Enabling Coastal Adaptation

Economic Evaluation Methodologies to Support Proactive Adaptation to Sea-level Rise

December 2021

Adolf Stroombergen & Judy Lawrence

Coastal

RESILIENCE TO NATURE'S CHALLENGES
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Economic Evaluation Methodologies to Support Proactive Adaptation to Sea-Level Rise

December 2021

Adolf Stroombergen *Infometrics,* Wellington, New Zealand

Judy Lawrence *PSConsulting Ltd*

We propose guidance for the use of appropriate economic evaluation tools to support proactive adaptation to Sea-Level Rise, focussing on how Real Options Analysis (ROA) can augment and complement the Dynamic Adaptive Policy Pathways approach. We develop a basic ROA tool that could be used in a wide variety of situations.

Cite as: Adolf Stroombergen[1], Judy Lawrence[2] (2021). *Economic evaluation methodologies to support proactive adaptation to sea-level rise*. Wellington, New Zealand: Resilience to Nature's Challenges National Science Challenge - Enabling Coastal Adaptation programme.

[1] Infometrics
[2] PSConsulting

Contents

1. Introduction

This report was prepared as part of the *Coastal Environment Programme* within the Resilience to Nature's Challenges National Science Challenge ("Resilience Science Challenge") funded by MBIE. It contributes to *Pillar 3 Coastal Adaptation: Enabling proactive coastal adaptation in a changing climate risk environment.* It builds on and should be read alongside the 2017 national *Coastal Hazards and Climate Guidance for Local Government* [3], by elaborating how to apply decision tools under uncertainty and changing risk, in particular, Real Options Analysis (ROA). It thus informs the policy and practitioner community when advising on risk reduction in a changing climate.

Background to Real Options Analysis

Investment in coastal and fluvial (river) flood risk management measures can be expensive, but not investing in them can also be expensive and cumulative. This applies to the full range of 'protect', 'accommodate' advance and 'retreat' options available to those making adaptation decisions under enhanced climate risk from extreme events and ongoing sea-level rise (SLR). Balancing the cost of such investment and their timing against the value of the reduction in economic losses from the consequences, is not an easy calculation in the context of uncertain impacts of climate change that could substantially alter flood frequency and magnitude, and the rate of SLR.

There is a growing discourse around methods that are suited to addressing changing risk and uncertainties, including for large infrastructure projects under a changing climate (see for example Marchau et al, 2019, especially Ch 15). Also, the New Zealand *Coastal Hazards and Climate Change, Guidance for Local Government*, (Ministry for the Environment 2017) (Guidance) (see Appendix A) presents a range of decision support tools to analyse uncertainty and different strategies to adaptively deal with the effects of SLR.

Of the various tools listed in the Guidance, our interest is in Real Options Analysis (ROA) and Dynamic Adaptive Pathways Planning (DAPP). They are summarised as:

- ROA: Allows economic analysis and evaluation of future-option value and the economic benefit of flexibility. This aligns with Policy 27 (NZ Coastal Policy Statement) of "*identifying the consequences of potential strategic options relative to the option of 'do-nothing'*".
- DAPP: Anticipatory, scenario-based assessment tool to assess options' failure conditions and 'use-by' date, robustness and flexibility using signals (warnings) and triggers (decision points), to enable uncertainty and change to be managed without locking in path dependent outcomes (maladaptation).

As may be inferred from these descriptions, the two tools can be used together, although this is not to imply that the other tools mentioned in the Guidance are less complementary. In particular, traditional Cost Benefit Analysis is a subset of ROA, as is Cost Effectiveness Analysis. Multi-Criteria Analysis can be used with ROA to value assets and benefits that are difficult to quantify in monetary terms (Lawrence et al 2019). Real Options Analysis can usefully be applied within a Robust Decision-Making framework or an Info-Gap approach (Hall et al 2012). Portfolio Analysis can be applied to any set of ROA results.

[3] Chapters 6 & 9 and Figure 44 of the Guidance

ROA and DAPP

Papers on the use of ROA to analyse adaptation responses to SLR have become common in recent years, but almost all of the reported analyses rely on the user supplying assumptions about the probability of SLR scenarios (for example Buurman and Babovic, 2016). This is a challenge as SLR scenarios relate to not only climate change scenarios (driven by different greenhouse-gas emissions), of which there are many – but many more projections of their downscaled effects through the atmosphere, ocean, and cryosphere system (besides local factors like vertical land movement) (Levy et al 2020). It is also unfortunate as it has led many researchers (eg. De Neufville & Smet, 2019; Dittrick et al, 2019; Kwakkel, 2020) to underestimate what ROA can do and how it may be used, particularly in relation to DAPP.

In contrast our approach turns the usual question around. Instead of asking what adaptation strategy delivers the highest expected net benefit for a given (assumed) time profile of SLR, we ask how robust our strategies are to different probabilities of SLR. This approach is not new; it was suggested by Yohe (1991), albeit not within an ROA context.

Figure 1 presents a schematic of how decision support tools such as ROA complement DAPP. The core of, and essential to, the decision-making process for ongoing SLR, is the DAPP approach. This identifies and assesses options and sets out alternative adaptation pathways that meet the desired performance objective (over the planning timeframe) for addressing SLR (including managed retreat), the feasibility of options within pathways, under what conditions they will fail and how switching between pathways or the next option in the preferred pathway could occur once signals and decision triggers alert the responsible manager. Without the DAPP framework the risk of a maladaptive response to SLR is increased (ie too much or too little adaptation).

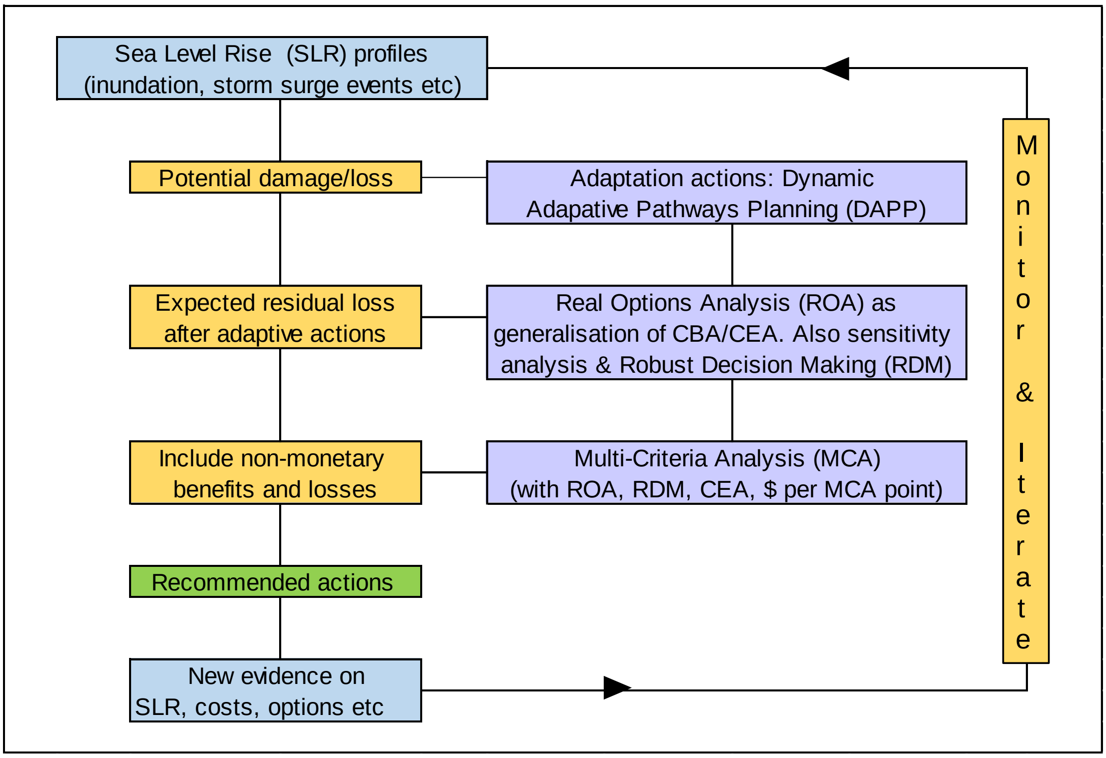


Figure 1: Decision Support Tools Applied to SLR Risks

Real Options Analysis provides a way to quantitatively analyse in monetary terms the various DAPP pathways. The reliability of the results is tested by sensitivity analysis around key variables (such as the rate of SLR or protection costs, including operational and maintenance costs) to enable a range of scenarios to be assessed, such as within a Robust Decision Making (RDM) framework.

Non-monetary benefits and disbenefits are better suited to Multi-Criteria Analysis (MCA). The results from the application of ROA/RDM could be one of the criteria in the MCA. Another approach, however, is to exclude all monetary values from the MCA and compare the total score for each strategy with its investment cost – that is excluding the expected residual loss from any SLR event and losses from nuisance and moderate events (Paulik et al, 2021).

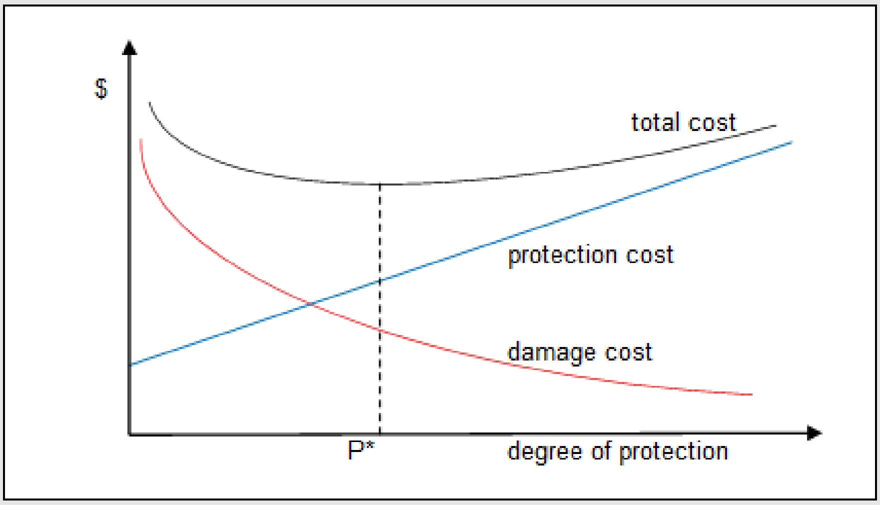
Excluding the expected residual loss means that it is possible to examine the efficiency or value for money of each pathway, expressed as the ratio of benefits (non-monetary) to costs (monetary). For example in developing the coastal hazards strategy for Hawke's Bay[4] the list of MCA components included the core requirement that any strategy should not only manage the risk of storm surge and coastal erosion, but also the impacts of each strategy on natural coastal ecosystems, cultural sites and the welfare of future generations, As avoiding or minimising the risk of damage from SLR is generally the major component in the MCA score, it would be illogical to also include that benefit (in the form of the residual expected loss) as a cost as it would amount to double counting.

Recommended actions should follow from the combined results of ROA, RDM and MCA, or whatever technique is appropriate.

Applying ROA requires a reasonable understanding of risk, probability, and uncertainty, and how to express a given problem in terms amenable to the DAPP/ROA approach. In the next section we present the basic concepts and propose a model that can be applied to a wide variety of situations by users with minimal familiarity with ROA (see Box 1).

Box 1: A note on residual loss

With the exception of pre-emptive retreat, it is highly likely that every protection option carries some residual risk of damage or loss, 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. It is likely 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 degree of protection the lower the expected damage cost, but the higher the cost of protection. Expenditure to enhance protection beyond point P* is inefficient, as P* represent the minimum total cost, at which the marginal cost of protection equals the marginal reduction in damage cost. Thus some residual expected loss remains.

[4] Accessed at https://www.hbcoast.co.nz/

ROA Shortcomings

Like any technique for evaluating risk, ROA has some disadvantages leading some researchers (eg Kwakkel 2020) to shun its application to the economic evaluation of flexible SLR adaptation strategies. Common criticisms about ROA include:

1. *It relies on a discount rate*. Any form of CBA relies on a discount rate. Although the choice is particularly problematic in the context of climate change (Stern 2007, Weitzman 2009) the issue of how to compare costs and benefits over time can be addressed with sensitivity testing. In any case, even though SLR is a very long-term problem, investment in adaptation frequently involves actions that may nonetheless be economic in the short term. Furthermore, to paraphrase an earlier point, the question is not what discount rate should be used, but what would the discount rate have to be to affect one's chosen strategy (Hall et al 2019)[5]

2. *Also like CBA it aggregates welfare over individuals which is known to be of dubious theoretical validity* (Arrow, 1950). There are ways to ameliorate this problem, although it can never be perfectly solved.

3. *ROA cannot handle strategy dependencies*. This is precisely what ROA can do. For example if the details of a strategy C depend on which of two prior strategies A and B are implemented, the dependency could be evaluated as the expected value of C given A versus the expected value of C given B.

4. *Multiple uncertainties (eg frequency of storms, pace of SLR and future value of assets) cannot be incorporated in ROA*. Multiple uncertainties can be incorporated into ROA but dealing with multiple types of uncertainty is always complex, especially with multi-modal probability distributions. See for example Martin and Pindyck (2015). Some types of uncertainty that typically feature in ROA are listed in Box 2.

5. *Not all scenarios, nor the ways options can be used within scenarios, are known in advance.* This is not unique to ROA and is mitigated by using it within a DAPP approach, which entails a re-evaluation of the options and scenarios whenever a trigger point is reached.

6. *All ROA analysis relies on exogenous assumptions about the probability of each SLR scenario occurring* (eg Dittrich 2019). In many applications of ROA this is indeed the approach taken, but as shown below that approach is unnecessary and probably not helpful. The approach used here uses probability differently from most applications, by asking how robust strategies are to different scenario probabilities, not dissimilar to stress testing for financial institutions.

7. *ROA is complex and so not always worth undertaking*. This is not unique to ROA as an evaluation technique. However, we present a relatively straightforward ROA template that reduces complexity and can be applied in a wide range of contexts and especially for ongoing SLR impacts.

[5] In the context of very long-term options for addressing flood risk in London, Hall et al do not discount at all, arguing that it suppresses the costs and benefits over the various options. Although it is useful to present the numbers in this manner, we suggest that not discounting will distort intertemporal resource allocation.

Box 2: Types of uncertainty

Many types of uncertainty are relevant to ROA, including:

- The relationship between emissions and global warming
- The impacts of global warming eg SLR, storm size & frequency, compounding flood hazards (coastal-river-groundwater)
- Non-climate related variability in storms, local/regional vertical land movement rates etc
- The regional distribution of those impacts
- The value of assets at risk (taking into account exposure and vulnerability)
- Population change
- Change in societal attitudes, especially as adverse events become more common
- Economic development (growth or decline)
- Technological developments
- The cost of adaptation measures, including managed retreat

Rohmer et al. (2019) classify uncertainty into two types:

1. Aleatory: stochastic or statistical uncertainty that can be described by a probability distribution, such as for the toss of a coin. The uncertainty is irreducible.

2. Epistemic: uncertainty due to a lack of knowledge or lack of collective policy action (where deliberate action can reduce subsequent uncertainty margins, such as in the case of global emissions); the distribution of events is unknown but may become known with time or with research. The uncertainty is theoretically reducible, although more knowledge does not always reduce uncertainty. This type of uncertainty is also known as 'deep uncertainty'. See Lempert et al (2003).

With respect to sea-level rise we know it will keep rising for centuries from the greenhouse gas emissions already emitted into the atmosphere and the lag-time inherent in the oceans as they warm. However, we do not know and cannot know before adaptation action is necessary exactly when and by how much the seas will rise beyond around mid-century. This means that deep uncertainty tools that address the path dependency of decisions taken today for assets that will persist for at least 100 years, are needed to address coastal hazard risk.

2. Towards an ROA Tool

Cut-off probability

Consider a decision on whether to buy an umbrella if there is possibility of rain. If your clothes and accessories get wet, they will cost $500 to clean or replace. An umbrella costs $100 and would limit the damage to $100, implying a cost of $200 in total. Should you buy an umbrella or not?

The situation may be simply expressed in the following table.

Table 1: Total Cost plus Loss

Action	No rain	Rain
Do nothing	[1] $0	[2] $500
Buy umbrella	[3] $100	[4] $200

Null Hypothesis: No rain.

- [2] is a Type II error (accept a false null hypotheses)
- [3] is a Type I error (reject a true null hypothesis)

Figure 2 presents a diagrammatic representation. The two lines intersect at a probability of rain of 25%. This is the cut-off probability of rain, above which it is a better bet to buy an umbrella than to not buy an umbrella. The decision does not require an assessment of the precise probability of rain, merely a judgement as to whether it is more or less than 25%.

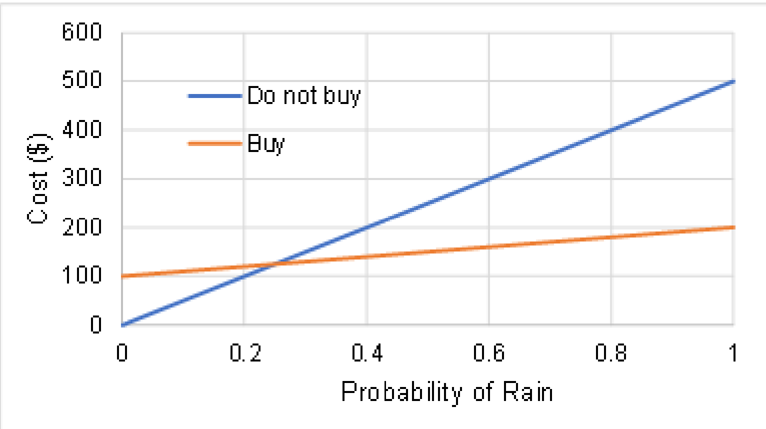


Figure 2: Cut-off Probability

> *In essence the question is not how likely is a given rain scenario, but how likely does that scenario need to be to affect one's chosen strategy?*

The cut-off probability is the risk-neutral probability at which the statistically expected cost from over-investing in protection (i.e. spending more than turns out to be required because the expected adverse events did not materialise) is the same as the statistically expected cost of damage from under-investing in protection (because the adverse event did occur, and damage turns out to be worse than expected). The same idea is used in an application of RDM in Sriver et al (2018).

Delay

There may be value in delaying a decision on buying an umbrella. For example, an official weather forecast may influence the decision, reducing the likelihood of a wrong decision. Waiting for more information could be worth $100 or $300 depending on the decision and the actual outcome.

Consider a scenario in which it takes some time for more information to become known and that there is another course of action available – a jacket which provides only partial protection. Assume the cost of the jacket is $50 and that the residual damage/loss is $250.

Now the cut-off probability compared to doing nothing falls to 20%, and compared to buying an umbrella, it is 33%. What does that mean? If the probability of rain is expected to be more than 20%, the jacket should be bought, but if the probability of rain is expected to be more than 33%, the umbrella should be bought.

Hence the possibility of a cheaper, but less effective protection strategy has raised the cut-off probability required to justify adopting the more expensive strategy immediately.

If the decision is not to buy an umbrella, but to buy a jacket, and it does not rain, the expected benefit is $50, but if it does rain the expected loss is $100. Symmetrically, if the decision is to buy an umbrella rather than a jacket, and it does not rain, the expected cost is $50, but if it does rain the expected benefit is $100.

The ratio of these two amounts is 1/3 to 2/3, confirming that if the perceived probability of rain is more than 33%, the umbrella should be bought. The option to delay buying an umbrella, given that one can buy a jacket, is valuable up to a probability of rain of 33%.

As used here ROA is more a generalisation of Cost Effectiveness Analysis than Cost Benefit Analysis as the value of the benefit of not getting wet can be ignored – we considered only the residual loss (disbenefit) associated with getting wet.

The above example ignores the actual timing of decisions, referring only to waiting. In our more realistic example below of strategies to address SLR, the timing of events and adaptation decisions becomes very important, so the use of a discount rate is advisable to validate comparative choices that have different time profiles of costs and benefits.

Two situations that could arise are where:

1. An area (unexpectedly) reaches an adaptation threshold or tipping point such that it is nigh certain that a prompt decision about adaptation is required.
2. With sea level rise being inexorable the planning horizon, even if it's 100 years, may be too short, leading to suboptimal adaptation.

For (1) ROA should reveal a cut-off probability value close to zero for at least one adaptation strategy, implying immediate implementation. For (2) the first step is to extend the planning period used in the ROA. However, the analysis may nonetheless show that some temporary adaptation is efficient in the meantime, even though the eventual choice may be managed retreat. The greater the uncertainty about the rate of sea level rise and the higher the discount rate, the more likely it is that temporary adaption measures make economic sense. Few assets endure for 100 years without continual maintenance, so flexible protection options than can be adapted to changing risk – even something as simple as more or less maintenance – could be sound short-term solutions.

ROA Tools

Dittrich et al (2019) illustrate an 'accessible' use of ROA applied to afforestation as a flood management measure in Scotland. Their methodology uses backward induction to find the protection strategy with the least currently expected total cost (investment plus maintenance plus damage plus opportunity cost of land use) to get to the desired end outcome. That is, the decision in period t is affected by the options available and the possible weather event (eg rainfall) in period t+1, and so on. The method has five steps:

1. Establish a decision tree with attached transition probabilities of weather events (derived from a UK climate model).
2. Determine physical effects with and without adaptation
3. Damage analysis with and without measures
4. Cost of adaptation measures
5. Backward induction to determine the least cost action

The method has much in common with an approach used to assess policies for adapting to SLR risk in Hawke's Bay (Lawrence et al 2017) but has two key differences in steps 1 and 5. Steps 2-4 are essentially the same.

- In step 1, rather than a decision tree with probabilities of weather events, we use a full DAPP diagram which shows feasible adaptation pathways and trigger/decision points. It does not need explicit probabilities of future climate-ocean scenarios or damage events.
- In step 5, for some given (non-BAU) climate scenario and its associated profile of SLR and hazard events, we calculate the cut-off probabilities; action under which a pathway with delay is preferable to one with no or less delay. We then select a favoured pathway after identifying several that will meet the objectives, starting with the first actions (that enable options to be left open) and identify signals (early warnings) and triggers (decision points) and monitor them, review periodically and if the adaptation threshold is pending (including an allowance for implementation lag time) we shift pathways (noting that each permutation of options is considered to be a pathway).
- Then we test the sensitivity of the cut-off probabilities to different assumptions about (notably) costs and benefits, the discount rate, and the evolution of different hazard profiles. For instance does an increase in the frequency of present-day AEP=1% events under BAU alter the cut-off probabilities by an amount sufficient to justify a change to another pathway?

The approach used by Dittrich et al. (2019) does not seem easily usable by local government in New Zealand, as it requires an understanding of backward induction as well as explicit assumptions about the probability of weather events.

Guthrie (2019) presents what he describes as a 'simplified approach' to incorporating ROA into analysing evaluating investment in adaptation to climate change. In Guthrie's model the true climate regime is unknown, but the probability of adverse weather events is known for each possible climate regime. As the frequency of adverse weather events changes, the probability of one of the possible regimes being the true regime increases progressively, with the probabilities for the other regimes approaching zero.

The cost of protection (a broad term presumably encompassing accommodation and retreat) is the same for each adverse weather event, as is the cost of damage from each event, albeit lower with protection than without protection. This implies that the different frequency of adverse events is the only factor that causes damage costs to differ between climate regimes, which is implausible in the real world. In a later paper Guthrie (2021) allows for the introduction of temporary adaptation measures that, although not necessarily cost-effective in their own right, provide a valuable option to defer investment in expensive, perhaps irreversible adaptation measures.

That approach is closer to the application of ROA to SLR risk in Hawke's Bay which recognised that for any given (but uncertain) climate change regime, the frequency and severity of adverse events (storms, floods, erosion and SLR) increase over time and thus the cost of the protection options also rises over time. Hence the merit in valuing an option to delay investment in expensive adaptation measures. The Hawke's Bay analysis also included some amount of expected residual damage.

The question of which of numerous climate change regimes will prevail, or how quickly the climate may change can be addressed via sensitivity analysis.

It should be stressed that Guthrie's model can be made far more general. So too could the model that was used for Hawke's Bay. Guthrie suggests for example, that a transition matrix for the probabilities of the climate changing from one regime to another could be included. However, such probabilities are even more difficult to determine than the probability of any single climate change scenario and its associated damage distribution – precisely what we try to avoid with our modified ROA.

The model presented by Guthrie is more complex than the Hawke's Bay model but, as in the approach by Dittrich et al, is simultaneously less useful as it requires explicit assumptions about the probability of either weather events or climate regimes. SLR has a widening cone of uncertainty as one looks further into the future, so incorrect assumptions about risk could increase exposure and lock in path dependency, rather than actually mitigating risk as it evolves.

In practice we have found that although a lack of analytical expertise and a dearth of good data seriously constrain what councils can typically do, the limitation that tends to be most prominent is funding. Generally, only a few scenarios can be examined with little if any budgetary scope for sensitivity analysis, application of multiple methods or implementation of ongoing monitoring of changing risk. In applied situations compromises are inevitable. However, fewer scenarios mean less robust and potentially misleading results. Accordingly, we have developed a simple tool for applying ROA for considering the effect of uncertainty and changing risk over time.

A Simple Tool for Applying ROA

Description

Practitioners in the real world need tools that they can apply simply and affordably to complex problems and in doing so have confidence that the results can satisfy their objectives without increasing risk over time. Without considerable resources it is difficult to design a model that can value in monetary terms every conceivable combination of SLR profiles, damage costs, adaptation pathways, and assets.

Accordingly, we present an example of a tool that includes the essential high-level attributes:

- A DAPP diagram that portrays each potential adaptation option and pathway, including managed retreat.

- The relative costs of adaptation actions for each pathway, which should span a time frame of at least100 years.[6]
- Specification of the likely timing or conditions under which a pathway is no longer fit for purpose (relative to objectives, values, or levels of service) at the adaptation threshold, such as when SLR reaches a certain level the severity and frequency of flooding attains some pre-agreed benchmark, for example a number of times in a given timeframe, or a coping capacity indicator.
- The associated value of residual loss for each strategy (linked to SLR, weather events etc). Residual loss could include assets, production, life years, loss, or effective/acceptable level of service etc as relevant.

In addition, any tool should be able to handle alternative assumptions about important parameters such as the discount rate and enable the timing of adaptation actions to be altered.

A pilot model is presented in the accompanying file *ROA Pilot Model.xlsx*. The example has the following features:

1. It is assumed that the on-going rise in sea level means that managed retreat (MR) is the only long-term solution to preserving asset values and levels of service, albeit that the assets may need to be re-located. Nevertheless, it may still be cost-effective to implement temporary short-term protection options and preparatory land-use planning controls on the journey to MR that incur costs before active retreat, which can take many decades to implement (Olufson, 2019).
2. We consider two temporary protection measures; a low rock revetment (LR) and a high rock revetment (HR), plus an option to build a low revetment initially and a high revetment later. The strategies are illustrated in Figure 3.
3. The low revetment is required to maintain a minimum degree of protection against coastal hazards even without significant SLR, but its degree of protection under significant SLR may be considered inadequate by the community – we make no judgment on adequacy. (Note, we use SLR as a convenient abbreviation for some expected rate of SLR and the associated coastal-storm flooding risk over some given time period. Although ROA is not concerned with particular climate change scenarios it may be useful to express SLR in relation to one or more RCP scenarios, for example RCP6.0 median projection or RCP8.5 10^{th} percentile projection).
4. The high revetment provides total protection (no residual loss) if there is no significant SLR (as under say RCP6.0) over the life of the revetment, however asset life might be defined.
5. Accelerated managed retreat is also possible, but if that strategy is pursued nothing is spent on revetments. Incorporating short term protection in this pathway is also possible but omitting it here does not lessen the generality of the example.
6. All costs include losses associated with more frequent but less severe ‘nuisance’ events that may damage roads, lead to temporary evacuations and so on.
7. Clean up costs are incurred after managed retreat, including if it is delayed.

We are interested in the following questions:

- What probability of damage from SLR (for some given SLR profile) is required to justify pursuing any of the strategies compared to the LR strategy?

[6] At least 100 years is the timeframe mandated in the New Zealand Coastal Policy Statement under the Resource Management Act and as recommended for application using the national Coastal Hazards and Climate Change Guidance for Local Government.

- Under what circumstances is there value in delaying a decision to adopt HR?
- Under what circumstances should MR be accelerated?

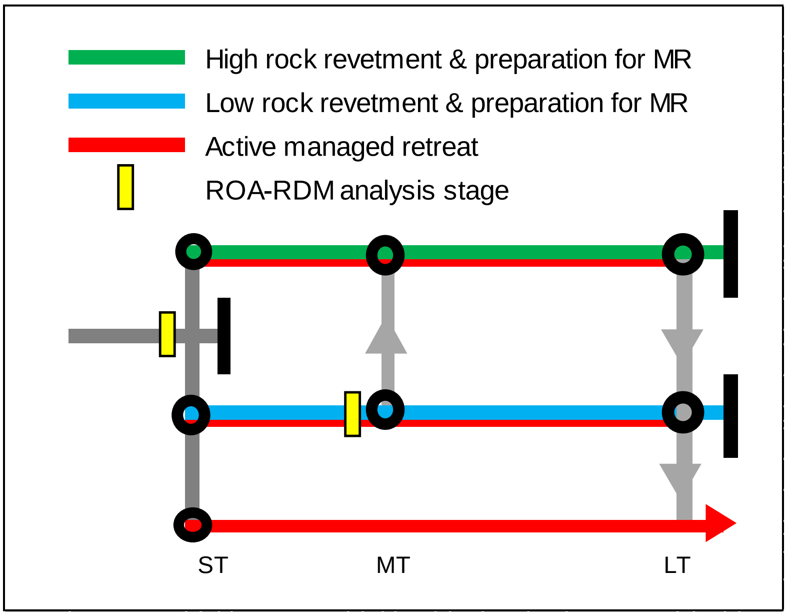


Figure 3: DAPP Diagram for Example in Tool

Results

Drawing on the output from the tool, the results are summarised below.

1. The HR strategy requires the probability of the SLR profile to exceed 60% (59.7%) for it to be preferred to LR as a once-only decision, assuming no delay option exists.
2. However, if it is possible to delay HR to around 2065, that strategy should not be pursued unless the SLR probability is considered to exceed 79%. The logic here is that if the more expensive action can be deferred, it is worthwhile waiting while monitoring changes in SLR, updates in projections, ensuing damaging/disruptive events and changes in risk tolerability, to review and justify that action. That is, the option to delay leads to a more conservative investment strategy – reiterating that all revetment strategies involve incurring preparatory costs for managed retreat.
3. The value of the option to delay (starting with LR) ranges between $-5.0m and $18.3m.
4. If the community is willing to take the chance of adopting the Delay strategy (starting with LR), provided its expected cost is not more than the expected cost of adopting HR at the outset, the cut-off probability rises to almost 84%.
5. Although all pathways lead eventually to managed retreat for this example (around 2125-2130 for the active phase), bringing MR forward by 60 years or so is not cost-effective.

Figure 4 depicts the four strategies. The accelerated MR strategy (the red line) is everywhere above the LR and the Delay-HR strategies, illustrating why it is not a cost-effective option for this example where MR is not required until near the end of the 100-year planning timeframe.

There may be reasons why a community would select a strategy that is not least cost. For example, a high rock revetment could be unsightly, restrict access to the coast, result in loss of the beach and destroy wetlands. And although residual risk (such from the revetment being breached or over-topped) is taken into account in the analysis, the community may not be risk-neutral between spending $1m to protect an asset and losing an asset worth $1m. Considering such situations, the community may prefer accelerated MR, but at what cost? The analysis shows that if accelerated MR is adopted in preference to the HR strategy, the difference in expected total cost (given SLR) is $20m. Thus the question for the community would be whether avoiding the negative effects of a high revetment are worth at least $20m. Multi Criteria Analysis could be a useful extra tool to evaluate this question, as undertaken by the Panels during the Hawke's Bay coastal strategy (Lawrence et al., 2019).

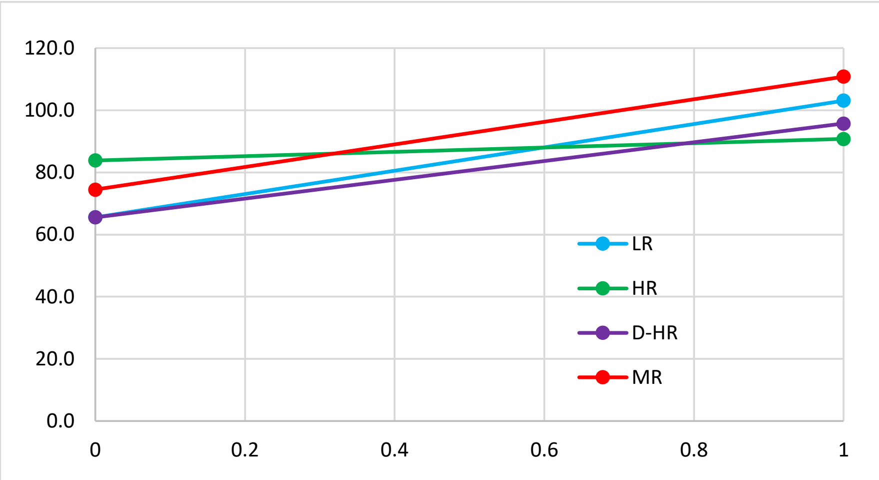


Figure 4: Cut-off Probabilities

Sensitivity analysis

The above provides a simple example of using ROA and DAPP to evaluate adaptation strategies for coastal communities to address the adverse effects of SLR and associated coastal flooding. In reality, the situation is likely to be more complex, involving issues such as:

- The timing of the decision review points. The cost of a delay increases with the number of years that the area is exposed to damaging SLR. Hence the required degree of certainty that SLR will occur as expected – needed to justify an investment – falls with exposure.
- Some adaptation strategies may be mutually exclusive, path dependent or very expensive to implement after other options are deployed.
- As noted above SLR is on an upwards trajectory. It is not solely an event (such as a storm). It evolves along a continuum of rising temperatures, rising seas and hazard risk (gradual salinisation and drainage difficulties for example). It is not on or off at a given point in time; it is ongoing for centuries (albeit more slowly if global emissions fall quickly).
- Typically, expected damage is related to time-varying annual exceedance probabilities, but the relationship and the probabilities are all subject to uncertainty (Stephens et al, 2018).

Hence a comprehensive analysis should include sensitivity testing of assumptions around the conditions/timing of managed retreat, the rate of SLR (and associated frequency of flooding) and the profile of costs. For example, what rate of SLR and thus potential economic loss would be required to adopt accelerated managed retreat? More generally, strategies must be formulated conditional on observed developments, which is fundamental to operating adaptive management approaches such as DAPP.

Another standard sensitivity test is to vary the discount rate. The above calculations have used 3%. Applying a discount rate of 1.5% leads to substantial reductions in all the cut-off probabilities. This is to be expected – a lower discount rate accords more weight to the wellbeing of future generations, raising the discounted damage costs and thereby making it easier to justify pursuing more costly adaptation measures earlier. See Figure 5.

1. The value of the Delay (LR to HR) option ranges from $-16.4m to $16.3m and is preferred to HR for any SLR probability less than 50%. This is effectively a 50/50 'coin toss' call so RDM would be useful here (e.g. Sriver et al., 2018) as it could produce an envelope for the sensitivity of the Delay versus HR strategies to different combinations of changeover dates, costs and discount rates.

2. Interestingly, accelerated MR now has a lower expected cost than the LR strategy if the probability of SLR is considered to be more than 60%.

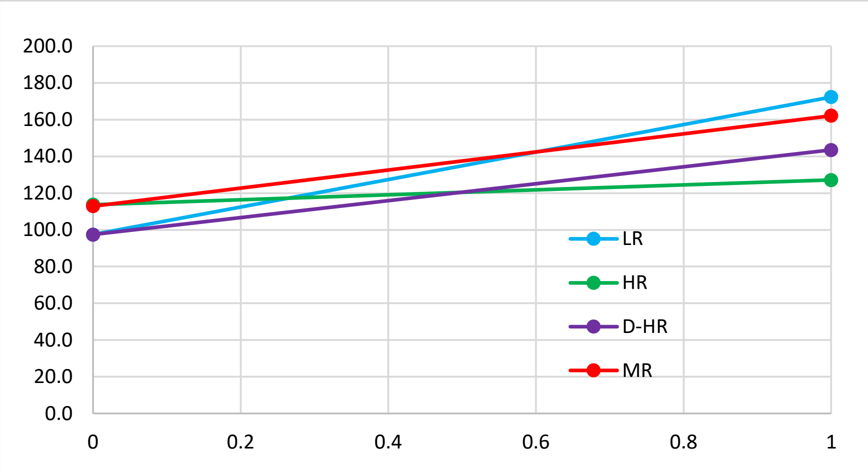


Figure 5: Cut-off Probabilities for Halved Discount Rate

One might ask why ROA seems to be concerned only with the value of flexible options to defer investing in particular adaptation strategies (including MR) in case SLR is slower than expected, rather than also considering the possibility that SLR might be faster than expected.

The fundamental point of ROA is that it places a value (which could be negative) on delay because more time can potentially bring more information from monitoring and updated projections on the changing risk – therefore less uncertainty down the track than we have today. If one is concerned about accelerated SLR scenarios (conveniently parameterised in the form of say median RCP8.5 instead of median RCP6.0), such scenarios should be assessed with RDM/sensitivity analysis, in which case ROA is concerned with valuing delay if those more rapid SLR scenarios eventuate more slowly than expected. Other factors being equal, accelerated SLR will entail a higher residual loss at any point in time, thereby enhancing the case for earlier and/or more expensive adaption strategies. Hence the value of delay is likely to be lower.

At the theoretical limit, 100% certainty about a particular SLR damage scenario means that protection or adaptation could be designed to perfectly match the desired level of residual loss, in which case the delay option would have no value. Indeed ROA would be unnecessary.

In conclusion, ROA is a useful tool to assess the impact of waiting for more information about the risk of damage. On the one hand waiting can reduce the likelihood of investing too much or too soon in adaptation measures that are extremely costly to reverse. On the other hand waiting can increase the costs of adaptation by locking in costly measures that increase exposure to sea level rise, such as seawalls that convey 'safety' for further development. ROA can be useful in these circumstances as it compares the cost of such measures with the increased risk of damage from less protection in the meantime. Using ROA as a tool within DAPP enables the risks of lock-in to be assessed in the preparation of adaptive plans for addressing progressive sea-level rise.

Technical notes

Residual Loss

The total cost of a protection strategy includes the cost of the protective measures themselves (capital and maintenance) and any expected residual loss. It is very unlikely that any protective measure, except managed retreat, can reduce residual loss to zero.

We assume that regulations or other measures prevent additional development behind the protective structure. Then residual loss will decline as protection is increased. If additional development is not prevented it would be mathematically possible for the residual loss to rise as protection is increased. Then an ROA solution may or may not exist. One solution might be to do nothing and let existing assets succumb to SLR.

We have found that estimating the value of residual loss under different risk and adaptation scenarios is more straightforward than estimating the value of protected assets. For instance, one adaptation strategy may leave an expected residual loss of $10m, while another leaves a residual loss of $20m. These numbers are generally easier to estimate than comparing $90m of protected assets and $80m of protected assets respectively. The differences in residual loss capture the differences between strategies with regard to their degree of protection. Differences in residual loss equal differences in asset value saved.

Of course at some point one does have to consider whether any adaptation investment is worthwhile, especially when one of the options is managed retreat (Siders et al 2019; Lawrence et al., 2020).

We assume that the assets or parts of assets that are not included in the value of residual loss are not exposed to risk. This includes assets such as cultural sites and recreation spaces that may be difficult to monetise. Consequently, they can be ignored in the ROA unless they constitute a component of residual loss. They should of course be included in multi-criteria analysis.

Asset Values

It may seem odd to discount the (real) value of an asset as the current value of an asset is essentially the discounted value – measured this year – of the future flow of services it will provide. A house provides the services of shelter for example. From the perspective of the current year though, next year's value of the house is a little less, (other factors equal) reflecting the rate at which future consumption is discounted over current consumption – notably the social rate of time preference. This rate is theoretically more appropriate and generally lower than the cost of capital that is used in most cost-benefit analysis.

One of the standard assumptions in applying CBA/ROA to investment in protection from SLR is that the value of the assets at risk does not change, including if they are shifted to a new location. This is a neutral assumption, avoiding the possibility that asset values could rise if investment in protection is perceived to reduce the risk of damage from SLR (with less residual risk), and also avoiding the opposite scenario in which assets gradually depreciate because there is insufficient certainty about the future degree of protection.

Nevertheless, the simplified ROA model can be run under the assumption that the residual loss declines in accordance with some prescribed depreciation rate. However, using this approach is really only valid if in the 'do-nothing' option, the assets were not going to be maintained – for example if an industrial plant was being phased out due to technological obsolescence or new regulations about discharges.

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Appendix A: Decision Support Tools

The figure and table below are taken from MfE (2017) *Coastal Hazards and Climate Change, Guidance for Local Government*. Tools in light-blue colour relate to more traditional approaches and those coloured green to newer approaches to decision-making under uncertainty.

Range of decision support tools

DECISION SUPPORT TOOLS	APPROACH	SUMMARY
Traditional decision support	Multi-criteria analysis	Allows consideration of both quantitative and qualitative data in the scoring and weighting (ranking) of alternative options
Uncertainty decision support	Dynamic adaptive policy pathways planning	Anticipatory, scenario-based to assess options 'use-by' date, robustness, flexibility and monitor trigger/decision point
	Iterative risk-based adaptive planning	Uses iterative framework of monitoring, research, evaluation and learning to improve future strategies
Traditional economic decision support	Cost-benefit analysis	Values all costs and benefits to society of all options, and estimates the net benefits/costs in monetary terms
	Cost-effectiveness analysis	Compares costs against effectiveness (monetary and non-monetary) to rank, then cost-curves for targets/resources
Economic decision-making under uncertainty	Real options analysis	Allows economic analysis of future option value and economic benefit of waiting/information/flexibility
	Robust decision-making	Identifies robust (rather than optimal) decisions under deep uncertainty, by testing large numbers of scenarios
	Portfolio analysis	Economic analysis of optimal portfolio of options by trade-off between return (net present value) and uncertainty (variance)

Applicability of different decision support tools

Cost–benefit analysis (CBA)	Short-term assessment, particularly for market sectors.	Most useful when climate risk probabilities known. Climate sensitivity small compared with total costs and benefits. Good data is needed for major cost–benefit components.	Low- and no-regret option appraisal (short term). As a decision support tool in iterative risk management for relative costs and benefits between options.
Cost-effectiveness analysis (CEA)	Short-term assessment for market and government sectors. Particularly relevant where clear headline indicator and dominant impact. Less applicable for cross-sector and complex risks.	Most useful when: as for CBA, but for non-monetary metrics (eg, ecosystems, health). Agreement on sectoral social objective (eg, acceptable risks of flooding).	Low- and no-regret option appraisal (short term). As a decision support tool in iterative risk management.
Multi-criteria analysis (MCA)	Integrates both quantitative and qualitative (intangibles) information when comparing options.	Highly adaptable but requires careful application and documentation. Needs to be tailored to circumstances, but can build in considerations, such as ability to adapt, interdependencies, futureproofing and cost.	Simple and effective general framework for comparing options in the short, medium, and long term, and can contribute to policy development. Relies on informed judgement. Identifies fatal flaws and degrees of difficulty. Different weighting systems can be applied to identify sensitivity to different criteria.
Iterative risk assessment (IRA)	Framework for assessment and planning for complex risks or long timeframes. Applicable at project and strategy level.	Most useful when: clear risk thresholds; mix of quantitative and qualitative information. For non-monetary areas and changing risks, eg, climate change adaptation, ecosystems, health.	Flexible, very relevant for medium to long term where potential exists to learn and react. Applicable as a general framework for adaptation policy development.
Dynamic adaptive policy pathways (DAPP) planning	For assessing and planning for risks over long timeframes where change is central. Applicable at project or strategy level.	Most useful when: high uncertainty in the future and when near-term decisions have potential to create path dependency and lock in. Can be used alongside CBA, cost effectiveness and ROA for economic valuation and sensitivity assessments.	As an analytical planning framework. Flexibility analysis of options for climate change adaptation using scenarios and for monitoring triggers for anticipatory planning.
Real options analysis (ROA)	Project-based analysis. Large irreversible capital investment, particularly where there is an existing adaptation deficit. Comparing flexible versus non-flexible options.	Most useful when: large irreversible capital decisions; climate risk probabilities known or good information. Good quality data exists for major cost benefit components.	Economic analysis of major investment decisions, notably major flood defences, water storage. Potential for justifying flexibility within major projects.
Robust decision making (RDM)	Project and strategy analysis. Conditions of high uncertainty. Near-term investment with long lifetimes (eg, infrastructure).	Most useful when: high uncertainty in rate and magnitude of climate change signal. Mix of quantitative and qualitative information. Non-monetary areas (eg, ecosystems, health).	Identifying low- and no-regret options. Testing near-term options or strategies across number of futures or projections (robustness). Comparing technical and non-technical sets of options.
Portfolio analysis (PA)	Analysing combinations of options, including potential for project and strategy formulation.	Most useful when: a number of adaptation actions likely to be complementary in reducing climate risks. Climate risk possibilities known or good information.	Project-based analysis for future combinations for future scenarios. Designing portfolio mixes as part of iterative pathways.