsuitable for such uses. Three approaches to include natural assets or other non-economic benefits in ROA are possible:

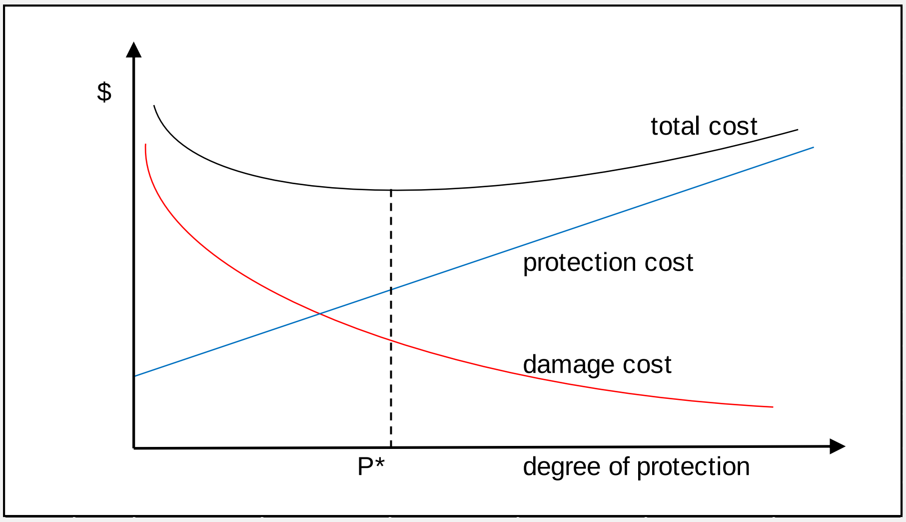
1. Application of valuation techniques for non-market and non-use services, such as hedonic pricing, stated preference and revealed preference methods (choice experiments). Such valuations can be directly incorporated into CBA and ROA.
2. If monetary valuations are too dubious, ROA suffers from the same problems as CBA. As with CBA, however, ROA can be used in a manner analogous to cost effectiveness analysis. which identifies the least cost way to achieve a minimum outcome. Costs are still expressed in monetary terms, but the benefits are the same across all adaptation options (such as resistance to a given AEP event) or are measured in some other unit. In the health industry for example this might be life-years saved and in the transport industry it might be tonnes of particulate matter from vehicles. Or it could be a score based on multicriteria analysis that assesses a number of non-monetised benefits simultaneously.
3. ROA can reveal the incremental cost of not proceeding with the least net cost strategy when another strategy that has non-monetised benefits is favoured. For example a stopbank may be the least expensive option, but could impede access to the river. If a more expensive option that preserves river access is adopted instead, the difference in costs is an estimate of the minimum value of river access.

As economists we can use techniques such as CBA and ROA to evaluate the relative monetised costs and benefits of different adaptation options and pathways, but our role is not to determine which is best, as such a call may involve more than financial metrics. That is a decision for the affected community and those who bear the costs.

A note on residual loss

With the exception of managed retreat, it is highly likely that every adaptation strategy carries some residual risk of loss that cannot practically be avoided, especially as the resources that can be devoted to protective measures are not unlimited. At some point a decision is required about how much residual risk is acceptable, relative to the cost of minimising it further.

The figure below provides an illustration. The blue line represents the cost of a protection pathway. It is smoothly linear merely for convenience. We would expect it to be convex and probably quite jagged owing to the lumpiness of capital expenditure.



The red line expresses the expected cost of damage, again drawn smooth for convenience. The greater the amount spent on protection, the lower the expected damage cost. Expenditure to enhance protection beyond point P* is inefficient, as P* represents the minimum total cost (the most efficient point), at which the marginal cost of protection equals the marginal reduction in damage cost. Thus some residual expected loss remains.

Note that the diagram is merely to illustrate a concept. The positions and slopes of the curves would likely change over time.

3. Analysis of Strategies

Introduction

The study area encompasses the lower Kaituna river land that is within 5m of current mean sea level. See Figure 1, with an example of more detail in Figure 2 – the light green areas. (Source: NIWA).

Figure 1: Study Area

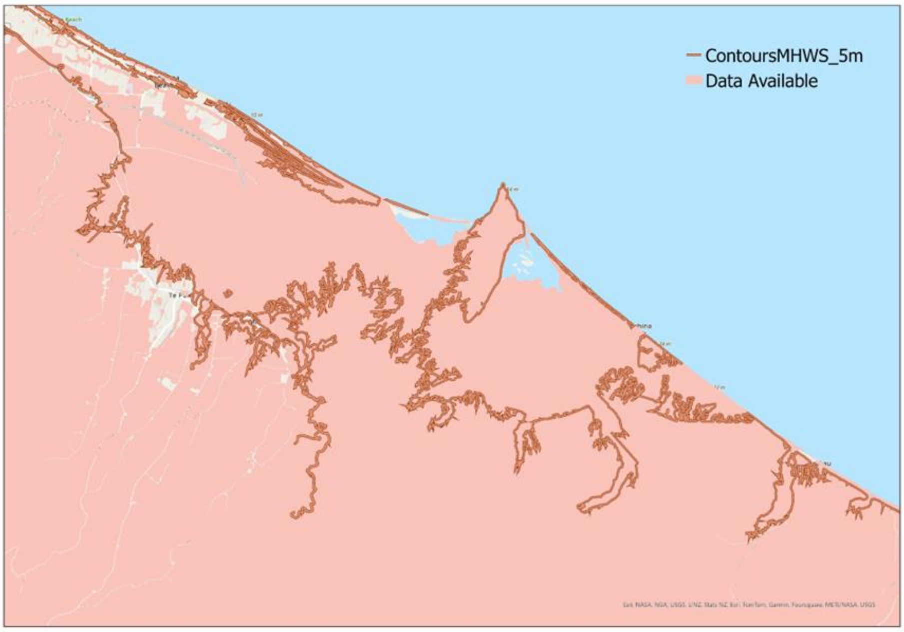
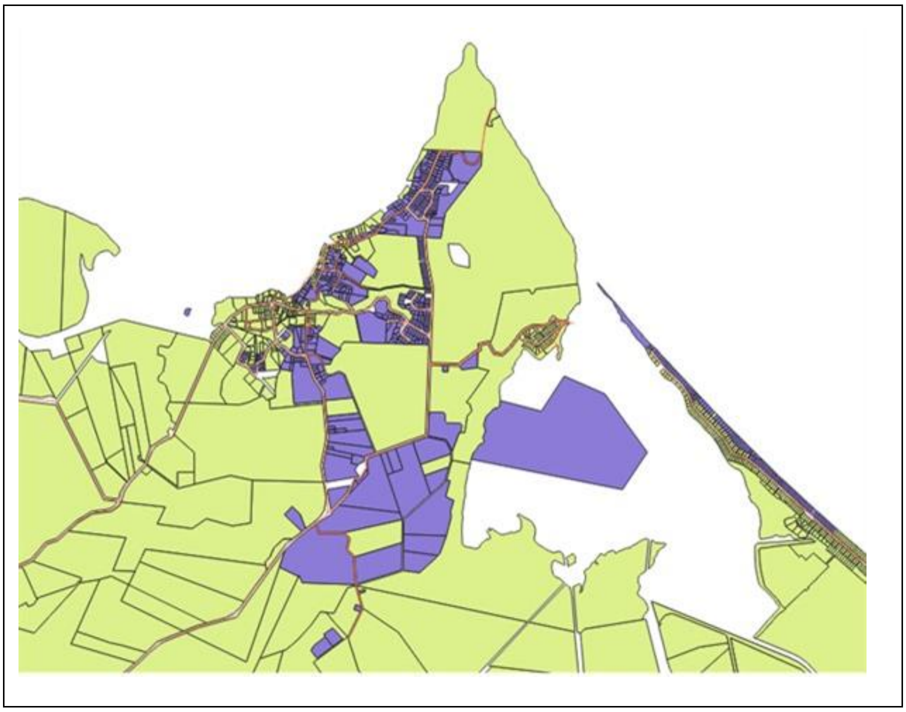


Figure 2: Enlargement of Subsection



We have a list of 1663 properties in the study area for which we know their id code, their area, their land use and their exposure to current and future AEP=1% events in the context of sea level rise (SLR) to 2130.[1] Some properties have more than one land use and we know the area devoted to each use.

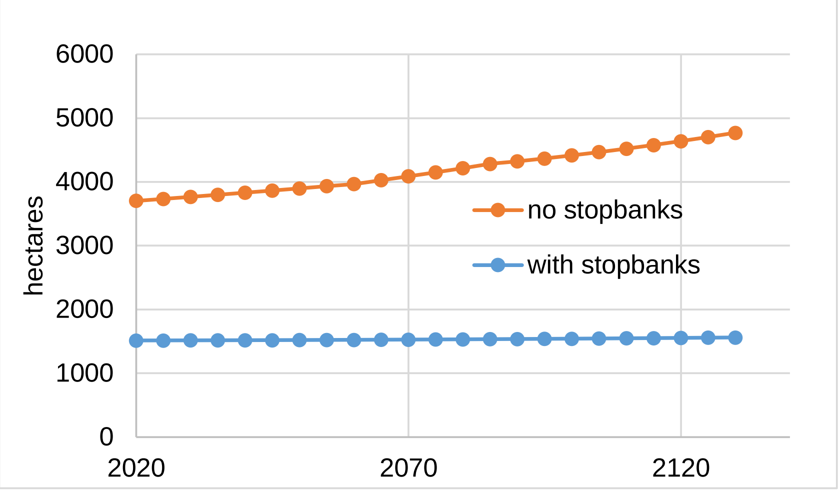
However, each property is assessed as whole for its risk of inundation. That is, we do not know, for example, if a dwelling is on higher ground than a surrounding farm. Consequently we must assume that protection provided by the existing stopbank and drainage network system applies to all land and assets on a property.

Stopbanks and drainage

We do not have data on projected inundation with and without the stopbank and drainage system. However, we do have two sets of data from NIWA on inundation projections from two different models; one based on hydrodynamic modelling that takes into account 'ground friction' caused by stopbanks, vegetation, buildings, farms and so on. It also accounts for rivers. The other model is a simple 'bathtub' model based on digital elevation data that ignores above ground features. Invariably the latter produces higher estimates of inundation so we use this as a proxy for scenarios without stopbanks and drainage.

Broadly speaking, under the bathtub approach at least twice the amount of land would be inundated compared to the amount modelled under the hydrodynamic approach – for an AEP=1% event out to 2130. See Figure 3. The mean inundation depth in the bathtub model is never less than 0.7m and increases over time. The analysis splits land use into dairy, urban (including lifestyle), and other. [2] Existing wetlands, estuaries and beaches are excluded.

Figure 3: Land Inundation (base case scenario)



With regard to the protection conferred by the existing stopbank and drainage system, we note that its current assets (flood gates, pump stations, drainage channels and stopbanks) are aging, but generally still effective. Based on BoPRC data (Appendix A) we estimate that on average their market value in 2020 was about 87% of their replacement value.

Commensurate with our inability to link protection of specific properties to specific components of the stopbank and drainage system, we assume that the system's average

[1] Over a period of 100 years an AEP=1% event has a 63.2% probability of occurring at least once.
[2] The Other category could be split further, identifying uses such as horticulture and forestry. However, most of these categories are relatively small, which leads to unreliable results. .

level of service can be maintained without significant maintenance until its value has depreciated by 33% of base year replacement value. This is projected to occur between 2030 and 2035. After that it needs to be maintained to prevent any further notable decline in its level of service – for the relevant adaptation strategies. Adequate maintenance is implicit in the blue 'stopbanks' line in Figure 3.

Groundwater

Excluded is the effect of slowly rising groundwater, although the effect of sea level rise on flood levels is included. That also has an effect on how quickly the stopbank and drainage system has to be upgraded (in the relevant adaptation strategy), thereby perhaps also capturing some of the effect of slowly rising groundwater.

Preliminary modelling of groundwater showed that without stopbanks and drainage the increase in exposed land due to groundwater equates to about 40% of the projected increase in the inundated area. However, from a practical perspective the question is whether the groundwater rises faster or slower than the rate of deterioration of the level of service of the stopbank and drainage system if it is not maintained. This becomes quite complicated from a spatial perspective, especially because, as noted above, we cannot link the protection of specific properties or parts of properties to individual components of the stopbank and drainage system. Further, the effects of incipient groundwater saturation depend on the type of structure in existence, including how wastewater and potable water are reticulated. Damage functions for slow impact groundwater intrusion are not well defined.

Clearly the effect of rising groundwater is a topic that merits further research.

SLR to time profile

The inundation data from NIWA is not explicitly linked to climate change scenarios, so has no time dimension. As time is a crucial factor in CBA/ROA we map the NIWA SLR-event data onto three RCP scenarios: RCP 4.5, 7.0 and 8.5, from the projected SLR scenarios given in the NZ Sea Rise programme.[3] We take the average of the 50th percentile projections for sites 1837, 1841, 1847 and 1853, including the effect of vertical land movement.

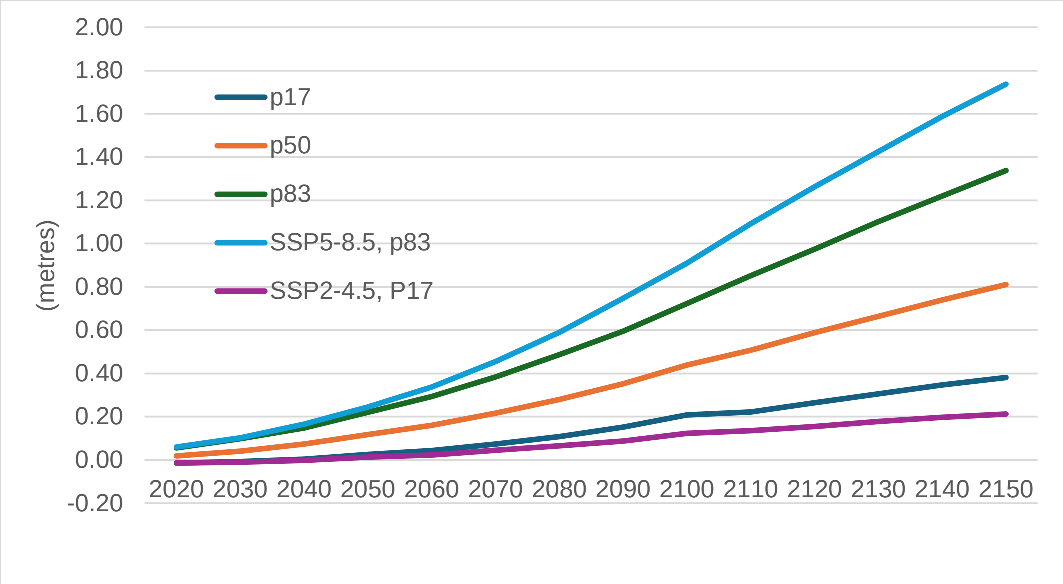
The three RCP scenarios are given initial weights of 45%, 45% and 10% respectively to form a base case RCP scenario. Note that these are merely statistical weights, not probabilities of any RCP scenario occurring. The end result has an SLR profile that is almost the same as that for the 40^{th} percentile for RCP 7.0. The weights are varied in sensitivity analysis.

Figure 4 shows the projected path of SLR for the weighted mean of the 50th percentiles (the orange line). This is our central scenario or base case. Also shown are the weighted means of the 17th and 83rd percentiles, plus two extreme profiles; the 17th percentile for the lowest SLR projection (SSP2-4.5) and the 83rd percentile for the highest SLR projection (SSP5-8.5). This information will be used in sensitivity analysis.

Note that the almost flat line for 'with stopbanks' in Figure 3 is not inconsistent with the upward trend in SLR in the base case (orange line) in Figure 4. It means that the (maintained) stopbanks are effective for SLR up to about 0.8m in 2150 – for that scenario.

[3] https://searise.takiwa.co

Figure 4: SLR Profiles



Adaptation Strategies

Strategies

The default strategy is No Action. Stopbanks and the drainage system are not maintained and allowed to deteriorate, so land, infrastructure and other assets that are currently or would be protected, are eventually inundated. Nuisance flooding may lead to people abandoning assets before serious flooding occurs.

Three active adaptation strategies requested by the project team are explored:

1. As in No Action, but including a monetised value of ecosystem services – discussed further below.
2. Maintain and enhance as necessary the existing stopbanks and drainage system so as to keep the risk of economic loss from an AEP=1% event the same as in 2020-25, so not increasing with SLR. (Possible actions to address the current level of risk – without climate change – are not within the scope of this study).
3. Managed retreat; allowing land to be repeatedly inundated and shifting buildings to or reconstructing them at a location or locations far enough inland where inundation is not a risk – strictly speaking rarer than an AEP=1% event.

These are broad strategies that will have varying impacts in specific locations, but our modelling is too high level for such detailed analysis, Similarly we cannot consider micro-level strategies (such as localised culvert construction) that might solve problems over short horizons.

Wetland restoration

We consider the possibility that land which becomes unsuitable for agriculture (notably dairy farming) due to repeated inundation is converted to wetlands. There are two possibilities here:

- Passive: The land is passively rewetted as sea level rises and AEP=1% events occur.
- Active: Similar to other adaptation strategies such as enhancing stopbanks, wetland restoration requires active investment before a possible AEP=1% event. That means converting some dairy land currently in active use. It also means that the alternative ecosystem services provided by wetlands (e.g. wildlife habitat and biodiversity, and water quality enhancement) accrue even if no SLR occurs.

We assume that the timing of conversion is proportional to the expected loss of dairy land as the stopbanks would deteriorate or are breached over the period to 2130. This implies an average conversion rate of about 15ha per annum.[4]

Arguably even without the exacerbating risk of AEP=1% events, currently exposed dairy land could be converted to wetlands. Indeed there may well be other land that is also suitable for wetland restoration, or there may be a desire to accelerate restoration well in advance of the loss of agricultural land. However, such actions are beyond the ambit of this project as they are not strategies to explicitly respond to the increasing risk of loss from adverse events.

To our knowledge there is no study that identifies the specific types of benefits that might be generated by wetlands in the Kaituna area. Hence we use the recent work by Yang et al (2024). This lists seventeen types of ecosystem services provided by salt marshes such as moderating extreme events (almost half of the total estimated benefit value), treating waste and providing recreational opportunities. Their combined annualised benefit stream is estimated at US$34,500/ha, although some caveats should be noted:

- It is not entirely clear that (in the original studies) the underlying components have been consistently calculated with regard to parameters such as the discount rate and the time horizon.
- The monetised values are not strictly additive as there is some double counting of types of ecosystem services.
- We do not know which types of ecosystem benefits are relevant to the study area, though moderation of extreme events is a top contender.
- Not all land would revert to salt marshes. Because of land shrinkage resulting from farming. a significant amount of land would be too deeply inundated to support salt marsh and become tidal mudflats with more limited ecosystem values.

Given these reservations we assume a tentative value of NZ$27,600/ha/year, being an arbitrary half of the USD value converted to NZD. This is varied in sensitivity testing.

Bayraktarov et al (2020) provide estimates of saltmarsh restoration costs, but the estimates span five orders of magnitude per hectare. The contexts are simply too diverse for us to infer a suitable value for Kaituna. Data provided by the Bay of Plenty Regional Council in connection with the Wainui Repo Whenua saltmarsh restoration project itemises various costs to date totalling $130,000, although not all costs are included and the area to which it relates is not specified. Thus the eventual total cost per hectare is unknown.[5]

[4] The precise conditions under which this would occur depend on many factors such as the degree, duration and depth of waterlogging and salinity, the type of grass, other vegetation and grazing. See Nichols (2024).

[5] The Wainui Repo Whenua project is described in BOPRC (2020).

Based on a study of peatland (note, not saltmarsh) restoration in Germany by Willenbockel (2024), we assume an initial investment cost of $15,000/ha, with ongoing costs of $200/ha per year – estimates that are entirely within the range in Bayraktarov et al. For modelling purposes it is assumed that there is a lag of 10 years between restoration and the delivery of any ecosystem services.[6]

Note that rewetting of drained wetlands is not the same as constructing completely new wetlands, which would have much higher costs. For example Matthews et al (2024) estimate that the cost of constructing wetlands systems (designed to reduce agricultural sediment and nutrient loads) on a flat and accessible site is $126,000/ha, with $4040/ha for annual operational costs. Both are central estimates that have accompanying error margins. Such a strategy may be worth analysing with better data.

Meantime, in sensitivity tests below we look at the effects of assuming a different monetised return from wetland ecosystem services.

Managed retreat

Analysis of managed retreat is unavoidably very tentative as we have no information on alternative locations for existing assets (dwellings and commercial buildings), let alone the costs of developing roads and other infrastructure at some arbitrary location. Relocation of agricultural, horticultural and forestry activities is excluded, so these are modelled as losses.

To be consistent with Strategy 2 we consider managed retreat only for those assets that become newly at risk with SLR, not those that are currently at risk. That is, it effectively keeps the risk of economic loss (to buildings and infrastructure) from an AEP=1% event the same as in 2020-25, so not increasing with SLR and climate change.

In any case the cost of rebuilding (or relocating) all dwellings, commercial buildings and infrastructure elsewhere, is much more than the statistically expected loss from SLR. Hence it is not an economically viable adaptation strategy.

Other assumptions

The analysis requires a considerable amount of data that is not available, although more may become available in due course. In the meantime we make a number of assumptions:

1. Any expansion or enhancement of stopbanks and drainage that is needed to cope with the increasing frequency of an AEP=1% event is assumed to have the same annualised resource cost per hectare protected as currently applies.

2. If the system is not maintained, the loss value of currently protected land, buildings and infrastructure will vary directly with the deterioration of the stopbank/drainage system and the rate of sea level rise.

3. All infrastructure that is on land protected by the stopbanks and drainage system is also thereby protected. This includes roads, access paths, driveways and so on.

4. Due to a lack of information we ignore the velocity and duration of inundation events. Changes in salinity and temperature in the river channel are also not modelled.

[6] Five to fifteen years Is estimated for the development of primary production for reconstructed salt marshes. See Craft et al (2003).

5. With regard to managed retreat we have no data. Our working assumption is that the cost is equal to the market value of existing assets[7], plus 10% for redevelopment and another 10% for cleanup costs at existing locations. These increments are applied pro rata in every year through to 2130 although in reality the redevelopment costs would be forward-weighted while cleanup costs would dominate in later years.

6. The NIWA modelling has focused solely on sea level rise and extreme events. It does not address rain-on-grid effects, which could lead to increased nuisance flooding as sea levels rise. For example, sea level rise will reduce the drainage efficiency of gated culverts and change the 'drainage window' worsening flooding behind stopbanks during rain-related event (Waddington et al, 2022). This could lead to changing land use before a 1% AEP event.

Results

The adaptation strategies are technically separate from one another. Hence we initially use ROA to determine cut-off probabilities and then explore the effect of changing the timing of a strategy – the value of the option to delay.

As discussed in Section 2 the cut-off probability is the probability at which the cost of investment in adaptive actions plus any residual expected loss, is equal to the expected loss under a No Action strategy, with all costs and losses discounted to present day values at a default discount rate of 3% pa.

A strategy with a cut-off probability of less than 100% indicates a potentially economically viable strategy relative to No Action. To reiterate an earlier point, this not attaching a probability to a specific climate change or SLR scenario. It is determining a probability at which a particular adaptation strategy would be economically justified, for some given SLR scenario. The cut-off probabilities for other SLR scenarios are tested later.

The cut-off probabilities occur where the strategy lines intersect with the No Action line, are summarised in Table 1 and illustrated in Figure 5. Table 1 also shows the discounted investment cost, and cost plus residual loss for each strategy.

Table 1: Discounted Cost plus Loss and Cut-Off Probabilities

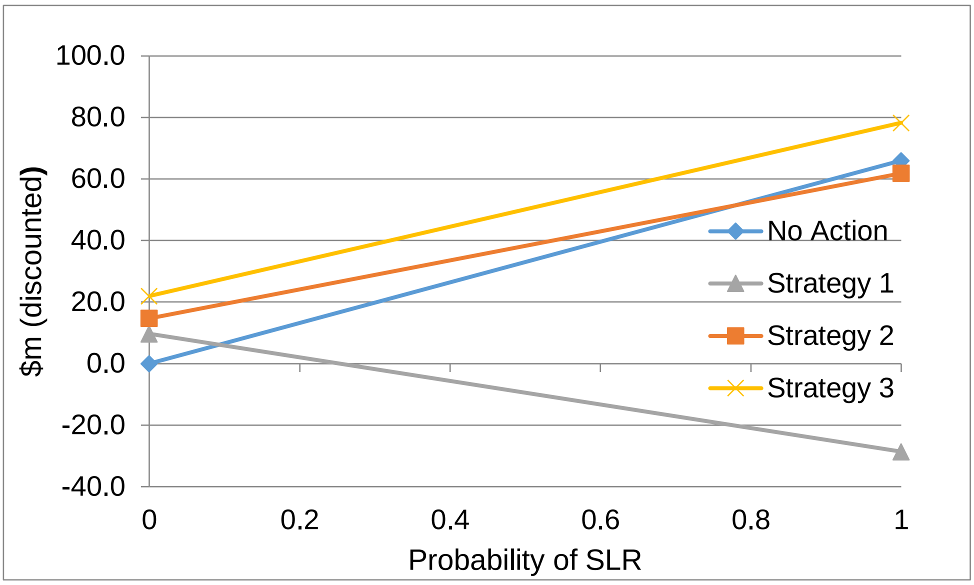
Strategy	AEP=1%	Cost	Cost + Loss	Rank
No action	--	$0.0m	$66.0m	3
1 Include eco-system benefits	9.3%	9.7	-28.6	1
2 Stopbank system enhancement	78.2%	14.7	61.9	2
3 Managed retreat	>100%	22.0	78.2	4

Unsurprisingly No Action has a high discounted economic loss, but this becomes a net gain in Strategy 1 under which a monetary value is placed on the benefits generated by restored wetlands, even recognising some costs of establishment. The Strategy 1 cut-off probability is less than 10% indicating that restoring wetlands is likely to be a viable adaptation strategy relative to No Action – provided of course that the estimated monetised values are indeed realistic. Alternatively one could say that if the chance of the

[7] We use market value rather than 'replacement with new' values as the latter represents an additional increment that is not strictly an adaptation cost.

given SLR scenario occurring is thought to be low (less than 10%) wetland restoration is not advised – No Action is preferred.

Figure 5: Investment Cost plus Residual Loss v Probability of SLR



Strategy 2 (maintaining and expanding the stopbank system) has a cut-off probability of 78% so is also a viable alternative if the given SLR scenario is seen as very likely, particularly if the value of ecosystem services of additional wetlands is doubtful. To obtain the same 78% cut-off probability for Strategy 1 the monetised benefit of ecosystem services would need to be lower at $18,900/ha. In other words, a lower benefit from wetland restoration demands more certainty about SLR before it is worth pursuing.

For Strategy 3 (managed retreat) the cut-off probability is over 100%. Although this makes no mathematical sense, practically it means that the investment cost of adaptation – in this case moving buildings and infrastructure or reconstructing them elsewhere – plus residual loss is higher than the expected loss from doing nothing – the No Action scenario. In Figure 5 the yellow line is everywhere above the blue line.

Note that as with any cost-benefit analysis based on probabilities of future events, once an event has actually occurred (which could be at any time), any previous analysis would need to be revised as a new baseline would prevail.

Option value

Taking Strategy 2 as an example, is there a value to the option of delaying when it is implemented? Delaying investment lowers its discounted cost. but because the time profile of investment is optimally linked to the expected rate of economic loss from SLR, the gain is less than the increase in the statistically expected loss from the greater exposure to SLR in the short term. Hence this is a riskier strategy, but it is not necessarily a poor choice.

For instance if all investment is delayed by 30 years until 2055 with no action in the meantime (call this Strategy 2a), the cut-off probability increases from 78.2% to just over 100%, so better to do nothing. However, Strategies 2 and 2a cross at a probability of 30.9%. Thus if the probability of the (base case) SLR scenario occurring is thought to be less than about 31% Strategy 2a should be pursued in preference to Strategy 2. If SLR turns out to be much less or slower than anticipated (as assessed in 2055), Strategy 2a would be justified. The discounted cost difference is or about 15% or $2.2m in present value terms.

If SLR turns out as anticipated (or worse) Strategy 2 would have been better, with a discounted cost plus residual loss difference of 8% or $5.0m. Indeed, referring back to Table 1 if the probability of the base case SLR scenario occurring is considered to be more than 78% Strategy 2 should be pursued in preference not only to Strategy 2a, but also in preference to doing nothing.

All of the above analysis is based on risk-neutral probabilities, but communities may not be risk-neutral. Those that are risk averse would likely favour Strategy 2, but Strategy 2a might be attractive to communities willing to take on more risk.

It is no doubt apparent that the number of combinations of strategies, their implementation dates and SLR scenarios is rather large. In this preliminary application of ROA we do not have the detailed data to constrain the number of combinations to something that is both manageable and relevant to the community involved.

In the next section we undertake sensitivity analysis that assesses each adaptation strategy against the No Action strategy. That should provide some guidance on which strategies merit further investigation, including investigating the option to delay, once adaptation strategies have been further developed and refined.[8]

An illustration of option value calculations using a simplified example is presented in Appendix C. The numbers are not related to the study area.

Sensitivity Analysis

There are many assumptions and uncertainties in the above analysis. Standard ones include the discount rate, estimates of asset values and investment costs, and the pace of sea level rise and the associated change in the frequency of extreme events (RCP scenario).

Less prominent are the potential monetised returns from wetland restoration and the rate at which stopbanks and the drainage system depreciate – and how that relates to the delivered level of service.

All of this provides ample scope for sensitivity testing. To do this in a meaningful way we firstly present separate sensitivity tests on the discount rate, and the drainage level of service. The other parameters are then jointly tested using Monte Carlo simulation. Table 2 presents the results of the discrete testing.

Discount rate

With a lower discount rate (1%) the cut-off probabilities fall, indicating that if potential economic losses from SLR are given more weight, less certainty is required about future SLR to justify taking adaptive actions – although Strategy 3 is still not economic. Conversely, a higher discount rate (6%) places less weight on future losses, so the cost of reducing future losses such as by enhancement of the stopbank/drainage system is relatively higher. However, Strategy 1 has a negative cut-of probability. As with probabilities greater than 100% this makes no mathematical sense, but the interpretation is that the future benefits of wetland ecosystem services are discounted to such an extent that the initial costs of restoration are not recoverable.

[8] See for example the development of strategies in Hawke's Bay; https://www.hbcoast.co.nz/

Drainage system level of service

As discussed above, the system is currently valued at an average 87% of replacement cost, but presumably able to fulfil its designed level of service (LoS) without significant maintenance costs until it is truly challenged. Our assumption is that by the time the system has depreciated to 67% its LoS would begin to noticeably deteriorate and will therefore require some maintenance, but only enough to prevent its value slipping below 67% of replacement value – as a proxy for its adequate LoS. Clearly the 67% threshold is somewhat arbitrary, even as a system-wide average. Table 2 shows the effect of lowering it to 50%.

The hurdle to implement an adaptation strategy, namely the probability of future adverse events and associated residual loss, is effectively lowered, so the cut-off probabilities fall. Recall that in Strategy 1 the pace of wetland restoration is a function of both the rate of SLR and the rate of decline of the LoS of the stopbank system. Thus if either of those constraints is eased, the opportunity cost of converting agricultural land to wetlands is higher, thereby undermining that strategy.

A higher threshold would have the opposite effects. The maximum that could be assessed is 87% – the current depreciated value of the stopbank/drainage system. Anything higher would imply that the current LoS is already below its design standard. If that is indeed the case it is an issue to be addressed irrespective of future SLR and thus falls outside our ambit.

Table 2: Sensitivity Tests of Cut-Off Values (%)

Strategy	Base case	Discount rate 1%	Discount rate 6%	Drainage LoS 50%
1 Include eco-system benefits	9.3	3.8	-15.0	-7.9
2 Stopbank system enhancement	78.2	71.4	84.2	36.5
3 Managed retreat	>100	>100	>100	>100

The ranking of strategies in all cases with sensible cut-off probabilities is unchanged from that in the base case: Wetland restoration with its estimated monetised eco-system benefits ranks top, followed by stopbank & drainage enhancement. Managed retreat remains economically unviable.

Joint analysis

There are other uncertainties in the analysis in addition to those studied above, notably the pace of SLR along with the associated change in the frequency of adverse events (RCP scenario). the potential loss from foregone agriculture, the value of the potential loss of infrastructure and buildings and the cost of maintaining and/or expanding the stopbank and drainage system – which (on the upside) may also capture the effect that slowly rising groundwater could impose on the system.

Rather than consider these item by item, we incorporate them into a Monte Carlo sensitivity analysis. Values for each variable are randomly drawn from statistical distributions appropriate to each variable; a 4-parameter Beta distribution for SLR under the RCP scenarios, and triangular distributions elsewhere. See Table 3.

For SLR in 2130 the minimum is the value at the 17th percentile for RCP 4.5, and the maximum is the value at the 83rd percentile for RCP 8.5, as illustrated above in Figure 4. The mean is as per the initial weights for the three RCP scenarios including RCP 7.0, at the 50th percentiles.

Table 3: Monte Carlo Distributions and Parameters

	Distb.	Mean	Minimum	Maximum
RCP, SLR by 2130, metres	Beta	0.66	0.18	1.43
Wetlands monetised value, $/ha/yr	Triangular	27,600	13,800	36,000
Agriculture value added, $/ha/yr	Triangular	3420	2800	4000
Value of buildings, $'000/bldg.	Triangular	400	300	500
Value/cost of stopbanks etc.	Triangular	71	60	90
Value/cost of infrastructure, $m	Triangular	315	250	400

For agriculture the minimum and maximum values correspond approximately to milksolids prices of about $6.00/kg and $8.20/kg respectively, relative to the base decade-average price of about $7.00/kg.

With regard to wetland restoration, as the monetised benefits are much larger than the costs and also more uncertain (and not necessarily well-suited to the Kaituna area), only the benefits are included in the sensitivity analysis. We explore a wide range from -50% to +30% of the mean value for benefits. These tests could also be interpreted as retaining the same value per hectare, but changing the number of hectares allocated to restoration.

The discount rate is omitted from this testing as although there are strong economic arguments governing the choice of a discount rate (see Appendix B), the pure rate of time preference, which is a component in the discount rate, is ultimately a value judgement.

The uncertainty in values for the variables in Table 3 are characterised by epistemic uncertainty, which is uncertainty that comes from a lack of knowledge. The distribution of values or outcomes is unknown, so can only be approximated on the basis of current knowledge. Better information may emerge with time or with research, so the uncertainty is theoretically reducible, although more knowledge does not always reduce uncertainty.[9]

The results for the cut-off probabilities are presented in Table 4, which shows the means, the values at the 5th and 95th percentiles, and the proportions of simulations that result in a sensible (0–100%) cut-off probability, for 20,000 draws from the distributions. All cut-off probabilities are set to a maximum of 100% and a minimum of 0% as values outside that range are nonsensical.

Table 4: Cut-Off Probabilities (%) from Monte Carlo Analysis*

Strategy	Base	Mean	5th percentile	95th percentile	% of runs ≤100%
1 Eco-system benefits	9.3	13.4	5	43	98
2 Stopbank enhancement	78.2	79.6	61	100	93
3 Managed retreat	>100	100	100	100	0

* These numbers will change every time the analysis is re-run.

[9] There is another type of uncertainty known as stochastic or aleatory uncertainty, such as applies to the toss of a coin. The uncertainty here is irreducible; no amount of research or waiting for more information will alter the probability distribution.

Strategy 3 – managed retreat, is clearly not economic with no model run producing cut-off probabilities less than 100%. Better data may change this result.

Strategy 2 – stopbank enhancement, is viable in 93% of model runs with a cut-off probability around 80% ±20%. A similar band would likely apply to any decision to defer its implementation.

Because the rate of wetland restoration is partly tied to the rate of SLR, the interaction between the distributions for SLR and the monetised benefits of wetlands is highly nonlinear, to the extent that the mean cut-off value for Strategy 1 is not reliable. Removing either of those distributions results in a mean cut-off probability of 9.3% ±0.1%, the same as in the base case. In contrast the fifth and ninety-fifth percentiles are sufficiently stable, so while we may infer that Strategy 1 is robust to a wide range of values for SLR and monetised wetland benefits, the central estimate for the cut-off probability is not a solid basis for adaptation policy decisions. More precision on the monetised value of wetland benefits in the study area would be helpful.

Again the relative order of the strategies remains robust. We should reiterate, however, that the foregoing analysis is based entirely on an economics perspective. There may also be sound non-economic reasons that over-ride economic considerations.

Distributional Implications

Although ROA has nothing quantitative to say about distributional effects, different adaptation strategies will have different distributional consequences. Two mechanisms are at play here. Firstly, the distribution of asset ownership, including of land, affects who bears the risk of inundation. Some socioeconomic or ethnic groups may be more exposed than others and therefore face varying degrees of potential economic loss.

The second mechanism is that of financing the adaptation strategies. Again this is well beyond what ROA can deliver, but clearly who pays for what, could have significant distributional effects. However, it does provide an opportunity to alleviate the unequal losses from potential inundation if the costs of adaptation are (mostly) imposed on the beneficiaries of the protection it provides, rather than across ratepayers more generally.

As the Hawke's Bay experience illustrates (https://www.hbcoast.co.nz/) it can take many years to reach what a majority of the community consider an equitable allocation of adaptation costs – more or less on a user pays basis. And that is even with much more detailed estimates of costs and losses than are available for the Kaituna study area.

Overall then, distributional effects are a challenge. To progress beyond broad qualitative comments requires a more refined set of adaptation strategies that have evolved from detailed financial estimates and a thorough understanding of how the community sees the trade-offs between monetised and non-monetised costs and benefits. Multicriteria analysis could be useful in this regard.

Policy implications

This analysis provides quantitative estimates of the potential economic value of investing in different adaptation strategies to address a 1:100 year flood event in the face of uncertainty about climate change and sea level rise. The findings of the analysis reflect what can be achieved with limited data. They are insufficient to select a final set of detailed, including spatially detailed, adaptation strategies. Rather, the findings should contribute to dialogue about socially appropriate adaptation with relevant interest groups. In this respect, a number of issues need to be considered.

- The data for the ROA was incomplete. Information on rising groundwater in the area was not available in a form for this to be included. If the stopbank and drainage system has to work harder because of rising groundwater, it could bring forward the investment needed to maintain its level of service. That would likely enhance the case for wetland restoration.
- Importantly, incomplete information on the environmental and sociocultural impacts of different adaptation options means that the total contribution of adaptation strategies to economic wellbeing could not be determined. Accordingly the rankings of the strategies could change. More research would be helpful.
- The economic value of environmental change arising from adaptation options is mostly excluded from the analysis. As discussed above, allowing the stopbank and drainage system to deteriorate over time could potentially contribute to the re-establishment of wetlands. Although that is included in the modelling, specific benefits such as improvements in biodiversity by supporting freshwater species are captured only coarsely.
- More emphasis on the economic value of environmental benefits from the restoration strategy could further improve its attractiveness, relative to maintaining or expanding the drainage and stopbank system.

Conclusion

The preceding analysis has looked at adaption strategies to address the increasing risk from climate change, notably the increasing damage caused by AEP=1% events in association with sea level rise. Adaptation strategies to deal with existing or unchanged risk have not been considered.

Although comprehensive and robust input data for quantitative modelling is scarce, we have endeavoured to address this disadvantage with extensive sensitivity testing. Our analysis suggests that:

- If the estimates of the monetised value of ecosystem services delivered by restored wetlands are correct (or even if substantially over-stated), allowing the stopbanks and the drainage system to deteriorate and thereby rewetting dried wetlands, may be the least cost adaption strategy.
- An engineering strategy of maintaining and enhancing the stopbank and drainage system to protect against increasing AEP=1% events is also a viable strategy, but likely requires more certainty about future sea level rise and climate change to be preferable to doing nothing. Delaying such action could be worthwhile.
- Managed retreat is not economically sensible at this stage, although we caution this may change if viable alternative locations are identified.

For the base case SLR scenario, wetland restoration has a 10% cut-off probability while the engineering strategy has a 78% cut-off probability, indicating that more certainty is required about SLR for the engineering strategy to deliver a net positive benefit (relative to No Action than for the wetland strategy to deliver a net positive benefit.

Neither of these probabilities is the probability of a particular SLR scenario occurring. Rather they are the risk-neutral probabilities at which particular adaptation strategies yield a net economic benefit for some given SLR scenario. The ranking of the adaptation strategies is reasonably robust to sensitivity testing, including with respect to different SLR scenarios.

There are many more combinations of strategies, their implementation dates and sea level rise scenarios than could be examined in this preliminary application of ROA. For example it has been suggested that a viable adaptation strategy could be moving stopbanks inland with associated changes in agricultural productivity. We do not have the detailed data to constrain the number of combinations to something that is both manageable and based on consultation with the community involved.

Finally we stress that our analysis is based purely on economic costs and avoided losses. Other than including the monetised value of wetland benefits it does not consider the social, cultural or environmental aspects of adverse extreme events associated with climate change and rising sea levels. Augmenting ROA with other techniques such multicriteria analysis would enable such effects to be better integrated into a more comprehensive evaluation framework. That might also enable distributional effects to be assessed.

We recognise that analysis frameworks such as CBA and ROA do not adequately capture sociocultural considerations like the effects of attachment to place amongst Māori communities. Such economic assessments may even be inappropriate. All economics can offer is to demonstrate that allowing for sociocultural considerations may not be costless.

4. Limitations

Although limitations to the foregoing analysis have been noted in various places above, we restate them explicitly here. Essentially there are three types of limitations; data, coverage and methodology, although they are not totally independent.

Data limitations apply to:

- The timing of projections of the rate of SLR and the frequency of adverse inundation events.
- Estimates of the value of production and assets at risk of future SLR and inundation.
- Estimates of the value of eco-system services provided by wetlands.
- Estimates of the costs of different strategies to address future SLR and inundation.
- Imprecise association between the protection each property receives and any particular aspect of the stopbank and drainage system.

Coverage of the analysis excludes the following:

- The effects of slowly rising groundwater and salinisation.
- Distributional effects – potential exposure to loss and to the cost of adaptation, related to land ownership.

Application of the ROA methodology is limited by:

- Adaptation strategies being too broad. Ideally ROA should be preceded by comprehensive community consultation that leads to more refined adaptation strategies.
- However, even then, analysis frameworks such as ROA and CBA do not adequately capture sociocultural considerations. At best they can be useful, at worst they may be inappropriate.

Appendix A: Default Values and Assumptions

All values and assumptions are open to improvement. Data is from various sources as listed in the Reference section.

Drainage infrastructure

Item	Quantity	Unit	Value
Floodgates etc	5	No.	
Pump stations	9	No.	
Stopbanks	69	km	≈$47m
Drains and canals	99	km	
Riverbank protection	7.5	km	
Total ORDC			$70.85m

Roads (including driveways)

	Value	Unit
Total length exposed	286	km
Capital cost per km (rural)	1.1	$m/km
Total cost	315	$m

Land and Dwellings (2020 approximate)

Item	Value	Unit
Max no. dwellings/buildings exposed	456	No.
Total value	182	$m
Other exposed lands (excl farming)	315	$m

Agriculture (dairying)

Item	Value	Unit
Farm area exposed (approx)	4181	ha
MS price	7.00	$/kg MS
Value added (970kg MS/ha, 50% VA)*	3400	$m/ha

* *Dairy Statistics*

Wetland ecosystem services

Item	Value	Unit
Benefit of ecosystem services	27,600	$/ha
Cost of restoration	15,000	$/ha
Maintenance cost	200	$/ha/yr

Appendix B: Discount Rate Theory

There are two fundamental properties of discount rates that are relevant to investment in adaptation to sea level and its related risks:

1. If a project delivers returns that can be reinvested at the same rate and risk profile as the project itself, the cost of capital is an appropriate discount rate. The rate should incorporate a market based risk premium, as set out in the Capital Asset Pricing Model (Treasury, 2008). Treasury's current discount rate for infrastructure projects is currently 5.0%, although it has previously been considerably higher.[10]
2. If the capital cost of the project does not truly represent the opportunity cost of that capital in other uses, a social discount rate is likely to be more appropriate.

The cost of capital is equal to the social opportunity cost of investment if a particular project displaces other investment that would have earned a rate of return. However, in the case of investment adaptation to climate change this equivalence is unlikely, especially if property rates or other 'user pays' levies are higher than they would otherwise be. Most of the opportunity cost of this funding is likely to be in the form of lower private consumption, not lower (private) investment.

In that case the cost of capital is not the appropriate discount rate to use for adaptation projects, or at least it should be substantially reduced towards something like the social rate of time preference (SRTP), which is appropriate when the opportunity cost is lower consumption. The SRTP is usually expressed as:

$$r = d + \varepsilon . g$$

r is the social rate of time preference

d is the rate at which future consumption is discounted over current consumption

g is the annual growth of consumption per capita

ε is the elasticity of the marginal utility of consumption

The variable d is frequently further disaggregated into two components:

$$d = \rho + C$$

ρ is the pure rate of time preference

C is the risk of a catastrophe which severely disrupts life on earth. See for example Stern et al (2006) in connection with climate change.

There is much debate on the values of these variables, but the debate is beyond the ambit of this paper. The interested reader is referred to Parker (2009), who suggests that a reasonable value of the SRTP for New Zealand is around 3.0% - 4.0%.

[10] See http://www.treasury.govt.nz/publications/guidance/planning/costbenefitanalysis/currentdiscountrates

Appendix C: Value of Delay

The example below is purely illustrative. The numbers are not related to the study area.

Once only decision

The matrix below shows discounted total costs (expected economic loss plus the cost of investment in flood protection) for two climate scenarios (simply with and without) and two adaptation strategies. There are four scenario-strategy combinations:

1. No climate change and invest in Strategy A
2. No climate change and invest Strategy B
3. Climate change and invest Strategy A
4. Climate change and invest Strategy B.

Table C1: Discounted Cost plus Loss

Action	No climate change	Climate Change
Strategy A	[1] $110m	[3] $186m
Strategy B	[2] $136m	[4] $154m

The two scenarios on the leading diagonal in Table C1 (1 and 4) are optimal in the sense that a correct decision is made. Scenario 2 is a Type I error with a cost penalty of $26m in over-investment, while Scenario 3 is a Type II error with a loss penalty of $32m from under-investment in flood protection.

For the given climate change scenario and its estimated economic loss, at what point (p) do the statistically expected total discounted costs of Strategies A and B coincide? That is:

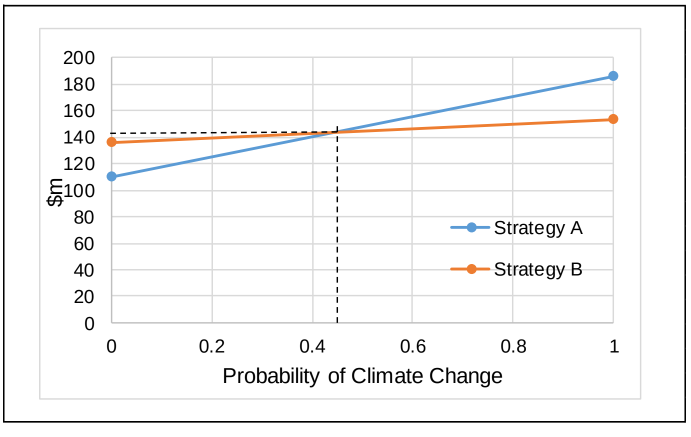
$$E(A) = 110(1-p) + 186p$$

Similarly the expected total discounted cost of Strategy B, E(B) is:

$$E(B) = 136(1-p) + 154p$$

These two equations yield the same solution at p=44.1%. So for p in excess of this value Strategy B should be pursued; otherwise Strategy A is preferred. See Figure C1.

Figure C1: Adaptation Strategies



Value of delay

However, the above is all based on the assumption that a decision is made only once to pursue a single strategy at the start of the planning period. When we know or suspect that the risk of SLR and adverse events are changing, is there value in pursuing Strategy A initially and delaying a decision to upgrade to Strategy B until some sort of trigger (such as the number of AEP=10% events, which are less serious, in a given time period) is reached?

For illustrative purposes we assume that Strategy A is implemented at the start of the period and that a review is triggered in 2055, at which point either Strategy B is implemented or nothing extra is done – until the next policy trigger point if there is one. See Figure C2 in which the Do nothing strategy is assumed to expire in the near term, whereas Strategies A and B can continue indefinitely. Likewise for a strategy in which A is adopted initially, with a switch to B at some point in the future.

As before, consider a probability (p). For what value of p does the expected cost of delay E(delay) equal the cost of proceeding with Strategy B at the start?

The calculations in Table C2 show that the expected discounted cost of pursuing Strategy A at the start of the planning period and then implementing Strategy B in 2055 is $166m.

Table C2: Expected Loss and Cost of Adaptation Strategies

	No Climate Change				Climate Change					
	Strategy A		Strategy B		Strategy A		Strategy B		Delay: A then B	
	Loss ($m)	Invest ($m)	Loss ($m)	Invest ($m)	Loss ($m)	Invest ($m)	Loss ($m)	Invest ($m)	Loss ($m)	Invest ($m)
2025	3.3	96.3	0.5	142.8	3.3	96.3	0.5	142.8	3.3	96.3
2030	3.3		0.5		5.7		1.1		5.7	
2035	3.3		0.5		8.0		1.6		8.0	
2040	3.3		0.5		10.4		2.2		10.4	
2045	3.3		0.5		12.7		2.7		12.7	
2050	3.3		0.5		15.1		3.3		15.1	
2055	3.3		0.5		17.4		3.8		17.4	66.2
2060	3.3		0.5		19.8		4.4		4.4	
2065	3.3		0.5		22.1		4.9		4.9	
2070	3.3		0.5		24.5		5.5		5.5	
2075	3.3		0.5		26.8		6.0		6.0	
2080	3.3		0.5		29.2		6.6		6.6	
2085	3.3		0.5		31.5		7.1		7.1	
2090	3.3		0.5		33.9		7.7		7.7	
2095	3.3		0.5		36.2		8.2		8.2	
2100	3.3		0.5		38.6		8.8		8.8	
2105	3.3		0.5		40.9		9.3		9.3	
2110	3.3		0.5		43.3		9.9		9.9	
2115	3.3		0.5		43.3		9.9		9.9	
2120	3.3		0.5		43.3		9.9		9.9	
Totals	20.9	89.3	3.5	132.5	96.8	89.5	21.2	132.5	51.9	114.3
discounted		110.2		135.9		186.2		153.6		166.2

Hence the equation we need to solve is:

E(delay) = 110(1-p) + 166p = 154

Table C3 shows the expected cost of delay for various values of p in the above equation. At p=77.5% the expected cost of delay at $154m is the same as the expected value of pursuing Strategy B at the start of the period.

Figure C2: Strategy Paths

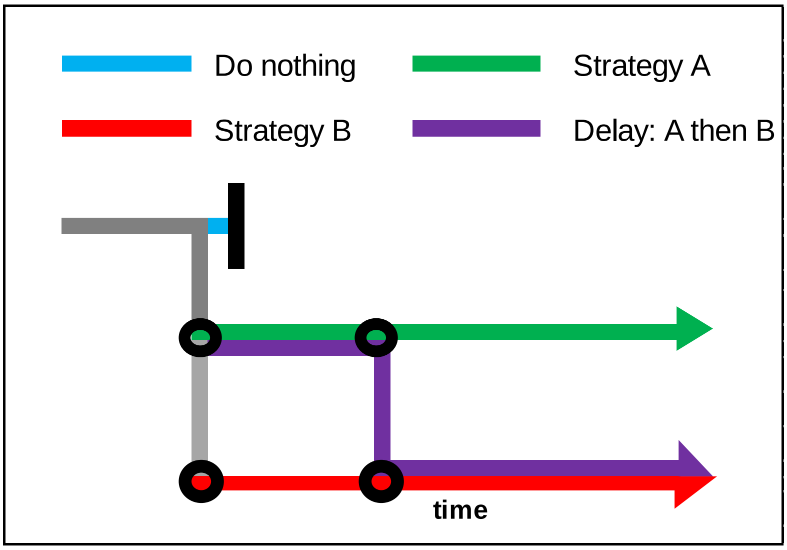


Table C3: Expected Costs under Uncertainty

Probability of climate change	Expected cost with delay ($m)
0.0%	110
20.0%	121
50.0%	138
77.5%	154
80.0%	155
100.0%	166

Therefore if the probability of the climate change (say some given rate of SLR) is thought to be more than 77.5%, Strategy B should be pursued immediately. Otherwise it should be delayed.

It is revealing to note that the cut-off probability when delay is possible is 77.5%, but that if delay is not possible the cut-off probability is only 44.1%. This difference is as expected; incorporating option values will usually lead to a more cautious adaptation strategy than relying on standard cost benefit analysis.

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