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TOWARDS THE DEVELOPMENT AND EVALUATION OF ADAPTIVE FLOOD RISK MANAGEMENT STRATEGIES FOR THE RHINE ESTUARY - DRECHTSTEDEN

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ABSTRACT: Flood risk in the western part of the Netherlands will increase due to climate change, socioeconomic development and subsidence if no measures are taken. The Delta Programme is looking 100 years ahead to develop a flood risk management strategy which, in light of future uncertainties, is both flexible and robust. Different possible strategies have already been studied in previous phases of the program and some choices have already been made. The preferential strategy will be a strategy which builds on the present system of strong dikes and flexible barriers. Within this strategy, opportunities exist to replace part of the necessary dike reinforcements with room for the river measures. In this paper we describe and apply a dynamic framework for the development and subsequent economic evaluation of those strategies.

Key Words: Flood Risk, Adaptive Management, Cost-benefit Analysis, Decision Support, Tools

1. INTRODUCTION

The western part of the Netherlands is a densely populated delta with high economic value and is home to one of the world's largest international harbours, the port of Rotterdam. The area is low lying and vulnerable to flooding from both rivers and the sea. It is expected that the vulnerability will increase due to the (combined) effects of sea level rise, higher river discharges, soil subsidence and socioeconomic development.

The problem of increasing flood risk is addressed in the National Delta Programme (2009-2015). This entails multi-level collaboration between the national government, provinces, water boards and municipalities. Five national 'Delta Decisions' are being prepared, including decisions on flood protection standards (Van der Most *et al*., 2014; van Alphen, 2014; Eijgenraam *et al*., 2014; Kind, 2013), fresh water supply, and spatial planning and adaptation. In six regional sub-programmes, integrated flood risk management strategies are further developed involving regional and local stakeholders. Those strategies contain the proposed specific measures that apply for implementation in the short, medium or long term. This paper is focussed on one of the regional sub-programmes:the Delta Programme Rhine Estuary–Drechtsteden (DPRD). This sub-programme is closely related to the Delta sub-programme for the Rivers (Schielen and van der Aarsen, 2014).

1.1 Adaptive Planning in the Delta Programme

Within the Delta Programme one of the largest challenges is dealing with uncertainties about the future climate, population, economy and society. The Delta Programme tries to handle uncertainty by an adaptive way of planning, i.e. maximizing flexibility, keep options open and avoid "lock in". Even so, scenarios are used to assess whether the measures sort the same effect under different conditions.

1.2 Work done so far

The Delta Programme was initiated in 2009 after the advice of the (second) Delta Committee (Deltacommisie 2008) and distinguishes several phases. The first phase (2009-2010) contained the initial problem analysis. The purposes was to assess the plausible future changes in flood risk and fresh water supply and demand, driven by factors such as climate change and socioeconomic developments. The problem analysis indicated that water level could rise in the area with up to one meter by the end of the century and potential flood damages would increase significantly if nothing would be done (Deltaprogramma Rijnmond-Drechtsteden, 2012). The problem analysis formed the basis to develop flood risk management strategies for the Rhine Estuary – Drechtsteden area.

In the second phase (2010-2011), 'first generation' strategies were investigated. Those strategies indicated the 'edges of the playing field' and included large infrastructural works which changed the areas' entire flood protection and fresh water supply system. First generation strategies ranged from a fully closed Rotterdam area, with dams and sluices which ships had to pass and river discharge which had to be diverted to the southern branches, to a fully open river-sea strategy relying solely on the protection by strong dikes. In Jeuken *et al*. (2013b) it was concluded that those strategies were either economically inefficient or had large negative environmental consequences. The reference strategy, which in essence is a continuation of the existing system where flood protection is maintained with dikes, room for the river projects and flexible storm surge barriers (amongst which the Maeslantbarrier), showed to be the preferred 'first generation' strategy.

More recently (2011-2013), the idea of changing the river Rhine discharge distribution over its main branches has been studied (van Rhee, 2013). One of those Rhine branches flows into the northern Lake IJssel instead of the south-western delta. Changing the distribution could therefore improve the flood protection in the Rhine-Meuse estuary. The studies, however, gave ambiguous results and the national net benefit of changing the distribution discharge remained far from clear. In combination with the unknown morphological risk of altering the discharge distribution, this led to the conclusion that a change is at present not wanted.

In the last phase (2013-2014), the preferential flood risk management strategy was developed, taking the most promising measures studied in all previous phases as potential "building blocks". In the preferential strategy, the existing system with flexible storm surge barriers and strong dikes is maintained. This strategy is further assembled using the following main elements:

- dike improvements necessary to comply with existing flood protection standards;
- dike improvements needed to comply with updated flood protection standards;
- dike improvements to compensate for rising water levels and subsiding land;
- measures to lower the water levels (water retention and room for the river); and
- measures which reduce the potential consequences of floods.

Cost-benefit analysis was used to derive an initial economically efficient flood risk management strategy taking the cost of the measures and the benefits of flood risk reduction into account. By also considering the environmental benefits and benefits due to an increase in spatial quality, as well as the preferences from regional stakeholders, the final preferential strategy is now being developed by the program.

1.3 This paper

In this paper we illustrate the derivation of the economically efficient flood risk management strategy (short: efficient strategy). The challenge we face is in finding a robust optimal combination and sequence of flood risk measures, interlinking the short, medium and long term, while complying with updated flood protection standards (that are still under discussion), and taking into account uncertain climate change and socioeconomic development. We present (yet unfinished) work on the development of an evaluation tool (the "Planning Kit DPRD") and discuss some of the first results we obtained from analysing several strategies. The approach we took suggests further (maybe academic, probably labour intensive) work to extend this type of analyses with no-regret or real option analysis. Since we fully deployed our modelling framework only in the last phase of the sub-programme, we expect that applying it to other delta regions, which are in an earlier phase of policy formulation and where more strategic options are still being considered, will yield additional valuable results to refine the approach.

2. DEVELOPING ADAPTIVE STRATEGIES

The challenge of finding a robust and optimal combination and sequence of interventions linking short and long term agendas is also part of the challenge of adaptive planning and adaptive management. We provide a brief overview of the current literature on the subject and then shift to the application in the Rhine Estuary - Drechtsteden area.

2.1 Adaptive planning and management

According to Sayers et al. (2012), central elements of adaptive planning are: “responses to changes that are effective under the widest set of all plausible future scenarios; responses do not foreclose future options or unnecessarily constrain future choice; relevant changes are foreseen through targeted monitoring and scenarios of the future are continuously being reassessed; and policies, strategies and structure plans are appropriately redefined”. A general procedure to make an adaptive plan and comply with the aims as described by Sayers et al. (2012) is given by the ‘Dynamic Adaptive Policy Pathways’ (DAPP) framework (Haasnoot et al., 2013) that combines the approach of adaptive policy making (APM) (Kwakkel and Walker 2010) and adaptation pathways (AP) (Haasnoot et al., 2012a).

Adaptive delta management (ADM) is the adaptive planning approach chosen by the Delta Programme for dealing with uncertainties to support the decision making process. It tries to link decision making now to options for adaptation in the future (van Rhee, 2012). Central elements in ADM are the use of so called Delta scenarios (Bruggeman et al., 2011), the assessment of key vulnerabilities by looking for adaptation tipping points (Kwadijk et al., 2010), the use of adaptation pathways (Haasnoot et al., 2012) to envision the portfolio of options, its effectiveness and its flexibility, and a systematic regional multi-stakeholder approach to combine challenges across different agendas (water management, water policy and spatial planning).

The adaptation tipping points (ATP’s) in combination with the Delta scenarios define the time range within which the current water management strategy will not meet its objectives anymore, which is a trigger to adjust the strategy or switch to a new strategy. In addition, opportunities may arise from other agendas to shift necessary investments to an earlier timeframe (Koukoui et al., 2013). ATP’s or opportunities not necessarily define the economic optimal moments for investments.

The idea of ADM, which has a lot of similarities with the Thames Estuary project in the UK (Reeder and Ranger, 2012; Jeuken and Reeder, 2011), has been previously applied within the Delta Programme Rhine Estuary-Drechtsteden (Van der Brugge et al., 2012). For this area the most dominant ATP’s are the end of life time of the major storm surge barrier the ‘Maeslantbarrier’ and the limitation of freshwater supply due to increasing salinization of the fresh water inlet near the city of Gouda (Kwadijk et al., 2010). In addition it is clear that increasing sea level rise, local subsidence and higher river discharges, together with socioeconomic growth, will increase the flood risks in the region if the protection level is not adjusted or other measures are not taken (Jeuken et al., 2013b). The latter is difficult to express as an ATP related to current management practice, since the existing policy already consists of a regular (6 yearly) assessment and improvement of the dike system based on clear targets that should be met according to the Water Act. Whenever a dike does not meet these targets, it is programmed for improvement in the national Flood Risk Management Programme.

2.2 Adaptive planning and the preferential strategy

Considering the choices that have already been made in the previous phase in the Delta Programme, one of the remaining challenges for the regional sub-programmes is to find out how to minimize the costs of flood protection over a longer time period of 50 to 100 years ahead. and by doing that also widening the scope by considering more options than dike improvement alone. Instead of waiting for local thresholds to be exceeded, the Delta Programme therefore is looking forward in its anticipating strategies for optimization of investment paths in time and in combination of different kinds of measures. Figure 1 shows the different measures that can be used to assemble the potential strategies in more detail.

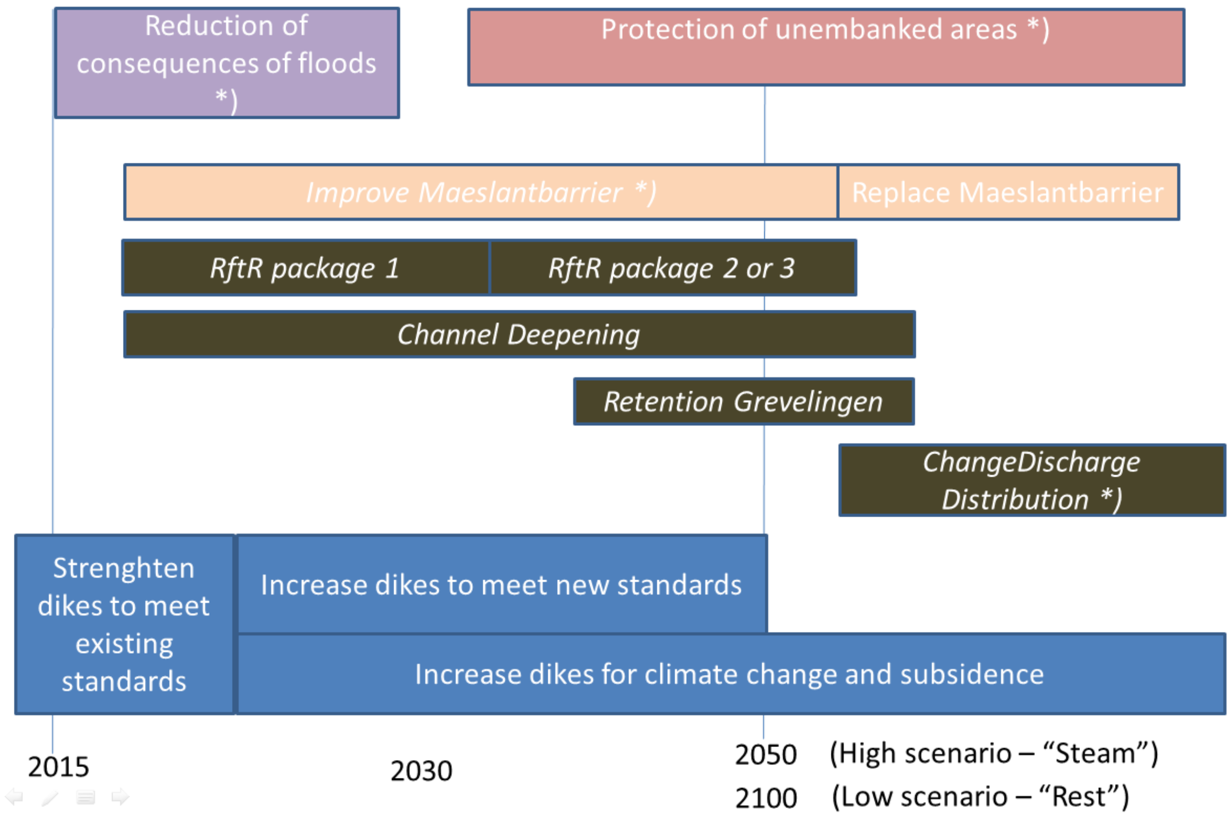


*Figure 1: Different elements of the potential strategies with indicative time window according to two of the Delta Scenarios (Steam and Rest). Each colour represents a different category of measures. From top to bottom: measures to reduce the consequences of floods, measures to protect unembanked areas (purple), measures related to the storm surge barrier Maeslantbarrier (pink), measures related to 'making room for rivers' (dark green). Measures for dike-improvement (blue) are divided into three categories. Improvements are needed because dikes (i) are not meeting existing standards, (ii) are not meeting new standards or (iii) have to be improved to cope with future water levels due to climate change or soil subsidence. Measures indicated with *) are not assessed within our framework, those have either already been rejected or have little interference with the other elements in the strategy.*

To cope with increasing climate change, more and larger measures can be applied. This can be viewed as the final portfolio of options from ADM. However, it is not a portfolio of options one can simply choose from. This has to do with:

- the area is so large that different measures in different areas are needed to reach the targets set by the programme. For instance, applying room for the river solutions is only reaching part of the targets set by the programme because the size and impact area is limited. However, the impact areas of different measures, do overlap;
- the effects of the different measures is different. Some measures increase the strength of a dike, some the height, some decrease the water levels and some reduce the consequences of floods. Especially the strength of the dikes (piping) is a problem in parts of the area, which can be repaired by dike improvements only;

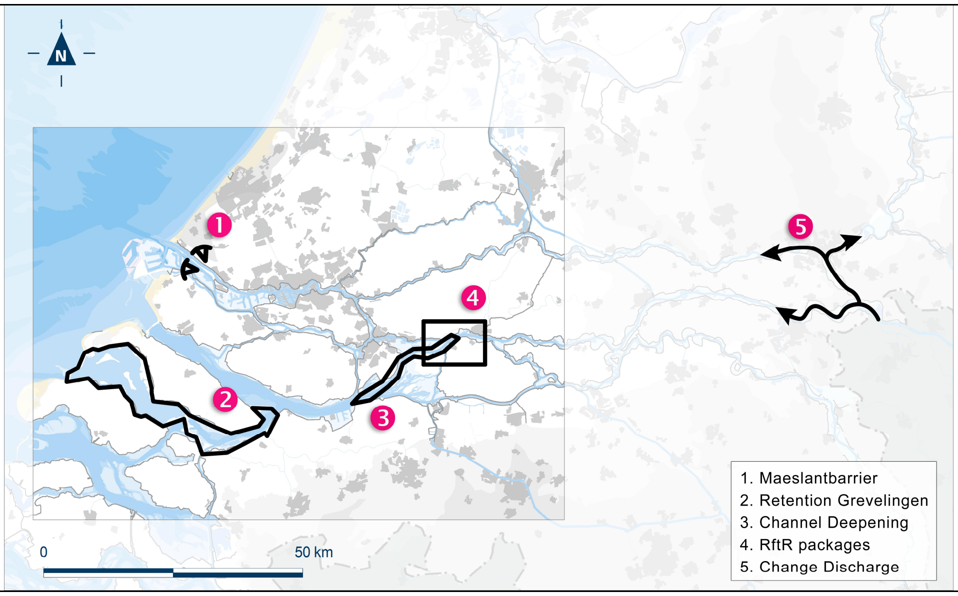
- there are good opportunities to combine the three challenges for dike improvement (mainstreaming agendas). It is in general much cheaper to add a meter once (to comply both with existing and new standards and to compensate climate change) than come back three times in a couple of decennia. The only drawback could be that since the climate signal is uncertain, there is a risk of overinvesting, since improvements in dikes which do not meet current standards, have to start in early years.

The bottom-line of the preferential strategy is thus a strategy of dike improvements that may or may not be diversified with other measures in particular parts of the area. The earlier mentioned ATP for the storm surge barrier is determining a decision point for replacing the barrier, or deciding differently. However, after the phase of the first generation strategies, it has been decided to develop strategies for the following phases in which the Maeslantbarrier is replaced.

Table 1 presents a short overview of the water level reducing measures which have been used as building blocks and as such as partial alternatives for dike reinforcements within the preferential strategy.

Table 1 Summary of the final set of potential options other than dike improvements

No on Map	Code	Description	
1	MLK	Maeslantbarrier	Replace Maeslantbarrier
2	Grev	Water storage lake Grevelingen during high river discharges	In 2015 the Lake Volkerak-Zoommeer is prepared for temporary water storage when exceptional conditions result in the combination of a closed storm surge barrier and high river discharge. In view of the expected climate change, it is being considered to expand the storage capacity of Lake Volkerak with Lake Grevelingen.
3	Chan	Channel deepening Boven and Nieuwe Merwede	Channel deepening is also a measure to lower the water levels near the bottle neck in the River Merwede. The deepening of the channel is located in the Boven Merwede and Nieuwe Merwede.
4	RftR1 *RftR2* RftR3	Room for the River package 1 *Room for the River package 2* Room for the River package 3	In the eastern part of the area is a bottleneck in the river Merwede during high river discharges. This causes backwater effects. The three *Room for the River* building blocks each consists of one or multiple measures with the aim to widen the riverbed to lower the water levels. Three different packages were developed. RftR1 and RftR2 can be deployed alone or in combination. RftR3 is a subset of RftR2 and can be deployed alone or in combination with RftR1, but not in combination with RftR2



3. THE PLANNING KIT, A TOOL FOR EVALUATION

The Planning Kit DPRD was developed as a decision support tool to evaluate a wide variety of flood risk management strategies, wider than the set of strategies finally evaluated since also measures which reduce the flood consequences (damages and/or casualties) are incorporated. In the Dutch situation, however, due to the existing high flood protection standards, measures which reduce flood consequences are in general not cost efficient; they are therefore no longer considered as important building block.

The tool is implemented in the *C#* programming language and consists of a database, a calculation module, a user interface and a post-processing module that transforms the results in the desired output (Kind et al., in prep). The tool determines nominal and present values of all costs of measures and the present value of the cost of expected flood damages.

The user can choose for the calculation the (new) flood protection standard, climate change and socioeconomic development according to one of the four Delta scenarios, and the selection of other measures which lower the water levels or reduce the consequences of a flood. Those other measures can be assumed for implementation at any year in the period 2017-2100.

The flood protection standard is expressed as a flood probability per year (Van der Most et al. 2014). Those can also be expressed in terms of design water levels - the water level the dike has to minimal withstand in order to provide the required level of flood protection. In the Rhine Estuary – Drechtsteden area, we have distinguished more than 200 dike stretches, with an average length of 3 kilometer. For each dike, hydraulic information is provided in the database concerning the actual height, the water levels for different return periods, water level rises due to climate change, soil subsidence, and so on. Also information on the cost of improving the dikes, in steps of 10 centimeters up to 2 meters, is included in the database.

Dike reinforcements are considered when its height is lower than the design water level, causing water to flow over the dike after which the dike eventually breaches and flooding occurs. This is valid under the assumption that the dikes comply with existing design rules, which state that dikes should be strong enough to withstand water up to the crest, in which case the dominant failure mechanism of the dike is “overflow and overtopping”. However, we should note that recent research has indicated that a substantial number of dikes in the Netherlands are not strong enough to withstand water up to the crest and have (severe) ‘piping’ problems (Jongejan et al., 2011). For the dike sections where the piping problem is known, the Planning Kit addresses the piping problem by strengthening the dikes, for which also costs are included in the database. After addressing the piping problem, the dikes comply with existing design rules and it is safe to assume that “overflow and overtopping” is the dominant failure mechanism. Now we can reduce the probability of flooding by heightening the dikes or lowering the (design) water levels.

Due to climate change, the water levels will rise over time. At the same time, subsidence is responsible for a gradual decline in dike height. If no action is taken, in some future year the dikes will be too low and will have to be heightened. Figure 2 shows as an example for one dike section the development in time of the design water level (blue line) and the dike height (continuous green line).

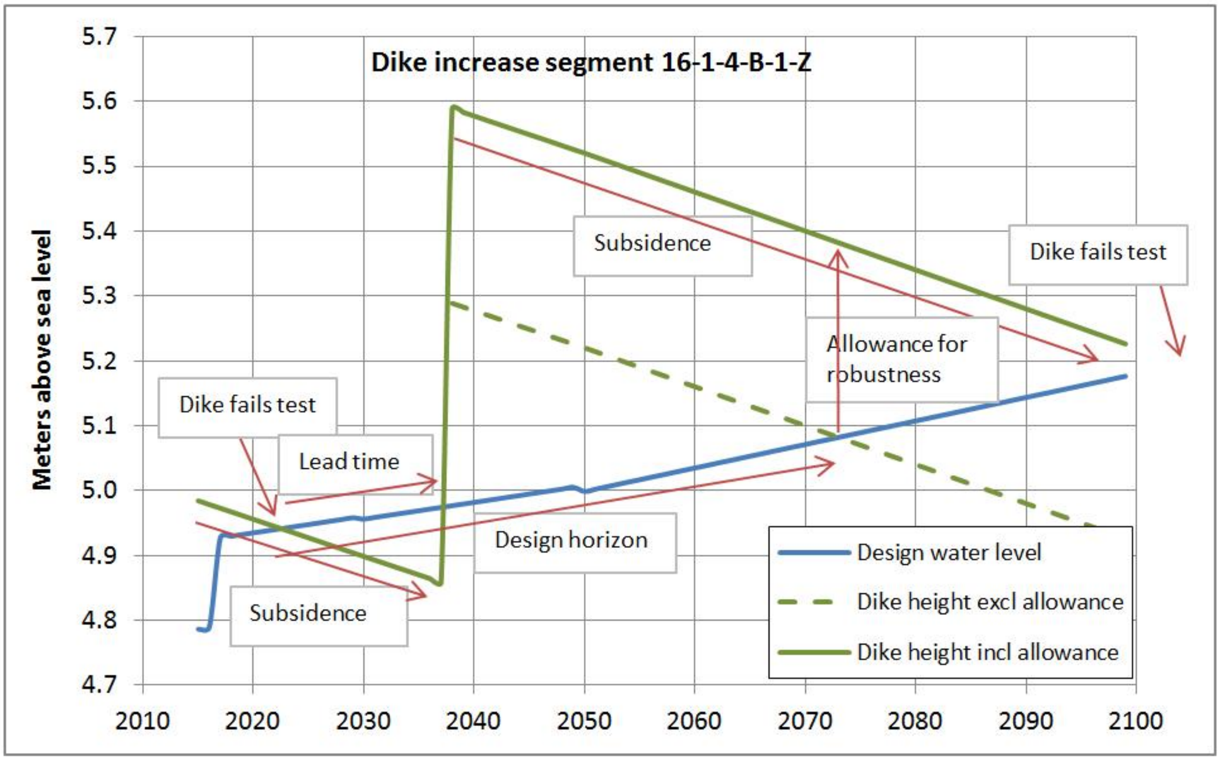


Figure 2: Dike reinforcement scheme, taking into account water level rise due to climate change and decline of dike height due to soil subsidence

The Planning Kit computes on an annual basis the design water level and dike height, taking into account the effects of climate change and soil subsidence. For each year, the dike has to withstand the dike height test. When a dike fails this test, the dike is heightened after a lead time of 15 years. We have incorporated this lead time to accommodate for the time laps between rejection and reinforcement of a dike, due to policy decisions, design of the reinforcements, procurements, etc. A period of around 15 years is also in line with todays' practices.

The amount of dike heightening is determined following the current design practices in the Netherlands (Ministerie van Verkeer en Waterstaat & Expertise Netwerk Waterkeren, 2007). To determine the amount of necessary dike heightening, a design horizon of 50 years is used, starting from the year of rejection. This means that after heightening, the dike has to withstand the dike height test for 50 years after the rejection, on basis of projections for climate change, soil subsidence and - if agreed upon - planned future measures which will lower the design water levels. An additional allowance for robustness of 30 centimeter in the design of the dike is added. The dashed green line in Figure 2 shows the amount of dike heightening based on the design horizon. The continuous green line shows the added dike height due to the allowance for robustness. Due to this allowance, the dike is expected to fail the test again only after the year 2100.

To lower the design water levels in the area, the design water level reducing measures described in section 2 can be selected in the Planning Kit, in any year between 2017 and 2100 and in (almost) any combination. Those measures will lower the design water level, causing the dike to pass the dike height test longer, and hence investments for dike reinforcement can be postponed. (In fact, the two small drops of the design water level in 2030 and 2050 in Figure 2 are caused by two assumed measures located far away from dike, causing it to have a minimal but visible effect). The postponement of dike investments ultimately translates in a lower present value of the investment cost; this makes up an important part of the benefits of the measures which reduce the water levels.

The Planning Kit also computes the expected flood damages in the area on an annual basis. This does not only include property damages, but also damages due to business interruption, indirect damages, and the damages due to casualties, following the approach of Kind (2013), Eijgenraam et al. (2014) and Bočkarjova et al. (2012). The Planning Kit contains information on damages and casualties based on in total about 110 inundation scenarios (Kind, 2013 and Eijgenraam et al., 2014). The damages increase on an annual basis depends on the Delta scenario chosen for the calculation (e.g., Steam or Rest).

The potential damages are combined with the flood probabilities of the dike. The flood probabilities are computed on basis of the projected surplus or deficit in dike height in reference to the design water level. Without measures, the probability of flooding, and therefore also the expected annual damage, will increase over time due to climate change and subsidence. Investments in heightening the dikes or lowering the design water levels will decrease the expected annual damage. Those are the second part of the benefits.

The Planning Kit calculates the present values of all costs of measures and of expected damages. For discounting costs and benefits, we use the 5.5% real discount rate per year, as prescribed by the Dutch government. Although we are only interested in developing and evaluating strategies for the period till the year 2100, we use a time horizon of 200 years (2015-2215). By using such long time horizon, there is no need to worry about salvage values of measures for the remaining useful lifetimes after the year 2100, which may affect the outcome of the analysis.

4. EVALUATING THE STRATEGIES

Given the constraints imposed by the policy decisions already taken in the previous phases of the regional sub-programme, notably that (i) the ‘backbone’ of the preferential strategy for the Rhine Estuary – Drechtsteden area is the continuation of the existing strategy with a flexible storm surge barrier, and (ii) no change in the discharge distribution over the river Rhine branches is warranted, the preferential strategy will in essence be a strategy based on further dike reinforcements. A number of measures which lower the water levels are however available as (partial) alternatives for dike heightening, either alone or in combination. Economic evaluation can help decision making by answering the following questions:

1. which water level reducing measures are cost efficient?;

2. when should those measures be considered for implementation?; and

3. what is an optimal combination of measures, sequence and timing?

Determining the optimal combination, sequence and time frame for implementing the measures is both relevant and challenging, because (considering only one Delta scenario):

a) some of dikes have to be reinforced in the short term because of the existing problems with piping; opportunities to combine the investments with dike investments needed for to climate change or higher flood protection standards exist leading to substantial synergies and cost savings (hence: choose dikes and postpone water level reducing measures);

b) other dikes are strong enough and have excessive height (hence: postpone water level reducing measures);

c) still other do not suffer from piping problems and have no excessive height, those will soon have to be reinforced due to climate change and/or increased protection standards, unless the water level is lowered by other means (hence: speed up water level reducing measures);

d) the water level reducing measures will affect multiple dike segments characterized under (a), (b) or (c) (hence: it is complicated to see what an optimal timing for alternative measure is); and

e) part of the effect area of the measures overlap (hence: system approach is needed).

If we take the five water level reducing measures from Table 1 and if we consider for each of them four time frames for implementation – say short term (2030), medium term (2050), long term (2070), or not at all - this would already give 1024 possible combinations of measures in time ('strategies'). Such evaluation calls for batch or optimization functionality in the Planning Kit, which we did not develop. The actual relevant number of combinations is, however, much smaller, for example since the Room for the River-3 package cannot be combined with the Room for the River -2 package, or due to the limited overlap between the impact area of the retention measure in the Grevelingen and the other water level reducing measures. Within our project, we have chosen to evaluate only 16 strategies, which are schematically presented in the Figure 3.

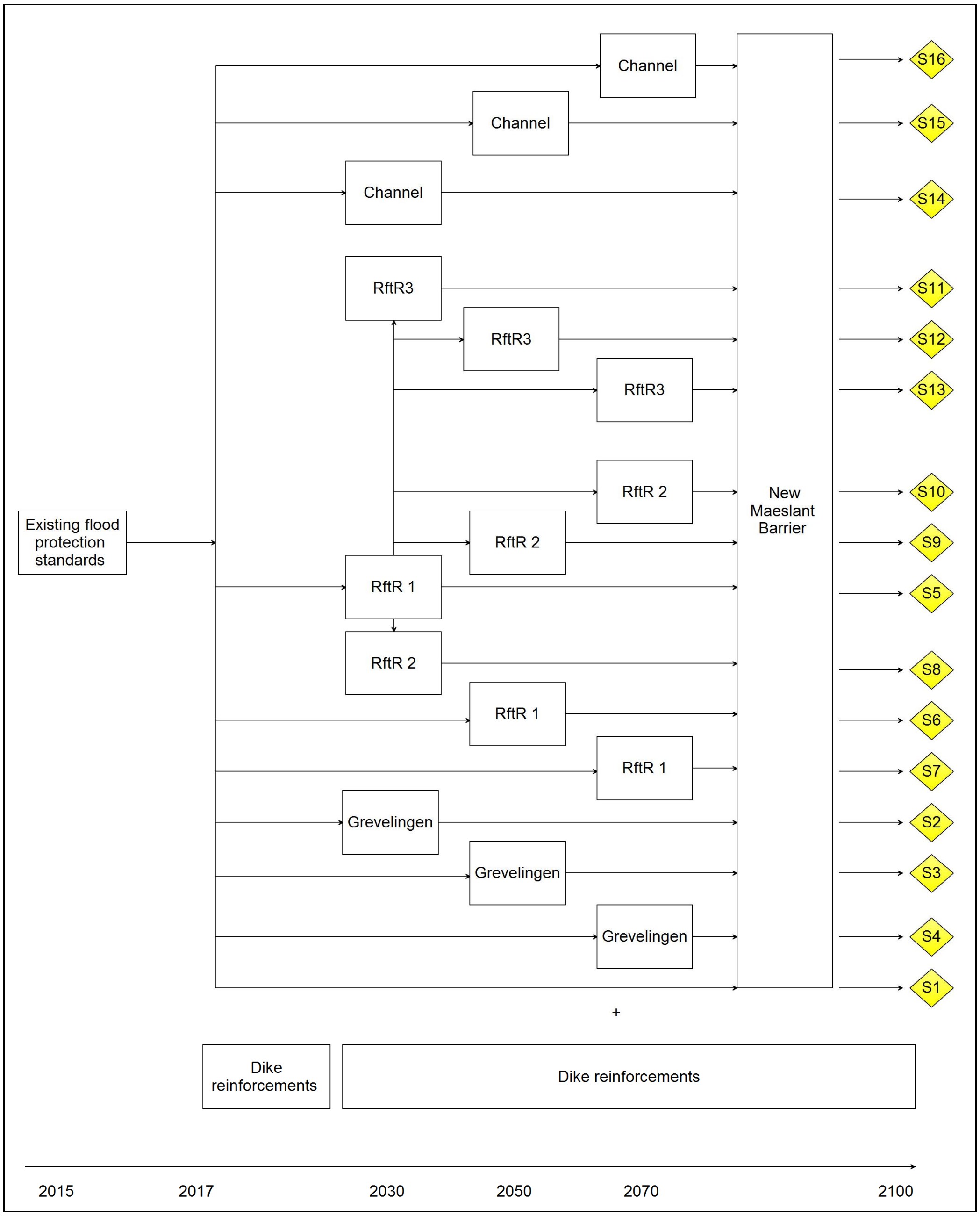


Figure 3: Evaluated strategies, Steam scenario

We evaluated the strategies using two of the four Delta scenarios, Steam and Rest. In the Steam scenario, high climate change is combined with high economic growth; the rise in future flood risk is highest. The Rest scenario is at the other end of the spectrum – low climate change and low economic growth. Strategies which perform well under all scenarios are often called "no-regret", while strategies which perform well under only few (normally high climate change and high socioeconomic growth) scenarios do imply potential regret and may be considered for implementation in a more temporized manner. We will illustrate the results for the Steam scenario.

Table 2 gives the present values of the costs of the measures and the cost of expected damages for the different strategies. The strategy with the lowest total cost is the most efficient strategy.

Table 2: Summary of strategies and present values of costs and expected damages Steam scenario

Strategy No.	Measures of the strategy with assumed year of implementation					Costs, in Million Euro Present Value, 2013 prices			
	Grev	RftR1	RftR2	RftR3	Chan	Cost of Dikes	Cost of Water Level Reducing Measures	Cost of Expected Damages	Total Cost
S1						1771	58	1763	3592
S2	2030					1730	184	1709	3623
S3	2050					1732	101	1752	3585
S4	2070					1767	73	1752	3591
S5		2030				1737	314	1749	3800
S6		2050				1742	146	1767	3655
S7		2070				1771	88	1762	3620
S8		2030	2030			1710	552	1740	4003
S9		2030	2050			1726	396	1750	3873
S10		2030	2070			1737	342	1748	3826
S11		2030		2030		1686	334	1749	3768
S12		2030		2050		1723	321	1750	3794
S13		2030		2070		1736	317	1747	3800
S14					2030	1734	125	1742	3601
S15					2050	1740	81	1765	3586
S16					2070	1771	66	1759	3596

Total costs range between 3.6 and 4.0 billion euro present value (nominal between 6.3 and 7.3 billion euro). The relative small difference is because in each strategy the majority of the dike reinforcements are needed to meet existing and future flood protection standards and to compensate for climate change and soil subsidence. Strategies S1 (reference strategy with no water level reducing measures), S3 (Grevelingen in 2050), S4 (Grevelingen in 2070) and S15 (Channel deepening in 2050) are the strategies with the lowest total cost.

On basis of the total costs of the strategies we are able to analyze the costs and benefits of individual water level reducing measures. We distinguish two types of benefits of the measures, which we derive from a comparison with a reference strategy. First is the reduction in the present value of the cost of dike reinforcements. This benefit arises since investments in dikes are postponed as a consequence of water level reducing measures. The second benefit is the reduction in the present value of the expected damages. This benefit arises only when measures are implemented relatively early, before a dike which has a positive water level reducing effect from the measure has failed the height test. This will lead to temporarily excesses (above the legal standard) in flood protection for certain dikes, and hence to a further reduction of the expected damages. Having defined those two types of benefits, we calculate benefit-cost ratios by dividing the total of the two types of benefits by the cost of the measures, see Table 3.

Table 3: Differences in present values of costs and damages compared to a reference situation (in million euro), and benefit-cost ratios. Steam scenario.

1 Strategy No.	2 Reference	3 Cost differences between Strategy and Reference Dikes	4 Water Lowering Measures	5 Expected Damages	6 Cost	7 B/C= -(3+5)/(4)
S2	S1	-41	126	-54	31	0.75
S3	S1	-39	43	-11	-7	1.17
S4	S1	-5	15	-11	-1	1.10
S5	S1	-35	257	-14	208	0.19
S6	S1	-29	88	4	63	0.29
S7	S1	-1	30	-1	28	0.07
S8	S5	-26	238	-9	202	0.15
S9	S5	-10	82	1	72	0.11
S10	S5	0	28	-2	26	0.06
S11	S5	-51	20	-1	-32	2.63
S12	S5	-13	7	1	-6	1.85
S13	S5	0	2	-3	-1	1.24
S14	S1	-37	67	-21	9	0.87
S15	S1	-31	23	2	-6	1.26
S16	S1	-1	8	-4	4	0.54

Note that the Room for the River 2 and 3 packages (S8-S13) have been analyzed against a reference including the Room for the River 1 package (S5), and all other strategies have been analyzed against a "dikes only" strategy (S1).

Table 3 gives a good indication which measures are economically efficient and also in which period. Retention in the Grevelingen basin is profitable at the margin, with a benefit-cost ratio of 0.75 in 2030 (S2), 1.17 in 2050 (S3) and 1.10 in 2070 (S4). Most dikes which benefit from retention in the Grevelingen do not suffer from piping problems and have initially surplus height, hence waiting for climate change to occur is a good strategy.[1] Room for the River 1 and 2 are not efficient in the short, medium or long run (S5-S10). Room for the River 3, however, which has only been analyzed in combination with 1, shows to be very efficient (S11-S13). Channel deepening of the Merwede is a profitable measure in the medium term (2050, S15). If we wait too long (2070, S16), the measure will not lead to a reduction in the cost of the initial round of dike increases but will come too early to reduce the cost of the second round of dike increases (after the year 2100, due to the 30 cm allowance for robustness).

The results suggest an optimal strategy for the Steam scenario, with retention in the Grevelingen and channel deepening in 2050 (S3 and S15), and a small Room for the River 3 package in 2030 (on basis of S11). Analyzing this strategy with the Planning Kit results in total costs of 3569 million euro, which is lower than the total costs of all other strategies in Table 2.

5. DISCUSSION AND CONCLUSION

In this paper, we have described our approach on the economic evaluation of adaptive flood risk management strategies for the Delta Programme Rhine Estuary - Drechtsteden. We developed a hydro-economic model to evaluate the costs and benefits of single strategies (the Planning Kit DPRD). We have shown that even if we consider a few measures and a few years for implementation, the number of potential strategies to be evaluated may become already very large. Combining all results for different strategies under different climate change and socioeconomic scenarios in order to derive a robust optimal

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[1] In the Rest scenario, this measure is not beneficial at any of the three moments we examine.

strategy will certainly require assessment models comparable to the Planning Kit DPRD with batch functionality or optimization procedures.

An important simplification in our model is the summation of the effects of single measures on the design water levels. The water levels in the area are influenced by both tidal and fluvial effects. This makes it a complex system, with non-linear effects in the determination of water levels for high return periods. The summation of effects on design water levels might introduce an error. The overall effect of a combination of measures on the design water levels might be larger or smaller than the summation of the effects of single measures. At this moment, we cannot deal with this limitation in our approach.

The adaptive strategies we study in this paper do not differ a great deal from each other. They are basically strategies with dikes with a few options for other efficient measures. Comparable computations for the Rest scenario result in comparable optimal strategies, with measures that can be implemented in later years than in the Steam scenario. In this sense our approach provides robust guidance for the development of the strategy. We expect the application of the methodology to be much more interesting when the differences between strategies to be assessed are larger. A big challenge lies ahead to find optimal adaptation pathways which take also uncertainties into account. The framework described in this paper serves as a first step and can easily be modified to include no-regret analysis or real option analysis, but much remains to be done. Extending the framework with non-monetized cost and benefits could also be considered. We leave this all for future development.

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