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How the failure to account for flexibility in the economic analysis of flood risk and coastal management strategies can result in maladaptive decisions

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Abstract

This paper uses two alternative economic analysis approaches, Net Present Value (NPV) and Real In Options (RIO), to show how the failure to incorporate uncertainty and flexibility in the economic analysis of flood risk and coastal management strategies can result in maladaptive decisions. RIO offers a major development on the conventional NPV approach, because it integrates expected changes in future levels of uncertainty into economic analysis. We have applied RIO analysis to the semi-hypothetical case study of a coastal defence system in order to

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demonstrate its applicability for decision making on climate change adaptation. In the case study, two different adaptive strategies are analysed, consisting of a hard and soft structural alternative. Soft strategies are often inherently more flexible than hard strategies. The results of the case study show that the NPV approach increases the relative cost of soft strategies for the two alternatives compared with hard strategies, since it does not account for the value of flexibility built into adaptive strategies. We therefore recommend the use of RIO analysis for the choice between hard and soft strategies in order to avoid maladaptation. This is particularly significant in cases where there is both high climate uncertainty and high decision uncertainty concerning the best strategy.

Keywords

Climate change, flood risk management, maladaptation, real options, sea level rise

Abbreviations

AM: Annual Maintenance

ENPC: Expected Net Present Cost

NAP: Normaal Amsterdams Peil (or: Amsterdam Ordnance Datum)

NPC: Net Present Cost

NPV: Net Present Value

PC: Present Cost

q: discharge

RO: Real Options

RIO: Real In Options

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SLR: sea level rise

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Introduction

Climate change has introduced large uncertainties into the assessment and management of flood-related risks. These uncertainties make it difficult to decide how to devise adaptations and which measures (either single or portfolio) to use. In particular, it is widely recognised that there is a need to revise stationary-based procedures for developing flood risk and coastal management strategies (Kundzewicz et al. 2008). Otherwise, such strategies can be maladaptive, resulting in unnecessary costs of potentially irreversible measures (Barnett and O'Neill 2010). This is particularly significant for hard engineering strategies, which aim to reduce risks by modifying the water or flooding system through physical and built interventions. These strategies may lead to decreased flexibility to respond to uncertain changes in climate conditions. Therefore, soft engineering strategies will play a more important role than in the past and need to be considered in decision making on climate change adaptation, as these can more readily be implemented incrementally with inherent flexibility after future uncertainty is reduced. Soft strategies involve maintaining or restoring the natural land and water processes with the aim of reducing risks. In addition, these strategies provide additional benefits such as conservation of biodiversity, habitat protection and improved water quality and amenity (New Zealand Government 2010). Soft strategies can also be used in combination with hard engineering. Decisions on whether to use soft or hard adaptation should be taken based on appropriate economic analyses. This should take into account the effect of uncertainty and flexibility. However, there has been limited discussion to date of available approaches for incorporating uncertainty and flexibility in the economic analysis of flood risk and coastal management. Exceptions include the studies by Wang and de Neufville (2004), Woodward et al. (2008), Gersonius et al. (2011) and De Bruin and Ansink (2010).

The aim of this paper is to analyse how the failure to incorporate uncertainty and flexibility in the economic analysis of flood risk and coastal management strategies can result in maladaptive decisions by using two alternative economic analysis approaches, Net Present Value (NPV) and Real In Options (RIO). RIO offers a major development on the conventional NPV approach, because it integrates expected changes in future levels of uncertainty into economic analysis. We have applied RIO analysis to the semi-hypothetical case study of a coastal defence system in order to demonstrate its applicability for decision making on climate change adaptation. However, the results are not limited to coastal defence, and it would have also been possible to develop a flood defence, drainage or other water example. In the case study, two different adaptive strategies are analysed: defence raising (i.e. dike heightening) and sand nourishment (i.e. the placement of sand in front of the dike). The first comprises the hard alternative and the second the soft alternative.

Approaches for adapting to climate change

There are two kinds of approaches for adapting flooding systems to climate change: the static/robust approach and the managed/adaptive approach. These are explained in the following.

> The robust approach[1] applies to the implementation of adaptation comprising large-scale hard structural measures with high (fixed) capital cost, such as large embankments, major sewers, or similar potentially irreversible measures. The selection of a robust approach usually requires the infrastructure system to be initially designed to accommodate any possible change predicted in the system lifetime. This implies the adoption of a 'headroom'

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[1] In engineering, the concept of robustness generally refers to the maintenance of system performance when subjected to changes in conditions. In this paper however, robust designs are considered those intended to perform well under all future conditions—in contrast to those that have to be adapted in the future to maintain performance.

methodology (Ingham et al. 2006). Headroom is the excess capacity added on to the 'design capacity' to allow for future uncertainties that cannot be resolved at the present time and is standard engineering practice; frequently known as a 'safety factor'. Introducing this headroom capacity into the infrastructure system will help ensure that the expected levels of performance can be achieved even with uncertainty. The approach is thus designed to function without any performance monitoring and significant readjustment of management throughout the system lifetime.

> The adaptive approach allows for easier adaptation in the future via incremental adjustments to headroom allowances. It assumes an iterative process that includes formulating objectives, acceptable standards, models, and strategies, monitoring performance against these standards, and managing this through incremental adjustments, as new information becomes available. In this sense, the approach confers the ability, derived from keeping options open (i.e., in-built flexibility), to adjust to future uncertainties as they unfold. This reduces the effect of erroneous decisions made at the start of the process that could result in unnecessary costs of potentially irreversible measures, or in other terms: it helps to define the appropriate level of investment at the right time, in the right way and at the right cost. A portfolio of structural and non-structural measures is typically required for the implementation of the adaptive approach to ensure that cost-effective adaptation can take place in all future time periods. Non-structural measures correspond to the design and application of policies and procedures, and employing among other land-use controls, information dissemination, and economic incentives to reduce risks (EC 2009).

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Approaches to economic analysis of adaptation

Economic analysis without uncertainty and flexibility

Conventional economic analysis of flood risk and coastal management strategies generally includes, for each alternative adaptive strategy, a calculation of its NPV. This term is used to describe the sum of the discounted benefits of an alternative less the sum of its discounted costs, all discounted to the same base date (e.g. HM Treasury 2003). A negative NPV is generally referred to as a Net Present Cost (NPC). NPV analysis allows the comparison of alternative, adaptive strategies with different patterns of benefits and costs over time, because it converts all benefits and costs into a single value at the base date. In calculating the NPV or NPC, the most likely values of uncertain parameters are incorporated into the estimation of the benefits and costs. This should be analysed over the same time horizon for all alternatives. If a full benefit cost analysis has been undertaken, then the decision rule is to select the strategy that maximises NPV. In a cost effectiveness analysis, as applied in this paper, the decision rule is to select the strategy that minimises NPC.

There are unfortunately two major limitations of the conventional NPV approach, as applied in the case study below. Firstly, the approach is based on expectations of future investments (assuming an average or best estimate scenario). There may, however, be other more extreme scenarios where the life cycle cost will be different from expectations. Secondly, it uses a deterministic investment path for the adaptive strategy. The working assumption is that the adaptive strategy continues unchanged until the end of the time horizon. This reasoning neglects the effects that management decisions may have in the extreme low or extreme high scenarios, because it assumes management's commitment to a certain investment path. Consequently, the

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NPV approach does not reflect the flexibility that exists in the alternative, adaptive strategies. As an example from the case study: sand nourishment provides the flexibility to manage future uncertainties during the system lifetime, because there is the possibility to add sand when it is needed (as opposed to defining this in advance). If the value of this flexibility is not incorporated into the analysis, the cost of the strategy will be systematically overestimated. It is of note that some more complete approaches to dealing with uncertainties could partly address these limitations. For example, the use of NPV analysis in combination with Monte Carlo simulation could provide information on the life cycle cost of the alternative, adaptive strategies across a range of possibilities for uncertain parameters. However, this cannot properly quantify the value of managing uncertainty and flexibility.

Economic analysis with uncertainty and flexibility

Real Options (RO) is a recognised procedure to handle uncertainties in infrastructure investments by providing managerial flexibility (Myers 1984). Instead of assuming a deterministic investment path as in the NPV approach, RO analysis is able to deal with the possibility of many alternative investment paths through time. It explicitly considers the combinations of possible investment decisions. In this regard, it is an extension of the NPV approach. RO analysis determines the value of managing uncertainty and flexibility within a framework that builds on the financial options theory of Black and Scholes (1973). The value of flexibility stems from the capacity of the decision maker to learn from the arrival of new information and their willingness and ability to revise investment decisions based upon that learning.

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RO analysis applies the models from financial options analysis, such as the recombining binomial tree method (Cox et al. 1979), to inform the management of infrastructure systems under uncertainty. More recently, RO analysis has also been applied to the design of infrastructure systems (Zhao and Tseng 2003; Zhao et al. 2004; Wang and de Neufville 2004; Gersonius et al. 2011). This is known as Real 'In' Options (RIO) analysis (De Neufville 2003). Unlike conventional RO analysis, RIO analysis embeds real options directly *into* the infrastructure system (re)design. The application of RIO analysis, therefore, requires extensive knowledge about the infrastructure system. Another difficulty with RIO analysis is that the technical constraints often lead to path-dependency―that is, that the value of an option depends on whether some other part of the infrastructure system was or was not built. Path-dependency implies that the recombining binomial tree for financial options is insufficient for RIO analysis. In the recombining binomial tree, the valuation of an option on each node of the tree is path-independent. This means that the valuation of the option on a certain node is the same for any path leading into that node. Wang and De Neufville (2004) proposed breaking the recombination structure of the binomial tree (as shown in Fig. 1) to deal with path-dependency features.

<Insert Figure 1 here>

Figure 1. Breaking the recombination structure of a binomial tree

The development of RIO analysis provides a framework to find out which flexibilities, that permit the system to be adapted over time, are worth their cost. Previously this had not been possible—with the consequence that flexible design was traditionally neglected (de Neufville 2004). The crux of RIO analysis lies in the estimation of the value of flexibility built into infrastructure systems. This is because the estimation of the cost of acquiring flexibility is relatively simple; that is, it is part of the set of conventional economic analyses. The assessment of the value of flexibility is the novel part that requires additional procedures. These are (Wang and de Neufville 2004):

- Estimating the drift and volatility of the uncertain parameter. The drift is the average rate at which the uncertain parameter changes and the volatility is a measure of its randomness.
- Using the drift and volatility to develop a path-dependent tree representation of the different possible future paths followed by the uncertain parameter.
- Quantifying the value of flexibilities built into the infrastructure (re)design using this tree of the uncertain parameter.

Applying RIO analysis can help to overcome the limitations of the conventional NPV approach. However, there are a few limitations to RIO analysis. A theoretical limitation is that it assumes probabilities can be given to future SLR under climate change; although many climate scientists do not believe this is yet possible. A practical limitation is that it can be complicated to establish and then solve the binomial tree.

Case study: Dutch North Sea coast

The case study is typical of the Dutch North Sea coast, in which a single sea dike is in place to protect an area of low lying land from flooding. In the Netherlands, coastal defences have a protection standard of 1/10000 years; i.e. they are designed for a tidal event with a probability of occurrence of 10^{-4}. Overtopping of the defences is assumed to be the critical failure mechanism.

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The defences should be high (crest) and strong (inner slope) enough to resist a design overtopping volume of q=1 l/m/s at the hydraulic peak conditions.

The hydraulic load on the sea dike comprises of the overtopping discharge caused by the combination of the design water level and wave run-up. In the semi-hypothetical example, the design water level with a probability of occurrence of 10^{-4} per year equals NAP (Amsterdam Ordnance Datum) +5.0 m. The significant wave height accompanying the design water level is approximately 3.5 m with a steepness of 3.0 % and a period of 8.6 s. In addition to the hydraulic parameters, the overtopping discharge is primarily determined by the defence crest height. Other elements that influence the overtopping discharge are a gentle outer slope, a wide outer berm and/or a rough revetment. The most important elements of the sea dike cross section are shown in Fig. 2. The structure has a total length of 10.0 km. The crest height is circa NAP +12.0 m with a width of 3.0 m. The outer side of the sea dike has a slope above the berm (located at NAP +5.0 m) of 1:3 and below the berm of 1:4. The inner side of the sea dike consists of a 1:3 slope and an inner berm, with maintenance road and ditch.

<Insert Figure 2 here>

Figure 2. Sea dike cross section

Predicted accelerating sea level rise (SLR) as a consequence of climate change will increase the loading on the sea dike, such that the system performance progressively deteriorates over time. This means that there is a (recurring) need to adapt the structure to comply with the protection standard. Two potential flood risk and coastal management strategies will be discussed in the

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following. These strategies will be briefly explained and some preliminary calculations will be made for the required adaptation and costs for the measures needed to withstand the hydraulic peak conditions in future time periods.

The hard structural alternative

The hard structural alternative comprises the continuation of the current coastal defence strategy, which aims to meet the protection standard by simply raising the sea dike. In this case, the structure has to be strengthened in the landward direction by broadening the base. This requires a wider footprint of the dike at the landward side, which is some 6 m extra width per 1 m of dike heightened. Secondly, the infrastructure at the inner toe has to be relocated; i.e. the maintenance road and ditch. The inner slope of the sea dike comprises a layer of clay covered with grass. Where there is significant dike heightening, the existing clay layer first has to be removed in order to prevent the inclusion of sand between the clay layers.

The required adaptation to the crest level was determined based on its relation with SLR, using Hydra K (Veugdenhil et al. 2000) and the PC-Overtopping tool (TAW 2002). Hydra K is a probabilistic model to derive representative hydraulic conditions for coastal areas in the Netherlands. PC-Overtopping is an empirical model to make preliminary predictions for overtopping discharges for dike type structures. The capital cost of raising the sea dike to continue to maintain the protection standard in the face of climate change, was estimated based on unit cost prices from previous studies for the Dutch North Sea coast (Van Koningsveld 2004). The outcome of this analysis is presented in Table 1. It can be concluded from Table 1 that the capital cost estimates change almost linearly with the magnitude of SLR, with the following cost

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function: evolution cost = 17.00 * magnitude of SLR + 29.33. The marginal annual maintenance cost of defence raising is very low (*ibid*), and set at zero.

Table 1. Indicative capital cost estimates of defence raising

<Insert Table 1 here>

The soft structural alternative

The soft structural alternative comprises the placement of sand in front of the sea dike to maintain a higher foreshore level. An elevated foreshore reduces the energy of waves through the action of the added resistance to run-up and by causing the waves to break before reaching the dike. This can reduce the overtopping volume, which has a beneficial effect on the required crest level. In this regard sand nourishment can help to avoid the need for dike heightening in the (near) future.

The nourishment volume is calculated from the site area and height required. The part of the foreshore between NAP –9.0 m and the dike toe (located at NAP –2.0 m) has a 1:20 slope, and in the deeper parts, the slope is 1:10. Based on expert opinion, the foreshore length is taken to be about 0.5 times the wave length, which comes to about 50 m. The required foreshore height is determined as a function of SLR, based on the existing dike crest level (NAP +12.0 m). The outcome is presented in Table 2, along with the associated nourishment volume. The unit costs of nourishment are estimated to be 3 Euro per m^3 for foreshore nourishment and 6 Euro per m^3 for beach nourishment, after Morselt (2009). By applying these unit cost prices, the resulting initial capital cost estimates for sand nourishment are shown in Table 2. This gives the following linear cost function: initial capital cost = 8.04 * magnitude of SLR + 13.38. The cost function for expanding the initial design of the foreshore is then: evolution cost = 8.04 * magnitude of SLR. It can be seen from this that the capital costs of sand nourishment are lower than of implementing defence raising. However, replacing the sand as it is washed away requires annual maintenance. The costs for this are estimated to be approximately 10 % of the total nourishment volume (*ibid*).

Table 2. Indicative capital cost estimates of sand nourishment

<Insert Table 2 here>

Application

Economic analysis without uncertainty and flexibility

The application of the NPV approach requires the estimation of size and timing of investments within the system lifetime. Alternative, adaptive strategies should be defined in advance based on a specified scenario for the most significant uncertain parameter (as an average or best estimate) in order to obtain the investments. In the case study, the most significant uncertain parameter is the magnitude of SLR. Sea level scenarios for the Dutch North Sea coast are provided by the KNMI (Hurk van den 2007). Observed SLR between 1990 and 2010 is estimated to be 0.04 m. A set of two sea level scenarios has been produced for the periods 2050 and 2100, relative to 1990. The temperature increase in 2100 is taken as 2°C for the low scenario and 4°C for the high scenario. This results in a SLR of 0.35 to 0.60 m for the low scenario in 2100, and of 0.40 to 0.85 m for the high scenario. The KNMI sea level scenarios exclude the subsidence of land, and therefore 0.10 m should be added to estimate the relative SLR until 2100, i.e. this

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provides the combination of sea level rise and subsidence. The upper bound of the low scenario was arbitrarily used (as an average or best estimate scenario) to define the required adaptation. This gives a relative SLR of 0.65 m between 2010-2100.

Any analysis of the potential adaptation measures should subsequently consider how the predicted SLR is managed over time. In this regard, a decision had to be made on whether to select a robust approach or a managed/adaptive approach. This decision depended on the specific characteristics of the flood risk and coastal management strategy. The adaptive approach was considered wholly appropriate for the soft strategy, because of the possibility of implementing sand nourishment incrementally. For the hard strategy, the robust approach was considered more appropriate. This is justified by the fact that taking a one-off adaptation step at the outset will be cheaper than taking multiple adaptation steps over the whole time horizon, due to the high fixed cost of defence raising (29.33 M€).

Figure 3 shows how the strategies perform under the approach used for adapting to climate change. Under the robust approach, with a one-off adaptation step, the flood risk/probability decreases sharply at the outset of the project and then increases over time towards the level of acceptable risk (which is assumed constant). Under the managed/adaptive approach, with multiple adaptation steps, the level of risk follows a saw-tooth pattern over the system lifetime.

<Insert Figure 3 here>

Figure 3. Approaches for adapting to climate change (adapted from Defra 2006)

The valuation for the hard strategy is straightforward based on the robust approach. Applying the cost function from Table 1, the NPC for the hard strategy is €40.38 million. The valuation of the soft strategy is somewhat more involved. It requires the planning of appropriate investment timings, and then discounting back these investments at the real discount rate of 5.5% (Financiën 2009). The spreadsheet model for analysing the NPC of the soft strategy is shown in Table 3, assuming (arbitrary) adaptation steps of 15 years. The resulting cost for the soft strategy is €42.84 million. This implies that, as having the lowest NPC, the hard structural alternative would likely be selected for implementation.

Table 3. Spreadsheet model for analysing the NPC of the soft structural alternative

<Insert Table 3 here>

Economic analysis with uncertainty and flexibility

As an initial step in the RIO analysis, the drift and volatility of the uncertain parameter (i.e. the magnitude of SLR) were estimated from expert opinion. The expert (on climate change scenarios) gave an optimistic estimate for absolute SLR between 2010-2100 of 0.31 m, and a pessimistic estimate of 0.81 m, both with 90% confidence. Therefore the mean value over 90 years is 0.56 m and the standard deviation is 0.195 m, assuming the SLR rate is normally-distributed.[2] Given these values, the drift μ and volatility σ are calculated as follows: [3]

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[2] This is a somewhat arbitrary assumption, and the validity of this assumption should be further investigated for real world case studies to determine whether other models are better representations of the stochastic movement of the sea level.

[3] The volatility is calculated from the 95% confidence value, which is equal to the mean plus 1.65 times the standard deviation

$$\mu = \frac{\left(\frac{5.56-5}{5}\right)}{90} = 0.124\% \text{ per year}$$

$$\sqrt{90}\,\sigma = \frac{\ln\left(\frac{5.65 + (1.65 \times 0.195)}{5.56}\right)}{2} \qquad \text{or} \qquad \sigma = 0.296\% \text{ per year}$$

The evolution of the absolute SLR over time has been modelled by means of a path-dependent binomial tree representation (Wang and de Neufville 2004). The binomial tree arises from a discrete random walk model of uncertainty (e.g. Wiener 1923). This breaks down the time horizon into a number of time periods, or adaptation steps. The tree of the SLR uncertainty is then developed moving from the present to the end of the time horizon. According to the binomial tree, the sea level can only move upwards or downwards within each time period by a fixed factor. There is a specific probability of the up movement and down movement. Two methods are commonly used to develop the binomial tree: either the probabilities of the up or down movement are taken as equal and formulae are derived which give different up and down factors, or the uncertain parameter is made to move up or down by the same factor, in which case formulae are derived which give different probabilities for those movements. With a sufficiently large number of time periods, these two methods converge on a single value. Here, the method has been used with equal probabilities, known as the Jarrow-Rudd binomial tree (Barnett and O'Neill 2010). In this method, the up and down factors are calculated using the drift μ, the volatility σ, and the time period t:

$$\text{up factor} = e^{\left(\mu-\frac{1}{2}\sigma^2\right)t+\sigma\sqrt{t}}, \quad \text{down factor} = e^{\left(\mu-\frac{1}{2}\sigma^2\right)t-\sigma\sqrt{t}}$$

A binomial tree of absolute SLR with six time periods of 15 years has been developed. The reason for selecting a 15-year time period is that it typically takes one or more decades before a 'signal' of accelerating SLR can be detected in the observed sea level data. The binomial tree represents the different possible future paths of SLR uncertainty during the time horizon. However, this model is only a reasonable approximation of the evolution of the uncertain parameter when the number of time periods is sufficiently large. A path-dependent binomial tree with six time periods results in 64 future paths to consider. The resulting probability density function of the absolute SLR at the end of the time horizon is shown in Fig. 4.

<Insert Figure 4 here>

Figure 4. Probability density function of absolute SLR between 2010-2100

The way in which the effects of SLR uncertainty are dealt with over time will depend on the approach used for adapting to climate change. The robust approach, associated with a one-off adaptation step, can only deal with the full range of uncertainty by preparing for the worst-case path of SLR. This approach is selected for the hard strategy (as justified in the previous section). As such, the NPC of implementing the hard strategy is analysed for the worst-case path of SLR. This gives a higher NPC of €47.69 million, as opposed to the result of €40.38 million without any consideration of uncertainty. The reason for the higher NPC is that the defence is built higher than otherwise designed in the economic analysis without uncertainty. This is because of the minimal cost of building higher defences initially in order to deal with uncertainty, rather than the much higher costs of adapting in the future. The adaptive approach is selected for the soft strategy. This type of approach allows the flexibility to manage future uncertainties by changing the engineering design as knowledge advances. This implies that the effects of the various ways to provide flexibilities need to be incorporated for this alternative by using RIO analysis. Table 4 shows the spreadsheet model to analyse the flexibilities within the engineering design of the foreshore. The model incorporates the effects of the various ways to build in real options by changing the capital and maintenance costs to reflect the different possible design alternatives. The cost of the design alternatives is calculated with the help of RIO analysis. RIO analysis averages the NPC of the set of design alternatives over all possible future paths of SLR based on the probabilities derived from the stochastic process in order to obtain the Expected Net Present Cost (ENPC). The ENPC obtained for the soft alternative is €44.84 million. These outputs show that the soft strategy is preferable to the hard strategy when uncertainty and flexibility are incorporated into the analysis (as €44.84 million < €47.69 million).

Table 4. Spreadsheet model for analysing the ENPC of the soft structural alternative

<Insert Table 4 here>

Although the ENPC of the soft alternative is lower than the NPC of the hard alternative, this does not necessarily imply that the cost of the soft alternative will be lower for all possible future paths of SLR. It can be concluded from Table 4 that in this case study, however, the NPC of the soft alternative will always be lower than that of the hard alternative. As an example: even when the worst case path of SLR materialises, the soft alternative will have a lower NPC than the hard alternative (€45.98 million < €47.69 million). When the uncertainties considered do not actually materialise, or to a lesser extent, then the cost savings associated with the soft strategy will be higher due to the smaller required foreshore height.

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Discussion

Two approaches to the economic analysis of adaptation were considered. The key difference between the two approaches concerns the treatment of uncertainty and flexibility. While the conventional NPV approach assumes a deterministic investment path, and does not incorporate the value of flexibility into the analysis, RIO analysis is able to deal with the possibility of many different investment paths through time, and explicitly accounts for the value of flexibility. The remainder of this paper discusses the question of how the failure to account for flexibility can result in maladaptive decisions. Therefore, a sensitivity analysis has been carried out to analyse the effect of the volatility of the SLR rate on the investment decision. The sensitivity analysis focused on the volatility of the SLR rate as any flexibility built into adaptive strategies is more valuable when there is higher volatility. This does not count for (or counts to a lesser extent for) higher drifts (i.e., higher average SLR rates).

The results of the sensitivity analyses for the two approaches are shown in Fig. 5. The conclusion from Fig. 5 is that, in the NPV approach, the choice of the strategy is sensitive to variation in the discount rate only. The best strategy changes once the discount rate exceeds 6%. If the discount rate is below 6% then the hard strategy will likely be preferable, and if the discount rate is above 6 % then the soft strategy will likely be preferable. This means that the decision uncertainty concerning the best strategy is highest for a discount rate of about 6%. The degree of decision uncertainty reduces as the cost savings associated with the best strategy increase. In this approach, the volatility of the rate of SLR has no effect on the decision as to which strategy to use or on the degree of uncertainty associated with this decision.

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In RIO analysis, the choice of the strategy is sensitive not only to variations in the discount rate, but also to changes in the volatility rate of SLR. It can be concluded from these results that the relative cost of the soft strategy decreases as the amount of climate uncertainty increases. This is because the soft strategy is better able to manage future uncertainties as it has flexibility. When the value that this flexibility creates is not incorporated into the economic analysis, the cost of this strategy will be overestimated. Only where there is no climate uncertainty does RIO analysis give the same result as the NPV approach. It can furthermore be concluded from Fig. 5 that, in RIO analysis, increased volatility leads to decreased decision uncertainty concerning the best strategy. This is contrary to the common presumption that the presence of climate uncertainty leads to increased decision uncertainty, with this uncertainty frequently being cited as one of the main barriers to adaptation (EA 2008).

<Insert Figure 5 here>

Figure 5. Sensitivity analysis of the investment decision, according to the NPV approach (left) and RIO analysis (right)

The results of the sensitivity analyses for the two approaches suggest that the treatment of uncertainty and flexibility in the economic analysis has a significant effect on the choice of strategy. It has been demonstrated in this paper that NPV analysis does not account for the value of flexibility built into adaptive strategies. As soft strategies are often inherently more flexible than hard strategies, the NPV approach increases their relative cost compared with hard strategies. This may lead to erroneous decisions as to which strategy to use, and this is a typical

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example of maladaptation to climate change (Barnett and O'Neill 2010). It can be seen from Fig. 6 that the possibility of erroneous decisions based on the conventional NPV approach is highest in those cases where there is both high climate uncertainty and high decision uncertainty concerning the best strategy. In these cases, the use of RIO analysis is recommended for choosing between hard and soft strategies in order to avoid maladaptation.

<Insert Figure 6 here>

Figure 5. Possibility of erroneous decisions based on the NPV approach

Conclusion

It can be concluded that the use of conventional economic analysis approaches, such as NPV analysis, has significant limitations which could lead to maladaptive decisions with regard to flood risk and coastal management. In particular, NPV approaches do not reflect the flexibility that exists in alternative adaptive strategies. The failure to account for the flexibility built into flood risk and coastal management strategies has been subject to much criticism, and this is recognised for example, by HM Treasury and Defra (2009). This paper therefore recommends the use of RIO analysis for making choices between hard and soft strategies in order to avoid maladaptation. This is particularly significant for applications where there is both high climate uncertainty and also high decision uncertainty concerning the best strategy.

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Figure 1. Breaking the recombination structure of a binomial tree

Figure 2. Sea dike cross section

Figure 3. Approaches for adapting to climate change (adapted from Defra (2006))

Figure 4. Probability density function of absolute SLR between 2010-2100

Figure 5. Sensitivity analysis of the investment decision, according to the NPV approach (left) and RIO analysis (right)

Figure 6. Possibility of erroneous decisions based on the NPV approach

Figure1

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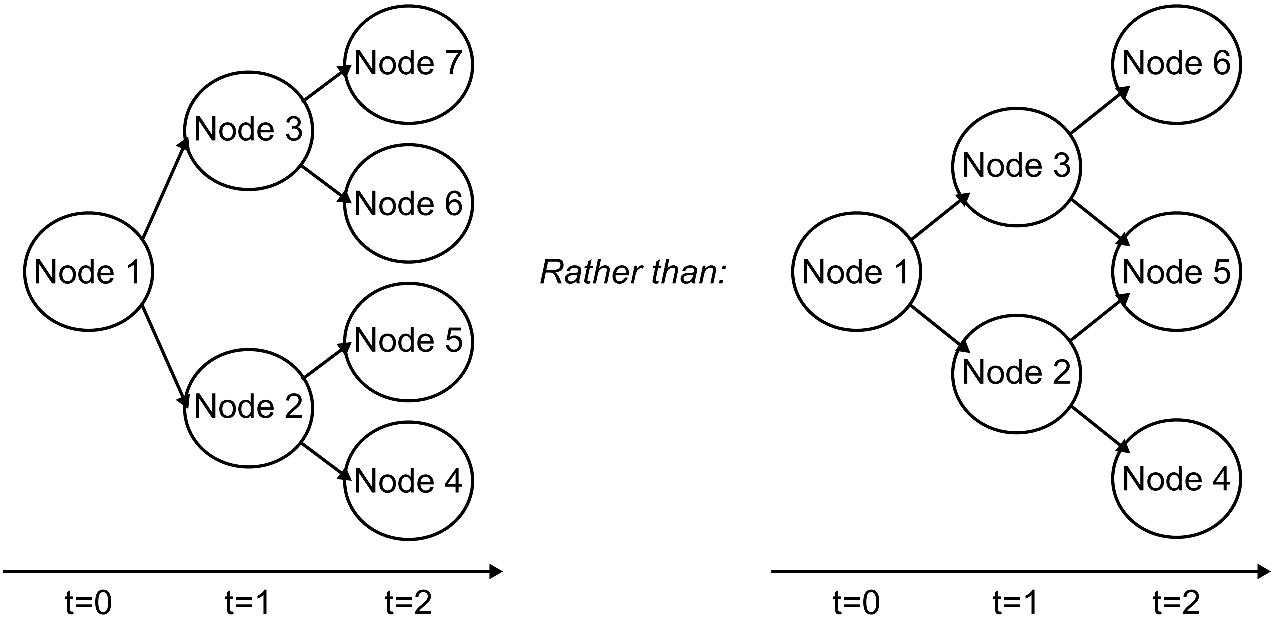

Figure2

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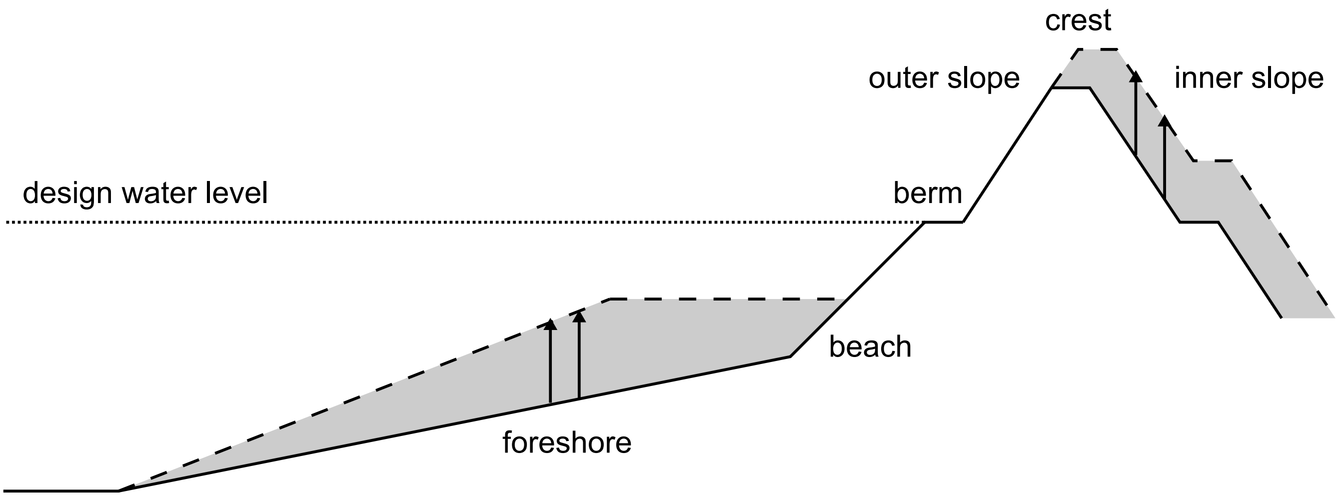

Figure3

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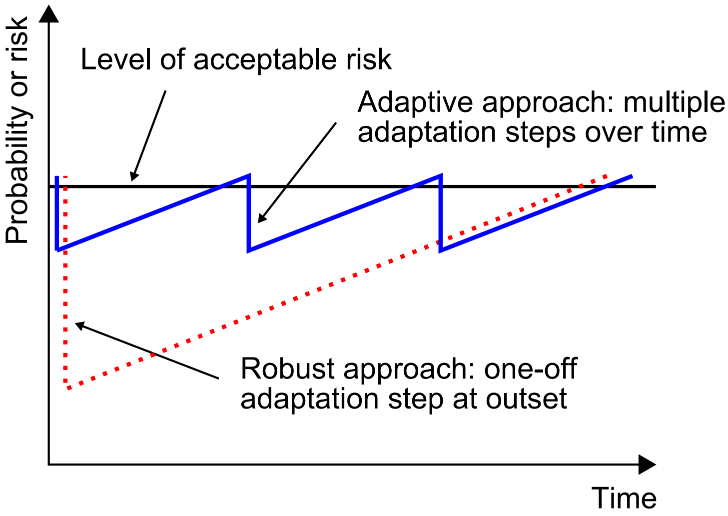

Figure4

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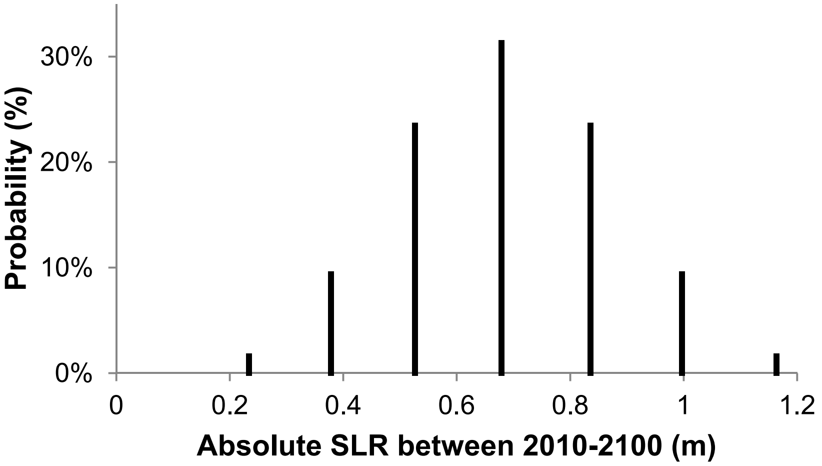

Figure5

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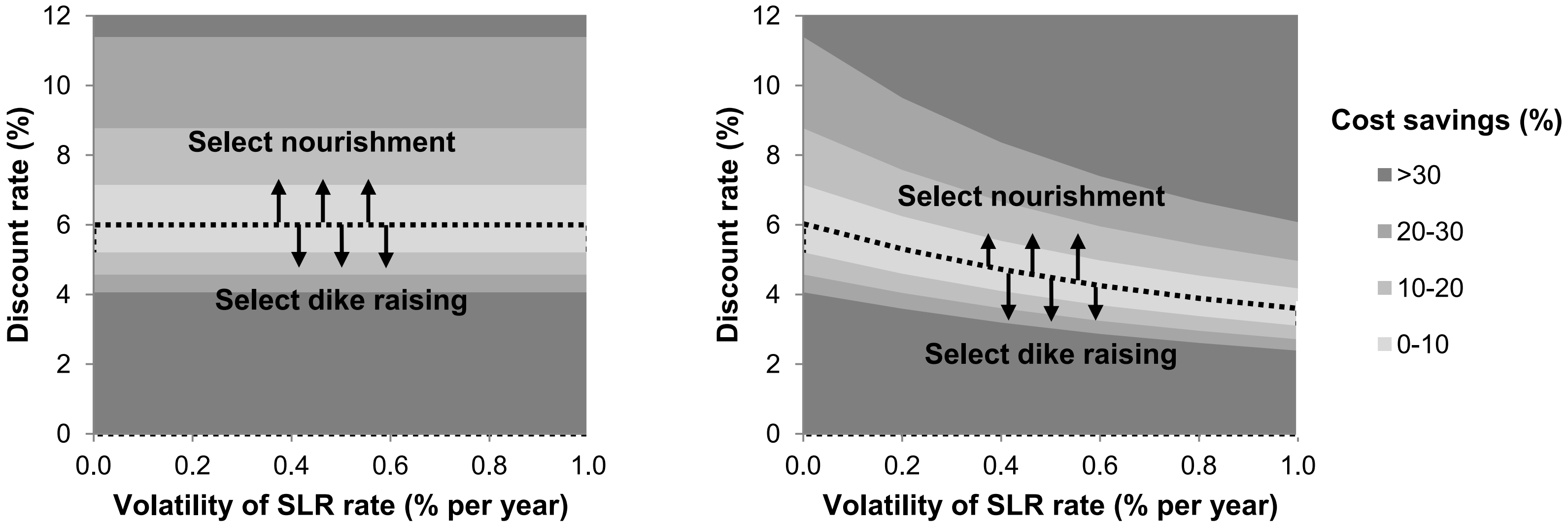

Figure6

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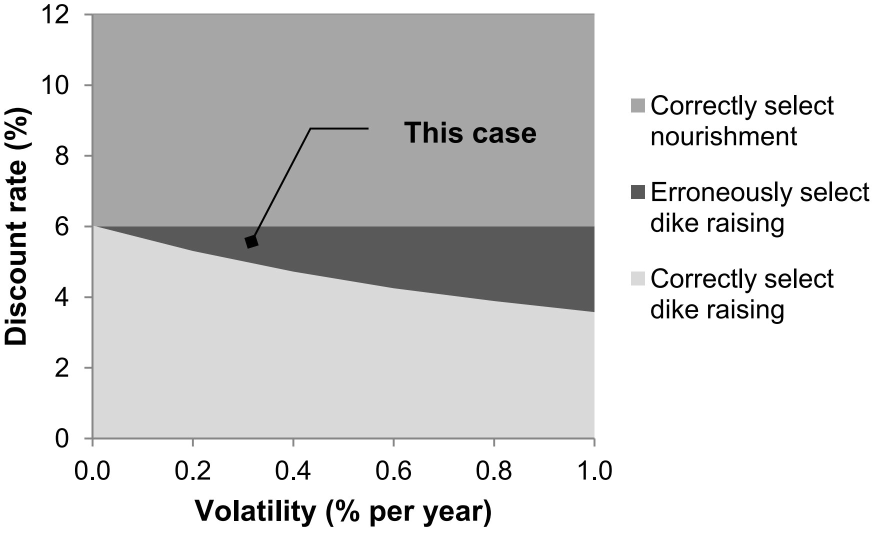

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Table 1. Indicative capital cost estimates of defence raising

SLR	**Required crest level**	**Defence raising**	**Extra required footprint**	**Capital cost**
[m]	[m +NAP]	[m]	[m]	[M€]
0.50	12.66	0.66	3.98	38.0
1.00	13.35	1.35	8.11	46.0
1.50	14.04	2.04	12.24	55.0

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Table 2. Indicative capital cost estimates of sand nourishment

SLR	**Required foreshore height**	**Required foreshore nourishment volume**	**Required beach nourishment volume**	**Total capital cost**
[m]	[m +NAP]	[m^3/km]	[m^3/km]	[Million €]
0.50	0.50	245,000	168,000	19.1
1.00	1.50	245,000	235,000	23.8
1.50	2.50	245,000	301,500	28.5

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Table 3. Spreadsheet model for analysing the NPC of the soft structural alternative

Time period	**Capital cost** [M€]	**AM cost** [M€]	**PC** [M€]
t=0	14.13	1.41	29.10
t=1	0.75	1.49	7.40
t=2	0.82	1.57	3.50
t=3	0.96	1.67	1.67
t=4	0.96	1.76	0.79
t=5	0.96	1.86	0.37
NPC			42.84

Table 4. Spreadsheet model for analysing the ENPC of the soft structural alternative

	Path														
	p=0			**p=1**			**p=2**			**p=…**			**p=63**		
Period	**Capital cost** [M€]	**AM cost** [M€]	**PC** [M€]	**Capital cost** [M€]	**AM cost** [M€]	**PC** [M€]	**Capital cost** [M€]	**AM cost** [M€]	**PC** [M€]	**Capital cost** [M€]	**AM cost** [M€]	**PC** [M€]	**Capital cost** [M€]	**AM cost** [M€]	**PC** [M€]
t=0	14.73	1.47	30.32	14.73	1.47	30.32	14.73	1.47	30.32	…	…	…	14.73	1.47	30.32
t=1	1.38	1.61	8.30	1.38	1.61	8.30	1.38	1.61	8.30				0.42	1.51	7.38
t=2	1.42	1.75	4.03	1.42	1.75	4.03	1.42	1.75	4.03				0.42	1.56	3.40
t=3	1.46	1.90	1.95	1.46	1.90	1.95	1.46	1.90	1.95				0.42	1.60	1.56
t=4	1.50	2.05	0.94	1.50	2.05	0.94	1.50	2.05	0.94				0.42	1.64	0.72
t=5	1.55	2.20	0.45	1.55	2.20	0.45	0.46	2.10	0.41				0.43	1.68	0.33
NPC			45.98			45.98			45.94						43.71
Prob			0.016			0.016			0.016			…			0.016
ENPC															**44.84**