# Optimal Infrastructure Adaptation to Climate Change

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## Introduction

Considerable emphasis has been placed on designing climate change mitigation policies, both in New Zealand and internationally. This paper, while also dealing with climate change, alters the focus to adaptation policy. Adaptation is important whether or not a country adopts mitigation policies in the face of climate change.

This paper examines some of the key issues that should be taken into account when designing and implementing climate change adaptation policies with regard to infrastructure investments. To make the analysis concrete, we refer to the case of adaptation to the prospect of coastal flooding. In this case a seawall can be considered as an infrastructure investment. However, the analysis is general.

The two key lessons of the analysis for infrastructure investments are: (a) to spread the nature of adaptation responses to climate change across margins that reduce the probability of an adverse event (such as a flood), the exposure given such an event, and the loss given the exposure; and (b) to be cautious in committing to irreversible infrastructure investments that may no longer be optimal as our understandings of the severity and frequency of climate change outcomes are revised.

Our concentration on adaptation reflects the analysis of Hallegatte et al. (2011). They emphasise that, in addition to mitigating climate change, adaptation to climate change is important. Mitigation may be fully or partly ineffective and, in any case, will take a considerable period to attain full effectiveness, whereas adaptation can occur quickly. Furthermore, adaptation can be implemented and be effective locally. By contrast, mitigation requires a global effort and a small country has no direct material impact on global climate.[1]

This note discusses two ways of thinking about issues of adaptation to climate change. In cases where risks can reasonably be quantified (i.e. where there are well defined probabilities – or likelihoods – of particular events happening) a "certainty equivalent" analysis based on financial market credit loss methods provides useful policy insights. Where uncertainties are prevalent, this certainty equivalent approach still offers insights but is an incomplete description of the analysis required to address adaptation issues. In these situations, "real options" theory provides useful insights for analysing policy issues.

We outline the relevance of both these economic approaches. Prior to doing so, we discuss some issues that climate change developments raise for adaptation policy more generally. The analysis throughout is based on economic insights and does not attempt to incorporate legal responsibilities, such as those that apply to Regional Councils in New Zealand; these responsibilities add extra layers of complexity to those considered here. Brief discussion of the relevance of the ideas for actual adaptation policies is contained in the conclusions.

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[1] A small country can, of course, play its part as a "good global citizen" and so be well-placed to encourage other countries to join the mitigation effort. In this way it may have an indirect effect on climate outcomes. Mitigation may also be warranted in order to enhance a country's image with international consumers or to ward off the prospect of trade restrictions. Thus mitigation and adaptation are complements, rather than substitutes.

Damage following Hurricane Sandy, 2012. American Red Cross/Les Stone.

## Issues and Background

Adaptation can occur at the level of central government, local authority, community, firm or household. Furthermore, adaptation can occur across many different facets of activity (for instance, irrigation, flood protection, sun protection at schools, and so on). Adaptation is defined by Hallegatte et al. as: "the set of organization, localization and technical changes that societies will have to implement to limit the negative effects of climate change and to maximize the beneficial ones" (p. 5). Adaptation can be reactive, by reducing impacts when they occur, or anticipatory, by reducing vulnerabilities prior to potential climate change induced events (Smit et al., 2000). Reactive policies use future resources to deal with events as they occur, while anticipatory policies use resources in advance of any potential effects.

Hallegatte et al. note that adaptation generally confers private benefits to individual agents, such as reduced risk of flooding for a given property. In most case, private benefits can be funded and implemented by private agents so there is no public policy role other than facilitating (or not blocking) the private agent's intentions. Sometimes these benefits are in the nature of "club goods" that confer a benefit on a group of people who could (if coordinated) club together to implement the adaptation policy and reap its benefits. However, as the number of people in the club grows large, the benefit becomes more of a public good, where, for instance, a seawall indiscriminately protects all who lie behind it over a large area.

A number of circumstances exist that may inhibit adaptation or optimal decision-making by private agents. These may include:

(1) Poor dissemination of available information. In this case, a key public policy role may be to ensure that the information is well publicised.

(2) Inadequate standards and regulations may lead private agents to build to publicly advised, but sub-optimal, standards (as occurred with the "leaky buildings" situation in New Zealand). The public policy role here is to ensure that standards and regulations are sufficient to meet the challenge of climate change induced events and do not mislead people to thinking that a lesser standard is appropriate.

(3) Barriers to local collective action. In this case, the public policy role may be to enhance local community ("club") coordination and decision-making structures, and to facilitate actions sought by such groups. Once the number of agents in the club becomes large, the appropriate public policy role may be for the local authority to act on behalf of all members (after public consultation) to draw up suitable regulations and/or investment plans.

(4) Short time horizons whereby decision-makers do not adequately account for potential events. This situation can be exacerbated if there is moral hazard potential. For instance, council permission to develop in an area may be interpreted as the council sanctioning the integrity of a development. The developer may then on-sell such a development to a long-term buyer with a supposed council "tick of approval". This situation is likely to give rise to moral hazard whereby stakeholders in a development that is (politically or economically) "too big to fail" will understate the costs of a climate event in the knowledge that a public bail-out is likely to be forthcoming if such an event were to occur.

(5) Borrowing constraints by developers or purchasers could lead to sub-optimal development whereby private up-front adaptation measures are curtailed (possibly with the intention of incorporating them in future) in the knowledge that public authorities will bail out losses if a climate event were subsequently to occur.

(6) Public sector costs due to an event may not be internalised by private agents. For instance, a public insurer (e.g. EQC) may have to pay out private sector agents for a climate event. Alternatively, hospitals may incur greater costs (not borne directly by those affected) in emergencies related to climate events.

(7) Publicly provided infrastructure (such as a road or ultra-fast broadband) that services agents both beyond and inside the affected area may effectively subsidise development within an affected area even though this was not the intention of the infrastructure development.

These considerations mean that even where adaptation is largely or wholly a matter of private benefit, the public authorities may still have a "social planner" role to play to ensure that suitable adaptation activities are implemented either by the private or public sectors.

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In implementing any approach to adaptation, a number of uncertainty-related issues arise (Hallegatte et al.):

(1) There are uncertainties about the long-run prospects for global climate change.

(2) There are uncertainties as to how global impacts will translate to the local climatic level.

(3) There are uncertainties as to how the local climate will impact on specific systems (e.g. flooding likelihoods, migration flows, demand for urban development).

(4) There are uncertainties about the dynamics of global and local climate change (e.g. how fast they will occur), as well as the dynamics of adaptation policies (e.g. how fast they can be implemented).

(5) There are uncertainties about the degree of inertia of socio-economic systems (e.g. how fast activities can be relocated from potential flood plains, especially in the absence of concrete evidence that flooding will occur).

(6) There are risks of maladaptation such as shoring up flood defences in the short term, so making it more likely that agents will locate on a flood plain. Some adaptation policies may require wholesale changes, for example relocation of an entire town. In such a case, the political problems of implementing the socially optimal policy may be insurmountable, resulting in maladaptation.

Where there is uncertainty about the potential for climate change induced events to occur and decision-making occurs sequentially, the insights of real option theory (Dixit and Pindyck, 1994; Guthrie, 2009) are relevant for policy. These insights are discussed in more detail after our analysis of a risk-based approach to adaptation, in which risks can be quantified and binding decisions can be taken by the appropriate authorities.

## Infrastructure Investment and Expected Costs

A risk management approach, used to manage banking sector risks, can be used to analyse issues with regard to flood protection decisions given risks of climate change. Three concepts are particularly useful: "probability of default", "exposure at default", and "loss given default" (BCBS, 2006). We use the words "an event" in place of "default" since we are talking about a climate change-induced event rather than an institutional default. The expected cost of an event is the probability of an event multiplied by the loss given an event; and the loss given an event is contingent on the exposure at the time of the event. Anticipatory policy can affect each of the probability of an event, exposure at an event, and loss given an event.

Our specific example examines the costs associated with a climate change-related event, specifically a potential flood that would not occur in the absence of climate change. We denote the probability of the event, in the absence of any preventative adaptation activity, as *prob(event)*.

The probability of an actual flood is denoted *prob(flood)*. This probability depends both on *prob(event)* and on the ex ante *investment* undertaken by agents to avert flooding, for example through building a seawall. *Investment* is a variable that can be chosen ex ante by the authorities or by private agents; it has capital and maintenance costs that are likely to be positively related to the scale of investment. If some

Stranded flood victims being transported in the bed of a dump truck following Hurricane Sandy, 2012. American Red Cross/Les Stone.

preventative *investment* has been undertaken, *prob(flood) < prob(event)*; i.e. adaptation is successful in reducing the probability of flood relative to the no-adaptation case. The two probabilities are equal where no preventative *investment* precautions have been taken.

If a flood occurs, the scale of damage will depend on the "loss given flood", denoted *loss|flood*. In turn, *loss|flood* depends on the *exposure at flood* (i.e. the value of assets that could be damaged in the affected area), and the *loss given exposure*. *Exposure at flood* is affected by *zoning* rules (and the like) that limit the degree of construction in a flood-prone area. *Loss given exposure* depends on rules such as *building* codes that restrict the nature of structures. For instance, codes may require that buildings are built on concrete piles that lift the living quarters of a house above potential floodwaters.

The expected loss from a flood *(ExpectedLoss)* is given by *prob(flood) x loss|flood*. The authorities have three policy variables that they can employ in advance of a potential flood: *investment*, *zoning*, and *building*. Use of each of these policies involves some potential costs.

*Investment* requires both capital and maintenance costs. The capital costs are borne up front while the maintenance costs are equal to the present discounted value of maintaining the structure (e.g. the seawall) over its lifetime.

*Zoning* incurs opportunity costs. If zoning decisions result in fewer structures being built than in the unrestricted case, some agents who wished to build in a privately optimal way will be denied building permission. They will have to site their house or business elsewhere in a location that is not perceived to be as favourable for them. The present discounted value of the foregone productivity (for a business) or the foregone amenity value (e.g. a beach-front view) for a household constitutes the opportunity cost. The greater the *zoning* restrictions, the greater are the opportunity costs.

Greater *building* restrictions incur extra construction costs. They may also potentially result in lost firm productivity or lost household amenity value (e.g. if people prefer not to live or work on stilts).

The optimal policy mix will minimise expected discounted costs over a long time horizon. These costs are attributable to the sum of *ExpectedLoss* and the costs associated with each of *investment*, *zoning,* and *building*.

If we were confident that the information base in the future will be similar to that which exists now, the optimal combination of *investment*, *zoning* and *building* is reasonably straight-forward to ascertain, at least conceptually. Here we discuss how certain factors affect the policy decisions and set out a number of key results that have implications for policy.

First, it is generally not optimal to reduce *ExpectedLoss* to zero by any combination of *investment*, *zoning* and *building*. Since each of these policy choices involves some cost itself, and especially where the additional costs are increasing in the degree of intervention, it will be optimal to moderate these policy choices so that while they reduce expected flood costs, they still leave some of the cost burden to be shared through the *ExpectedLoss* of a flood.

Second, as capital or maintenance costs rise, it will be optimal to reduce the protection afforded by a seawall and instead have greater restrictions imposed via *zoning* and *building* controls, as well as some heightened *ExpectedLoss*. Thus, if it is very costly to prevent a flood (e.g. because any seawall will continually be eroded) it becomes increasingly attractive to prevent development from incurring in a flood-prone area and/or to increase the severity of building code restrictions so that the cost of any flood that does affect structures is moderated.

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Third, if a flood-prone locality stands out well above other localities as a place in which people wish to locate, then the costs imposed by more severe *zoning* restrictions rise. The implication of this situation is that it becomes preferable to increase prevention (i.e. the size of the seawall) and to increase requirements imposed by *building* code restrictions.

Fourth, if people find *building* code restrictions designed to minimise flood costs to be onerous (either in monetary or amenity terms), then greater weight should be placed on *investment* and *zoning* policies. The effect of *building* restrictions on costs may differ depending on the nature of activities that private agents wish to pursue in a given locality. Manufacturing business owners may not be as concerned with amenity costs caused by *building* restrictions as are homeowners. Thus where costs of a *building* intervention are low, the authorities may place greater reliance on these measures, and be less willing to protect against a flood (*investment*) or to reduce the number of structures in the path of a flood (*zoning*). By contrast, a highly desirable beach-front locality that has high amenity values may place greater weight on building a seawall to protect against a flood. In this situation, authorities will therefore concentrate on reducing *prob(flood)* rather than reducing *loss|flood*.

## Implications of Uncertainty

The preceding analysis is based on a "certainty equivalent" world in which we take information as given and unchanging over time. In practice, the science of climate change is evolving rapidly and new information about the probabilities of climate change events and their severity can be expected. We cannot know, at this juncture, whether current probabilities and estimates of severity are over- or under-estimates. We assume that current information for policymakers is based on the best available scientific estimates and so we may reasonably assume that there is a positive probability of these estimates being revised either upwards or downwards in future. Uncertainty also exists over the probability distribution of the severity of events in the case of substantial climate change. Large changes in climate bring with them the chance of "fat-tailed" (catastrophic) events that need to be incorporated into decision-making today.

The evolving state of knowledge, coupled with irreversibilities in investments, has implications for the way in which our preceding results should be implemented within a dynamic setting. Real options theory (Dixit and Pindyck, 1994; Guthrie, 2009) is useful here. The theory demonstrates that in most cases when investments are irreversible, new information is expected over time, and decision-making is sequential (i.e. future as well as current decisions are possible), one needs to be cautious in making irreversible investments. In particular, one generally needs to adopt a more cautious approach to investment than would be indicated by analysis based on certainty equivalents (expected values).

The reasoning behind this result can be demonstrated with the simple case of whether to build either a large or a small seawall (i.e. the policy choice variable *investment*). The large seawall costs more than the small alternative but is effective in preventing a wider range of possible floods. Current information may make the benefit:cost ratio of building the large seawall higher than for the smaller alternative, and so would favour the large option under a standard (certainty equivalent) benefit cost approach.

However, new information about climate change possibilities may subsequently come to light in which the probabilities and expected severity of flood events are reduced relative to what we understand now. If a seawall was being built at that (future) time, a new benefit:cost analysis may find that only a small seawall is warranted. If the large seawall were built now, based on current best information, the investment will be larger than turns out to be optimal in future with resulting higher capital and maintenance costs than would be optimal.

By contrast, if the alternative exists of building a small seawall now that could be enlarged as new information came to light, that option could be preferable to take now, even though current information suggests that a large seawall is required. The reason that the smaller seawall (capable of enlargement) may be optimal to build now is that it provides an option to enlarge or not to enlarge in future. By contrast, building a large seawall now provides no such option to change in future; it therefore foregoes the benefit that could potentially be gained by "purchasing the option" of enlargement through building the smaller alternative initially. The value of this option must be weighed against the value (based on current information) of preventing a greater range of floods over the period from now until when the seawall could potentially be enlarged if future information warrants that action.

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The value of this option, therefore, depends on:

- the cost difference between building the two walls now;
- the cost of enlarging the wall in future, if considered necessary;
- the risk of flood in the intervening period that could be contained by the large seawall but not by the small seawall;
- the volatility in likely new information flows.[2]

The small seawall will tend to be favoured where:

- the (capital plus maintenance) cost difference between the two seawalls is sizeable;
- the cost of enlarging the wall in future is low; or
- the risk of flood in the intervening period is low.

High volatility in new information flows (i.e. where the parameters from the scientific models are particularly uncertain and subject to revision) will also favour the smaller alternative being built now. This is due to the increased risk of revising estimates of flood propensities substantially downwards (which is the relevant direction for this example given the irreversibility of the investment).

The same logic applies to the other two policy choice variables, *zoning* and *building*. High volatility in new information flows favours a conservative approach to irreversible investments. In these circumstances, it will be preferable to begin with harsher *zoning* and *building* restrictions than would be implied based on current information about flooding propensities. The reason is that if estimates of flood propensities are revised higher, the authorities (or private building owners) would then find it costly to remove or remodel buildings to take account of the higher risk of flood. By contrast, if flood propensities were revised downwards in future, it is simple to reduce restrictions and so allow more development (and fewer building code restrictions) in the potentially affected area. There would still be a cost of the restrictions in the intervening period but this cost will likely be less than the costs of having to remove or reconstruct existing buildings. Given the asymmetric costs of adjustment in response to new information, it is therefore generally better to be conservative (relative to current best estimates) in setting initial *zoning* and *building* restrictions in the face of uncertain climate change estimates.

## Discussion

Authorities need to consider both mitigation and adaptation measures in response to climate change. For a small country, mitigation measures will have negligible effect on climate outcomes. By contrast, adaptation measures can materially affect the impact of climate change on outcomes for the country and for a region. However, adaptation measures can be costly and they must be implemented in a situation where considerable uncertainty exists about the probability and severity of future climate change-induced events.

[2] It will also depend on the discount rate applied to both costs and benefits. A higher discount rate will tend to penalise more costly up-front projects. The appropriate discount rate to employ when considering long time horizons is a matter of considerable debate (Weitzman, 1998; Stern, 2007). For expositional simplicity, we henceforth ignore discounting in our discussion.


Damage following Hurricane Sandy, 2012. American Red Cross/Les Stone.

The analysis here highlights several key considerations that should be accounted for when infrastructure investments and other adaptation measures are being implemented in response to climate change. First, the analysis should consider three aspects of the risk environment (which we consider in the context of a flood, but which can accommodate possibilities such as erosion, wind damage, and so on): probability of flood, exposure at flood, and loss given exposure. A reduction in any of these three margins will reduce the expected loss from a flood. Differing measures can be taken with respect to each margin, and each measure will incur its own costs. Adaptation policy needs to consider the best combination of measures to keep the sum of total costs (including expected loss from a flood) to a minimum. Other than in special circumstances, concentration on one margin alone (e.g. *exposure at flood*) is likely to be sub-optimal; a combination of policies will generally be required.

One adaptation measure may be to invest in a large piece of infrastructure (e.g., a seawall) to reduce the probability of flood. Another may be to reduce exposure at flood by way of zoning restrictions. It may also be optimal to reduce infrastructure investments in an area prone to flooding, both to reduce direct costs of flooding on the infrastructure itself and to reduce the incentive for other agents to locate in the flood-prone area. Another adaptation measure may be to alter the nature of construction in an area in order to reduce loss given exposure. Again, there may be implications for infrastructure developments from this margin. For instance, a new transport artery may be constructed with built-in flood protection to reduce its vulnerability to any flood that does occur.

Climate change prospects are uncertain in terms of the severity and frequency of future events. The analysis of the impacts of uncertainty for optimal investment in irreversible structures highlights extra factors that need to be considered when making infrastructure and other investment decisions. The key result is that it is not necessarily optimal to build what appears to be the best adaptation measure based on currently understood probabilities about the severity and frequency of climate change events.

Climate change probabilities will be revised in future and the revisions may be towards an increase or decrease in expected severity of climate change events. Current decisions with regard to irreversible investments need to consider the possibility that climate change events may turn out to be either more severe or less severe than currently anticipated. It is costly to over-build adaptation measures in the situation where climate change turns out to be less severe than currently anticipated. By the same logic, it is costly to over-build in flood-prone areas if climate change turns out to be more severe than currently anticipated. The key policy implication, therefore, is that it pays to reduce irreversible investments, at least at the margin, in potentially flood-prone areas relative to a situation of known probabilities.

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Future costs are an important factor in deciding on initial scale and type of structure, and the nature of these costs can favour either an initially low-cost or high-cost approach to particular investments depending on circumstances. For instance, under conditions of uncertainty, a seawall may be built smaller than would be the case under certainty (using current known risks) if there were a low-cost alternative to extend the seawall in future to prevent greater floods. However, if an infrastructure investment such as a road must be built in a flood-prone area, it may be optimal to build it to withstand more severe climate change events than currently predicted where future remedial costs would be high if extra flood-proofing were required.

Political and social context is also important in deciding how much risk should be avoided when deciding on the scale of an initial adaptation mechanism. If the risk of maladaptation rises as a result of building a flood defence – and if political factors make the maladaptation unavoidable given the potential institutional options – then the initial preventative investment may have to be greater than a current risk estimate suggests is optimal. An example of the need for such a contextual approach has been the thinking behind the Thames Estuary 2100 project in the UK associated with the future of the Thames Barrier (Reeder and Ranger, 2011). In this assessment, the scientific projections on sea level rise have been considered within the context of current and future activities located within the affected area. Similarly, in Australia, emphasis is being placed on the nexus between the potential for coastal flooding with demographic, economic, infrastructure and landscape factors in the context of potential political and social barriers to adaptation (Preston et al, 2008).

Another important insight of the real options approach is that it may be optimal not to build a piece of irreversible infrastructure in a flood-prone area at present, even if a standard (certainty equivalent) benefit:cost analysis supports the investment. The reason is that if flood probabilities rise in future (relative to those predicted today) the investment may no longer be warranted or may necessitate high remedial costs to guard against floods. This approach is now being incorporated into scientific assessments of the implications for zoning decisions of climate change. For instance, in New Zealand, a NIWA assessment (Bell and Hannah, 2012) of the implications of climate change risks for Wellington concludes that, for planning purposes, a distinction should be made between existing coastal developments and coastal greenfield sites. For the former, the report recommends that a 1.0 metre sea level rise should be incorporated into planning and infrastructure decisions whereas, for the latter, the report recommends that a 1.5 metre sea level rise should be allowed for. The report explicitly makes the point that if future sea level rise is subsequently revised downwards, then the 1.5 metre allowance for greenfield developments could be scaled back to 1.0 metre. This approach is in keeping with the optimal approach under uncertainty outlined above.

Overall, the two key lessons of our analysis for infrastructure investments are: (a) to spread the nature of adaptation responses to climate change across margins that reduce the probability of a disaster, reduce the exposure given a disaster, and reduce the loss given exposure; and (b) to be cautious in committing to irreversible investments that may no longer be optimal as our understandings of the severity and frequency of climate change outcomes are revised.

## References


Basel Committee on Banking Supervision (BCBS). 2006. *International Convergence of Capital Measurement and Capital Standards: A Revised Framework, Comprehensive Version*. Basel: Bank for International Settlements.

Bell, R., and J. Hannah. 2012. *Sea-Level Variability and Trends: Wellington Region*. Wellington: NIWA.

Dixit, A., and R. Pindyck. 1994. *Investment under Uncertainty*. Princeton: Princeton University Press,.

Guthrie, G. 2009. *Real Options in Theory and Practice*. Oxford: Oxford University Press.

Hallegatte, S., F. Lecocq and C. de Perthuis. 2011. "Designing Climate Change Adaptation Policies: An Economic Framework", *Policy Research Working Paper 5568*, World Bank, Washington DC.

Preston, B., T. Smith, C. Brooke, R. Goddard, T. Measham, G. Withycombe, K. McInnes, D. Abbs, B. Beveridge and C. Morrison. 2008. *Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group*. Canberra: CSIRO Climate Adaptation Flagship.

Reeder, T., and N. Ranger. 2011. *How Do You Adapt in an Uncertain World? Lessons from the Thames Estuary 2100 Project*. Washington DC: World Resources Report.

Smit, B., I. Burton, R. Klein and J. Wandel. 2000. "An Anatomy of Adaptation to Climate Change and Variability", *Climatic Change* 45:1, pp. 223–51.

Stern, N. 2007. *The Economics of Climate Change: The Stern Review*. Cambridge: Cambridge University Press.

Weitzman, M. 1998. "Why the Far-Distant Future Should be Discounted at its Lowest Possible Rate", *Journal of Environmental Economics and Management* 36:3, pp. 201–8.