ROBUSTNESS ANALYSIS FOR FLOOD RISK MANAGEMENT PLANNING: ON RISK-BASED DECISION MAKING BEYOND SIMPLE ECONOMIC REASONING, EXEMPLIFIED FOR THE MEUSE RIVER (NETHERLANDS)

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ABSTRACT: Flood risk management planning involves making decisions on which measures to implement, and when to do so. Rational decision making on which comprehensive strategy to implement, or on which measures to take first, requires ex-ante assessments that question whether flood risk is effectively reduced, and against which societal costs. Such decision making is usually supported by cost benefit analysis (CBA) or cost effectiveness analysis (CEA). The key economic assessment criterion applied may be the ratio between the benefits and costs of a measure or strategy (B/C), or, alternatively, the minimum of the sum of costs and (residual) flood risk. However, these metrics treat low-probability/large consequence risk and high-probability/small consequence risk as equal, which is often considered unsatisfactory in a decision making context. Robustness analysis can be used to account for this 'flaw', as it gives insight into the relationship between flood magnitude and flood consequences at the scale of an entire flood risk system, thus revealing how sensitive such a system is and whether it can still recover. A more robust system is able to deal with a variety of extreme floods, including those that exceed the 'design flood'. This paper examines how a variety of strategic alternatives for flood risk management along the Meuse River in the Netherlands score on various economic criteria and how they would be assessed from a robustness perspective. The strategies include making room for the river, strengthening embankments, and various combinations of these. The results show that the three criteria indeed lead to a different ranking of which strategy to prefer. This supports our claim that a robustness perspective may help to select a strategy that is not only economically efficient, but may also be more sustainable in view of uncertainties into the future.

Key Words: Flood Risk Management, Climate Change, Robustness, Cost Benefit Analysis, Uncertainty

1. INTRODUCTION

The taking of measures to reduce flood risk or the decision for another risk management strategy is often triggered by a flood event or a near-flood event. Katrina (2003, New Orleans) and Sandy (2011, New York) were such triggers for the US, the UK has been recurrently alarmed by floods in 2007, 2009, 2012 and again in 2014, and Central Europe experienced vast flooding in 2002 and 2013. Such triggers tend to call for action, which is, however, not always rational ('This may never happen never again!'), as evidenced by the measures then taken. For our country, the Netherlands, disastrous floods lie already somewhere in the past (the 1953 flood disaster), although the 1993 and 1995 river floods did trigger immediate action (reinforcement of defences) as well as a change in policy.

The large number of recent floods worldwide and their increasing economic impact are reason to strive for a more rational flood risk management planning in many parts of the world, and for larger time horizons too. For example, the European Flood risk Directive (European Commission, 2007) requires all member states to draw up flood risk management plans by 2015, based on preliminary risk assessments as well as hazard and risk mapping (cf. Pieterse et al., 2012).

For the Netherlands, the so-called Delta Programme undertook the drafting of an adaptation strategy in response to climate change for the remainder of this century, which comprehends flood risk management, water resources management and sustainable spatial planning. In support of this programme, a number of policy analyses are being performed that rely on assessment frameworks comprising a large number of criteria related to a comprehensive definition of sustainable development (a balance between social equity, economic efficiency, and ecological integrity; Marchand et al., 2012; 2014).

As far as flood risk management is concerned, the key objective of this Delta Programme can be defined as: to reduce flood risk to a societally acceptable level, against societally acceptable costs (after Van der Most & Klijn, 2013). And the key question which then first needs to be addressed is obviously: do the proposed measures (or strategies) effectively reduce flood risk, and at which societal costs? Or rather: are the proposed strategies purposeful at all?

Flood risk management strategies can be understood as combinations of measures: measures in the catchment to lower flood levels, defenses along rivers and coasts to protect against flooding, spatial planning measures to reduce vulnerability in flood-prone areas, and disaster management measures. One of the challenges is hence to obtain a preferred strategy by a rational and thorough ex-ante assessment of a number of possible alternative flood risk management strategies. This requires the quantification of flood risk before and after the taking of measures or the implementation of a strategy, as well as estimating the costs of taking and maintaining these measures. It usually involves flood modelling, as well as calculating damage and fatality risk (cf. Jonkman, 2007).

Such an assessment usually relies heavily on a cost benefit analysis (CBA; cf. Jonkman et al., 2004; Eijgenraam, 2006; Kind, 2014) or a cost effectiveness analysis (CEA). In a CBA, the key assessment criterion applied may be the ratio between the benefits and costs of a measure or strategy (B/C), or, alternatively, the minimum of the sum of costs and (residual) flood risk. Both require that benefits and costs be expressed in monetary terms. The B/C ratio shows which measure or strategy has the highest ‘return on investment’. If the benefits are larger than the investment cost, then it is assumed that the strategy increases economic welfare (Eijgenraam, 2000). The B/C ratio forms the basis of the UK Environment Agency’s prioritization for funding local flood protection projects (Penning-Rowsell & Pardoe, 2012). The minimum sum, in contrast, shows which strategy is societally the cheapest in the long run. In the Netherlands, this approach has been applied to derive optimal protection levels for flood defences (Van Dantzig, 1956; Kind, 2013). Interestingly, the two CBA-based criteria may point in different directions.

If not all benefits and costs are – or can be - expressed in monetary terms, a CEA may support decision making. This requires an explicit objective, in the sense of a normative view on what to achieve: which risk reduction should be realized or which level of risk is acceptable? A CEA informs which strategy achieves a pre-defined goal in the cheapest possible way. And, interestingly, a CEA-based assessment may point in another direction again.

The abovementioned economic assessment criteria rely on accurate and reliable risk estimates, which requires treating low-probability/large consequence risk and high-probability/small consequence risk as equal in order to allow expressing these in unified terms (e.g. euros/year or dollars/year). This may not be satisfactory for two reasons. First, it is difficult to account for the many uncertainties about flood levels, flooding probabilities, consequences of flooding and especially the development of each over time. And secondly, it does not match the people’s perception of risk, which clearly distinguishes disasters from frequent but acceptable damage. Related are proposals to extend existing assessment frameworks by including additional criteria which take these uncertainties explicitly into account, namely robustness – in relation to uncertainty about natural variability - and flexibility – in relation to uncertainty about future developments (De Bruijn et al., 2008).

Mens et al. (2011) elaborated the concept of ‘system robustness’ and proposed it as additional criterion which would allow establishing whether a flood risk system is able to remain functioning under a wide range of discharge waves in rivers, or whether it might be affected beyond recovery (cf. also Klijn et al., 2012). A robust system can be understood as the opposite of a vulnerable system: it is a system that can deal with temporary external stress by a combination of resistance – no response of the system to the external stress whatsoever - and/or resilience – i.e. easy recovery after response to stress. Making vulnerable flood risk systems more robust, or striving for robust flood risk systems, may well be interpreted as a purpose of comprehensive flood risk management planning into the future.

A system's robustness can be analysed – and even quantified – by constructing a so-called response curve, which shows the consequences of floods as a function of their magnitude; in case of a river, for example, the river's discharge. Mens et al. (2011) argue that one of the added values of robustness analysis, in comparison to single-value flood risk, is that it shows the sensitivity of the system to varying discharges. This is expressed by means of the proportionality; a metric derived from the response curve. Earlier applications of robustness analysis (Mens et al., 2012; Mens & Klijn, 2014) show that the more proportional the response curve the larger the range of discharges a system can cope with; and the least sensitive to uncertainties.

We shall show that the use of different decision criteria ¬- two economic criteria (benefit/cost ratio and total societal cost) and robustness - may lead to a different ranking of strategic alternatives – and hence to a different preferred strategy. We shall do so for a real and actual decision making challenge, namely on a preventative flood risk management strategy for the Meuse River in the Netherlands for the remainder of this century. The results of our case study underpin our argument that neither benefit/cost ratios, nor lowest societal overall costs suffice to base decisions on flood risk management policies on, whereas a robustness analysis may further support the decision making by revealing within which range of external stress a flood risk system may still function satisfactorily.

2. MEUSE RIVER FLOOD RISK SYSTEM AND ALTERNATIVE STRATEGIES

The Meuse River is the second largest river in the Netherlands. It originates in France and runs through Belgium before entering the country. The upstream stretches of the Netherlands' Meuse River (kmr 0-150) lie in a natural river valley with terrace morphology, where about 40 tiny built-up areas are protected by low embankments. From about kmr 150 the river enters its actual delta, where sedimentation has dominated over erosion. Instead of a terraced valley, we here find extensive protected alluvial plains. These protected areas, which are protected from the river by almost continuous embankments and for the remainder adjourn higher ground, are called dike-ring areas. We geographically limit our case study to this non-tidal but fully embanked stretch of the Meuse River (kmr 150- 260), where we find 5 large dike-ring areas and 1 small (Figure 1), and 2 very small ones that are invisible on the map at this scale.

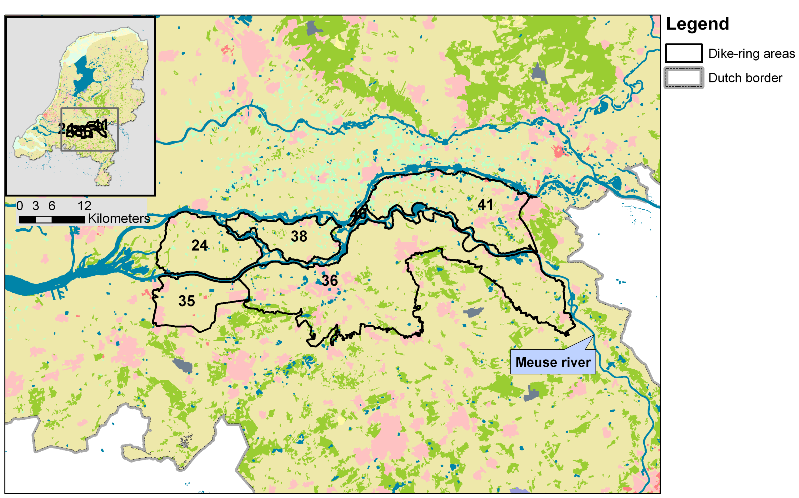

Figure 1: Non-tidal Meuse River stretch, with dike-ring areas (Mens et al., 2014)

Conceptually, our case study considers this area as ‘a flood risk system’: the combination of a physical system (the geo-ecosystem) and the society occupying it (the socio-economic system overlapping it). So we focus on the Meuse River with its active floodplains and embankments, as well as on the flood-prone area behind the embankments, but we equally focus on the people living there with their property and activities, as well as on their importance for the socio-economy at a larger spatial scale (to account for off-site effects of flooding). For after all: ‘without people no risk’ (FLOODsite, 2009).

For this area, alternative flood risk management strategies are being proposed and assessed in the context of the Netherlands’ Delta Programme (2011), which aims at drafting a flood risk management strategy for the whole country for the remainder of this century for a number of reasons: expected sea level rise, expected increasing discharges of the large rivers due to climate change, expected increasing rainfall intensities, and expected growth of the economy.For the investigated stretch of the Meuse River, more specifically, it is expected that climate change may cause the design discharge (according to current law the 1: 1250-year discharge) to increase from 3800 m3/s to 4600 m3/s in the course of this century. This would cause the 1: 1250 design flood level to go up by about 0.60 to 0.95 m, depending on location. Moreover, the current protection standards are considered outdated; they stem from the 1960s and have never been thoroughly updated, despite an increase of the population and economic growth since then. This calls for a revision of the protection standards, for taking precautionary measures to meet them and perhaps for a reconsideration of the current strategy. Because the nationwide revision of the protection standards was delayed, we performed some preliminary analyses (Kind, 2013; Asselman, in prep.). In this paper, we use the results of the analysis of Asselman to demonstrate our case. And we only discuss flood management and flood protection measures.

The current situation is considered as reference, but as doing nothing is no option, the continuation of the current strategy of raising the embankments according to the current standard of 1: 1250 per year may be considered a more realistic reference (cf. Klijn et al., 2012a). Possible alternative strategies taken into account include: giving more room to the river (to lower the flood levels so that the embankments do not need to be raised) in various degrees, raising embankments to meet higher standards (1: 4000; everywhere; or partially, with different protection levels related to the height of the risk: DS4000p), and the application of ‘practically unbreachable’ embankments (Table 1). For the analyses, all strategies have been dimensioned for the year 2050.

Table 1: Overview of strategies

Strategy abbreviation	**Strategy name**	**Explanation**
Ref	Reference	Do nothing, only maintenance
DS1250	Design Water Level 1/1250	Maintain the present protection level into the future by recurrently raising embankments with rising design water level
Room1	Room for the river package 1	Lower the design water level by making more room for the river
Room2	Room for the river package 2	Similar as Room 1, other and more measures
Room3	Room for the river package 3	Similar as Room 1, again more and other measures
Room1+	Room for the river package 1 plus additional raising of embankments	Similar, plus raising embankments as in DS1250
DS4000	Design Standard 1/4000	Raise embankments to meet a design flood probability of 1/4000 per year
DS4000p	Design Standard 1/4000 for vulnerable areas only	Similar, but only where potential flood damage is larger than €2*10^9
Delta	‘Delta dikes’	‘Unbreachable’ embankments at the current design water level (1/1,250 per year)

3. METHODS: FLOOD RISK ANALYSIS AND ROBUSTNESS ANALYSIS

Flood risk is defined as the integral of the consequences of flooding multiplied by their probability of occurrence (FLOODsite, 2009). For many analyses, it suffices to quantify the probability and consequences of the most likely flood event per individual dike-ring area. But it is obviously better to also include a worst case scenario: a higher possible flood, with the related probability of occurrence, and to account for that by a weighted contribution to overall flood risk for that specific dike-ring area. In the Delta Programme this is tackled in a standardized way, namely by including a worst case which is supposed to contribute 40% probability, and consequences corresponding to a 10 times less likely flood level. We have applied this standardized approach in our risk analyses too (despite justified objections).

For the robustness analysis, however, we need a response curve which represents the relationship between river discharge and flood damage for the entire area – not for individual dike-ring areas in isolation. Therefore, we also tried to estimate the consequences of a range of discharge waves in the river, lower and higher than the design flood, and both shorter and more prolonged, for the entire research area, in order to achieve at such a discharge-damage curve. This requires that interactions between dike-ring areas are taken into account, which can be qualified as 'whole river system's behaviour' (Van Mierlo et al., 2008; Van der Most & Klijn, 2013). For example, an upstream flood may lower the flood level in the river as it stores water or causes peak attenuation (negative feedback or 'positive system functioning'). In contrast, the flooding of one dike-ring area could also trigger a domino-effect when the water would also flood a next dike-ring area via a cascade (positive feedback or 'negative system functioning'). Below, we shall explain how we factored this 'whole systems behaviour' in.

3.1 Probability of Flooding

To establish the probability of flooding we started with the current 1: 1250 design *discharge*. Its exact size is, however, uncertain, and so is the shape of the flood wave belonging to it. For our analyses we began by following the standard approach, and assuming a relationship between discharge and frequency of occurrence.

The design discharge was then translated into a design *flood level* with the standard (prescribed) hydraulic model (WAQUA), whereas more or less frequent flood levels are derived by establishing the so-called 'decimation value': the difference (in m) between a 1: 125 and the 1: 1,250, respectively the 1: 1,250 and a 1: 12,500 flood level. This allows deriving, for example, a 1: 4000 flood level. The decimation value along the embanked Meuse River is about 0.8 m in the river reach relevant for our research.

Now the probability of flooding of protected areas obviously not only depends on the probability of flood levels, but also on the strength of the embankments. These are – according to law - designed to 'safely protect against the design flood level'. This qualification is of little help when we need to quantify their failure probability. Quantifying the failure probability of embankments is very difficult indeed, because it not only follows from overtopping or overflowing, but may also be caused by piping, sliding, slumping, erosion of the outer slope, etc. For reasons of consistency, we took the probabilities of flooding of embanked areas in the present situation from Deltares (2011) (cf. also Kind, 2013). These vary between 1:250 and 1:1,000 per year, depending on location. And for practical reasons, we assumed that changes in the probability of flooding depend on water level only; more specifically: that an increase in design water level with 1 decimation value results in an increased flooding probability with a factor 10. This assumption allows to make projections into the future and to derive flooding probabilities for different heights of the embankments.

As explained above, climate change may cause the 1: 1,250 design discharge to go up in the course of this century, resulting in flood levels along the embanked Meuse to go up too, by 0.8 m on average in the embanked lower stretch. Until the year 2050 an increase of the design flood level of 0.35 to 0.4 m is expected. This would translate into the flooding probabilities increasing by about a factor 3 to 4 in 2050 and a factor 10 in 2100. To maintain the present protection level, the embankments should be raised 0.4 m in 2050 to maintain the present protection level; or about 0.8 m to achieve a 1: 4,000 flooding probability level. With the room-for-river strategies the flood level can be lowered by 0.3 - 0.4 m to partly account for climate change; flooding probabilities however remain relatively high (same as in the present situation). This can be compensated by raising the embankments accordingly, as was done in strategy Room1+. The 'unbreachable' embankments are assumed to have a probability of overtopping 10 times smaller than the present breaching probability. The probability of breaching, however, is assumed to be 100 times smaller than in the present situation.

3.2 Consequences of Flooding

For each dike section, the flood damage resulting from a breach has been copied from an earlier study (De Bruijn & Van der Doef, 2011) for which the economic damage was systematically calculated for all 53 dike-ring areas in the Netherlands. The calculations rely on 1D-2D flood simulations (cf. Asselman et al., 2009) and on applying the national standard 'damage and fatality model' (Kok et al., 2005), which relates relevant flood characteristics to economic consequences and mortality (primarily through stage-damage curves for objects and land-use types). Flood simulations were performed for both the local design water level (in our case 1: 1,250) and for a flood level with exceedance probability 10 times smaller (in our case 1/12,500 per year). The results of the modelling exercise have been corrected for economic growth between 2000 and 2011, and have subsequently been extrapolated to 2050 and 2100 on the basis of a scenario for future growth, viz. 'Transatlantic Markets' (UNEP & RIVM, 2003). Also, to conform with the Delta Programme at large, fatalities were factored in against 6.7 million euros per person, as well as psychological damage, in order to achieve an overall 'economic damage figure' in monetary terms (cf. Kind, 2011; 2013). This allows expressing risk in euros per year as well as overall societal costs in the remainder of the century.

Finally, we assumed a linear relationship between river flood level and flood damage, so that we could interpolate between our two figures and even extrapolate to some extent. This is relevant, because climate change causes the flood levels to go up beyond the range we examined. And, in contrast, making room for rivers may lower the flood levels to below our lowest model result.

3.3 Costs

In order to enable a sound comparison of costs – both investment and maintenance – versus benefits – in terms of reduction of the flood risk, we discounted both the investment costs and the flood risk to the present, using a discount rate of 5.5% per year, as prescribed by the Dutch Government (see also Kind, 2013). This facilitates either estimating the benefit/cost (B/C) ratio or summation of investment costs and (residual) risk to achieve total societal costs.

Costs for dike strengthening were estimated using the standard cost calculation module KOSWAT (De Grave & Baarse, 2011), which is applied in the entire Delta Programme. Investment costs for the room-for-the-river measures were taken from Rijkswaterstaat Dienst Limburg (2003).

3.4 Response Curve, Resistance and Resilience

As explained above, a robustness analysis progresses from a 'simple' risk analysis by investigating a larger area and taking into account whole-system behaviour. The robustness indicators proposed by Mens et al. (2011) require a response curve to be constructed (Figure 2), showing a flood risk system's response (in our case 'damage occurring') to a whole range of possible discharge waves, instead of to only one or some discharge waves which are considered representative.

For the purpose of this case study, we simplified the robustness analysis by quantifying robustness as the sum of the resistance threshold and the *resilience range*, expressed in discharges (Figure 2). The *resistance threshold* is quantified by the lowest 'critical discharge' of all embankment sections, which is the lowest discharge that exceeds any of the critical water levels. The resilience range is the range of discharges that will cause flood damage, but where this damage does stay below the recovery threshold. In this context, resilience means that the flood risk system – especially the socio-economic subsystem – is able to recover from the consequences of flooding (Mens et al., 2011; De Bruijn et al., 2005). However, also resilience has a maximum. The recovery threshold shows the maximum consequences (economic damage, affected persons or casualties) from which the system can still recover (Mens & Klijn, 2014). The resilience range ends where the response curve exceeds this recovery threshold. Summarizing, the resistance threshold determines the resistance range, and the recovery threshold determines the resilience range. Robustness is the sum of these two ranges.

Following the proposal in Mens & Klijn (2014), the recovery threshold is arbitrarily set at 5% of the regional GDP. The GDP of the province of Brabant (where the study area is largely situated) was about €87 * 109 in 2010 (statline.cbs.nl, accessed: 07-04-2014), which translates into a threshold of about €4.4 109. If this threshold is exceeded, we assume that aid is needed from elsewhere, e.g. the national level. The national threshold, 5% of the national GDP, would indicate when aid is needed from other countries. According to our calculations this threshold, about €30 109, will never be reached as a result of flooding caused by the Meuse River.

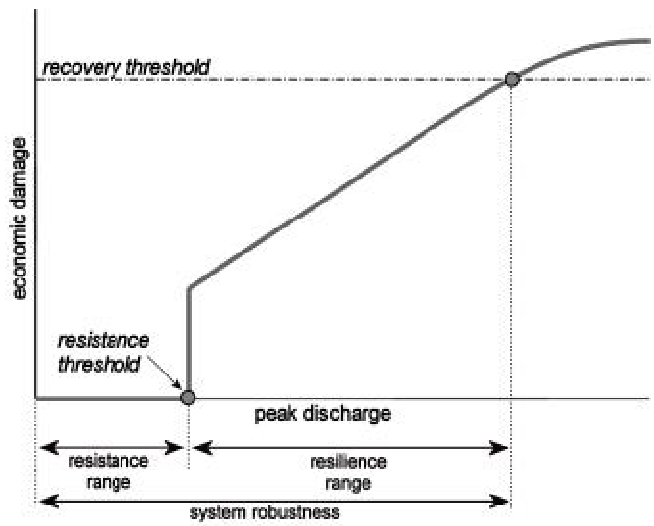

Figure 2: Theoretic response curve of a flood risk system (adapted from Mens et al., 2011)

To construct the response curves for all the alternative strategies in our case study, we pragmatically proceeded as follows:

1. For each embankment section, a ‘critical water level’ was established beyond which flooding may occur. For the reference, we assumed this to correspond with an exceedance probability of 1/250 per year. This is to account for failure mechanisms such as piping, which may occur already at flood levels well below the design level of 1/1250 per year.

2. Next, again for each embankment section, we derived the relationship between discharge and damage from a) this critical water level, b) the stage discharge relationship and c) the stage-damage relationship.

3. As step 2 was still per embankment section, we next calculated a weighted damage for each dike-ring area, based on the lengths of the individual sections. The weighted damage is calculated for a range of discharges and for each discharge separately.

4. To arrive at figures for the entire area under investigation, we could not simply add up all damage figures of the individual dike-ring areas, because they may fail in many different combinations. Therefore, we first calculated the summed damage of all possible failure combinations and then determined the median of this set, thus implicitly assuming that all combinations have the same

probability of occurrence. We assumed a maximum of 4 dike-ring failures in one event, since more was judged to be physically impossible.

4. RESULTS

Figure 3 shows the overall yearly societal costs (bars, related to left y-axis) of the alternative strategies we investigated, in comparison to those of the reference. The overall societal costs consist of the costs of implementing and maintaining measures, plus the remaining economic flood risk. Through the right y-axis Figure 3 also shows the benefit-cost ratio of the investigated strategies. All figures apply for 2050.

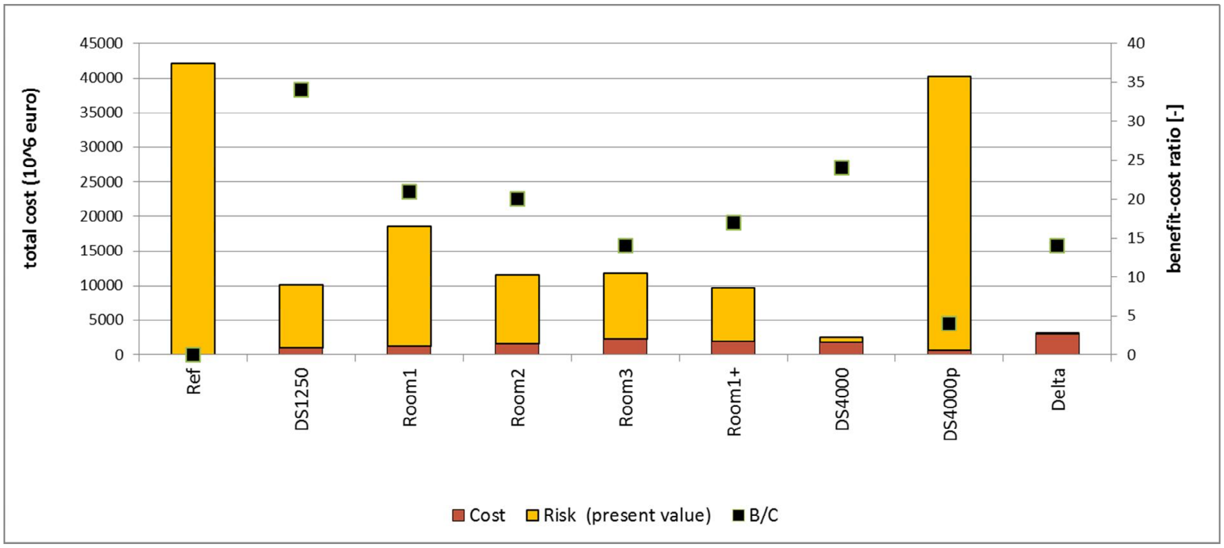

Figure 3: Economic decision criteria: benefit/cost ratio and total cost

Obviously, the implementation costs for the reference are nil, because no measures are being taken. This causes the risk to rise over the years as a consequence of climate change and economic development (cf. Klijn et al., 2012). Because current Netherlands' law does not allow this to happen, it is therefore more appropriate to compare the alternative strategies with the continuation of the present policy as reference (DS1250).

From Figure 3 we can first conclude that all investigated strategies have a B/C greater than 1, which indicates that each can be considered an economically justifiable investment, as the benefits are much larger than the investment in enhanced flood protection. But the differences are large. Continuing the current policy of meeting the existing protection standards (DS1250) scores best, whereas raising the protection standard (DS4000) is a good second. This can be explained by the fact that (slightly) raising existing embankments is, of course, relatively cheap; much cheaper than implementing entirely new Room-for-River measures. It is the difference between marginal costs versus full costs we see here.

When, however, we look at total societal costs, we should go for the alternative with the lowest possible overall costs. According to this criterion, raising the protection standards and correspondingly implementing DS4000 is to be preferred. This time, however, 'Delta' (implementing practically 'unbreachable' embankments) is a good second. It may be costly to implement, but the remaining risk is very low indeed. Only investing in better flood protection where risk is very high (DS4000p) is the cheapest from an investment point of view, but because total risk is almost as high as when doing nothing (Ref), not only the total societal costs are high, but also the B/C ratio is low!

From these economic efficiency perspectives the Room-for-River strategies score intermediate. Except for Room1, they require larger investments but reduce flood risk only to the same level as continuing the current policy of raising embankments (Room2 and Room3). Only Room1+, which also includes raising embankments where the flood level cannot be lowered sufficiently by implementing room for the river, reduces the risk slightly more. This alternative strategy combines sound protection over the full length - thanks to the embankments – with lower flood levels that pay back through less flooding extent and less flooding depth. We need to remark here that non-monetary benefits of making more room for rivers (increased natural values, enhanced landscape amenities) have not been factored in in our analysis (cf. Klijn et al., 2013).

Next, we shall take a robustness perspective and look at a whole range of responses of the flood risk system to various discharge waves in the river. Figure 4 shows the response curves that were constructed for each strategy.

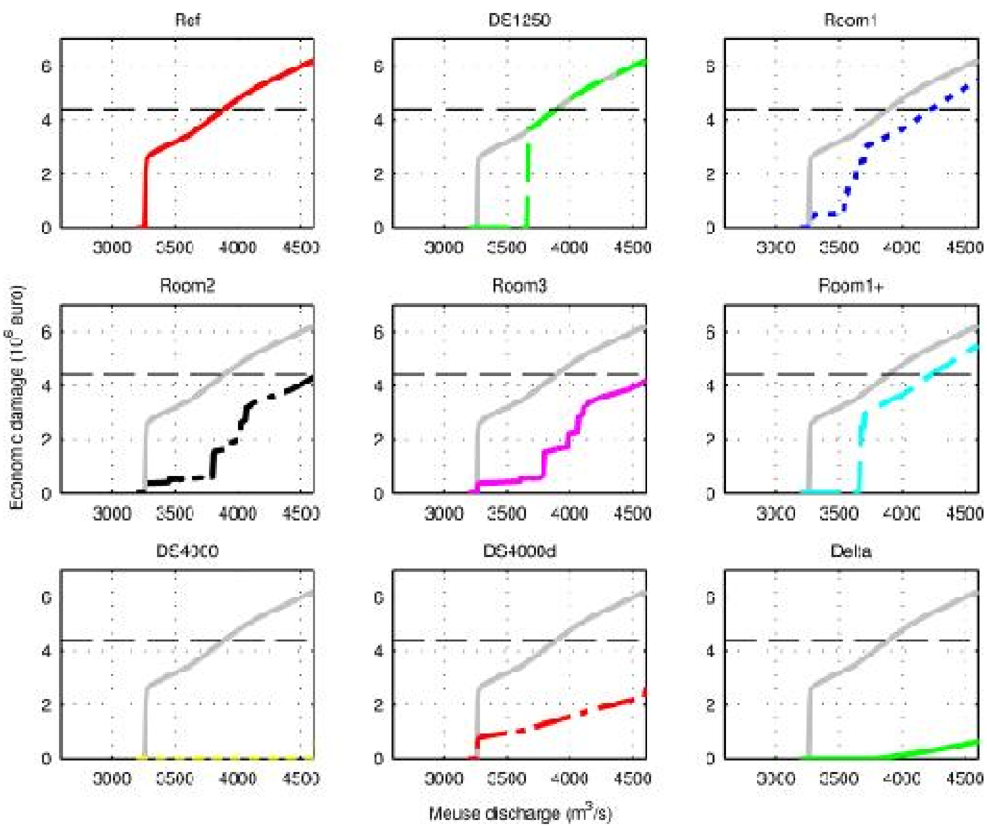

Figure 4: Response curves of each strategy

They reveal the following:

- In the reference (Ref), large damage occurs suddenly when the resistance threshold is exceeded. With higher discharge, the damage increases steadily;
- Continuation of the current policy (DS1250) causes the threshold to shift to higher discharges: from 3270 m^3/s to 3670 m^3/s; the' first' damage increases because the flood water levels are higher due to the climate change: as soon as the resistance threshold is exceeded, the damage exceeds the recovery threshold and the flood event becomes immediately 'unmanageable';

- In Room1+ the threshold is equally shifted, but the first damage is less, thanks to the lowered flood levels in the river;

- The other Room-for-River packages show much more gradual increases of the damage with increasing discharge, because the flood levels are lowered and so are the consequences of the flooding: most in Room3, least in Room1.

- With an overall raised protection standard (DS4000) the resistance threshold is shifted out of the range of the graph. We could hardly calculate any remaining risk for this alternative;

- With differentiated standards (DS4000p), in places 1:4,000, elsewhere gradually less than 1: 1,250, we see that the response curve resembles the reference in shape, but with much lower damages because flooding occurs in the least vulnerable locations first, and in more vulnerable places much later or not at all.

- 'Delta' ('unbreachable embankments') not only reduces the flood probability, but also limits the inflow into the area because the embankments do not breach, and the only water entering the area comes from overtopping.

Based on the response curves, we quantified the 'resistance threshold' and the 'resilience range', where we defined the latter as the range between the resistance threshold and the recovery threshold where the socio-economic subsystem does suffer significant damage but can still recover (cf. Figure 2). Both these metrics can be expressed in terms of m3/s (Table 2), which allows adding them up. Together, the resistance threshold and resilience range can thus inform us about the system's overall 'robustness'.

From a robustness perspective, Delta and DS4000p score best. Delta, because the 'unbreachable embankments' reduce the consequences so effectively that recovery is possible even after huge floods. DS4000p also scores well because of its large resilience range; only the least vulnerable areas are flooded which makes recovery easier. The room for the river strategies (Room1 to 3) have the same resistance as the reference, but they have a better overall score owing to a relatively large resilience range. Again, the flood consequences are effectively limited to remain below the recovery threshold for a large range of river discharges.

Table 2: Scores on resistance threshold, resilience range and overall robustness

Strategy ID	Resistance threshold (A) [m^3/s]	Resilience range (B) [m^3/s]	Robustness (=A+B) [m^3/s]
Ref	3300	400	3700
DS1250	3700	200	3900
Room1	3300	900	4200
Room2	3300	1300	4600
Room3	3300	1400	4700
Room1+	3700	500	4200
DS4000	4500	100	4600
DS4000p	3300	1800	5100
Delta	3800	3200	7000

Finally, we ranked the alternative strategies according to the three possible decision criteria applied: 'lowest total societal costs', 'highest B/C ratio', or 'most robust' in view of uncertainties about discharge frequencies, reliability of the embankments and climate change. From Table 3 we can conclude that the reference of doing nothing scores worst on all criteria, or in other words: all alternatives score better. This is the only conclusion that is supported by all criteria.

For the remainder, the decision making is not without difficulties. Continuing the present policy (DS1250) has the highest B/C ratio, but is not robust in view of uncertainties. It may fail with disastrous consequences. In contrast, the most robust strategy (Delta) is quite costly to implement – which explains the poor ranking on B/C ratio –, but is does score second best on total societal costs. DS4000p is second on robustness, but is not economically attractive at all (second worst scores on both economic criteria).

Table 3: Ranking of strategies based on the three criteria

Strategy ID	rank (total cost)	rank (B/C)	rank (robustness)
Ref	9	9	9
DS1250	4	1	8
Room1	7	3	6
Room2	5	4	4
Room3	6	6	3
Room1+	3	5	6
DS4000	1	2	4
DS4000p	8	8	2
Delta	2	6	1

5. DISCUSSION AND CONCLUSIONS

The aim of this paper was to examine if and to what extent different decision criteria would influence the ranking of different strategic alternatives for flood risk management. We assessed them by three key criteria: benefit/cost ratio and total (societal) cost – two quite common economic criteria –, and 'robustness' – a relatively new criterion in the field of flood risk management. All three criteria rely on risk analysis, and are therefore perfectly suited for decision making about flood risk management. We applied the criteria on a real decision-making case along the Meuse River in the Netherlands, where actual policy making is now underway in the context of the Netherlands' Delta Programme. In this case study, we investigated a number of strategic alternatives which are not completely comparable in their effect and also quite simplistic by character: either embankments, or room for rivers, or …. In real planning practice more balanced combinations are of course being composed, which implies that our present analysis primarily sustains the deliberations by the involved authorities and stakeholders about which elements to include in such more comprehensive strategies.

From the results, we can conclude that from a long-term perspective it is economically efficient and hence justifiable to raise the protection level, but that from a robustness point of view the measures which should be implemented to obtain these enhanced protection levels should preferably comprise 'unbreachable embankments', as well as room-for river measures – the latter partly because of their contribution to higher robustness, but also because of intangible advantages not factored in into our analyses. In the Delta Programme both types of measures are now actually being considered.

From a more scientific policy-analytic point-of-view it is interesting that the three criteria were indeed found to lead to a different ranking of strategies. Total societal cost is often considered the best criterion from an economic efficiency point-of-view when funding is not a limiting factor. This approach is now pursued in the Netherlands (Kind, 2013). The benefit-cost ratio is considered a good criterion in situations where funding is the limiting factor and the objective becomes to achieve the highest return on investment. This criterion is commonly applied in the UK (Penning-Rowsell & Pardoe, 2012), where a B/C ratio > 8 is required. Interestingly, the UK spends not much less on flood risk management than the Netherlands does (Flikweert et al., 2013), although over a much larger, but less flood-prone country.

By introducing robustness in the long-term as a third relevant criterion, we further complicated the decision making challenge about future flood risk management by implicitly introducing an additional goal, namely – apart from striving to reduce flood risk to an acceptable level against acceptable costs – to prevent disastrous consequences from which recovery is extremely difficult without help from outside. This criterion resulted in a ranking which again differed from those based on the two purely economic criteria. It consequently provokes further considerations about what should be the ultimate goal of flood risk management for the long term. We therefore propose not to rely on economic risk-based analyses only, but to also perform a robustness analysis and take a robustness perspective, as this may help to select a strategy that is not only economically efficient, but may also be more sustainable in view of uncertainties into the future.

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