Ensuring a Habitable and Sustainable Ijsseldelta

A research report providing a flood risk management plan under deep uncertainty for the upper branch of the Ijssel River

(Beeldbank Rijkswaterstaat)

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EPA1361 Model-Based Decision-Making

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Executive Summary

In this report, the Room for the River project for the Ijssel River is analyzed. Using modelling techniques, the question is answered how Rijkswaterstaat can implement flood risk management policy in such a way that it is maximally acceptable for all the parties involved, while at the same time being robust, thus effective for many different uncertain futures. Using the Exploratory Modeling Workbench, behaviour under different uncertain futures was first explored, after which Many-Objective Robust Optimization (MORO) was used to optimize signal-to-noise robustness for the 4 key performance indicators of 'Total expected number of deaths, 'Total expected annual damage', 'Total non-Room for the River policy costs' and 'Variance between the total location-specific costs', all of which were minimized. As was found, Doesburg and Zutphen are most vulnerable to damage and casualties: bad performance of their uncertainties mostly results in bad outcomes for Rijkswaterstaat. Specifically taking into account these 2 most vulnerable locations, 6 very promising policy alternatives were found, of which 4 policies seems to be most robustly effective overall. This recommendation is however limited, as it based on multiple assumptions of what Rijkswaterstaat values, method limitations and an ethically questionable decision-making method. Therefore, it is up to Rijkswaterstaat to make a well-informed decision based on this advice.

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1. Structuring of the policy problem

1.1 Introduction

With over half of the Netherlands at or below sea-level, it is no surprise that the people inhabiting the small country, have been battling the water for over a 1.000 years. Learning from past mistakes, the Dutch are now famous for their water management (The Guardian, 2014), which over the years has seen a shift towards a more comprehensive strategy that literally provides ‘Room for the River’, instead of higher and more building dikes (De Bruijn et al., 2015).

Room for the river is the largest Dutch water project since the Delta Works and is planned to be implemented at 34 different locations. Within the ‘Room for the River’ project, resilience is a key concept. Resilience can traditionally be defined as “a systems' ability to absorb changes and to spring back to the original system state” (Desouza & Flanery, 2013). In the case of a water management project, resilience relates to the ability to handle a rise in water levels. De Bruijn et al. (2015) argue that traditionally, resilience is interpreted in a technical sense, but that in reality it also includes a governance component. This is especially true for the IJssel river, since numerous cities, across different provinces depend on the river.

Desouza and Flanery (2013) regard cities as systems whereby components interact to make a whole, larger than the sum of its parts. These components are resources and processes, as well as people and institutions. In this paper, we will adhere to this view, and extrapolate it to the entire IJssel delta, regarding it as a system with numerous interacting components and stakeholders. Thereby aiming to develop and provide a flood risk management plan that incorporates both the technical and governance component of resilience planning and managing. Furthermore, the proposed flood risk management plan will both entail the focus on preventative measures, as well as damage limitation actions in the case of a flood. The eventual analysis that will be conducted will focus on developing a policy that remains robust under deep uncertainty.

1.2 Room for the River: The Ijssel River case

The massive Room for the River project sees work being carried out around the rivers IJssel, Rhine, Lek and Waal. Resulting in over 34 different project locations. The main objective was to create a safer river catchment (Room for the River, 2019). The unique approach of this massive undertaking was to create a safer river catchment, by allowing the river to flow more freely and thus safely. However, by doing so, an opportunity window materialized for the improvement of the spatial quality of the catchment areas, relating for example to the improvement of the urban and rural development as well as strengthening the economy (Room for the River, 2019).

This report will study five locations of interest, following the room for the river approach. These locations are Doesburg, Cortenoever, Zutphen, Gorssel and Deventer, each located within a different dike ring, and will from now on be called location A.1 to A.5 respectively. As can be seen in figure 1, all five of these locations are prone to flooding (Huizinga, 2012).

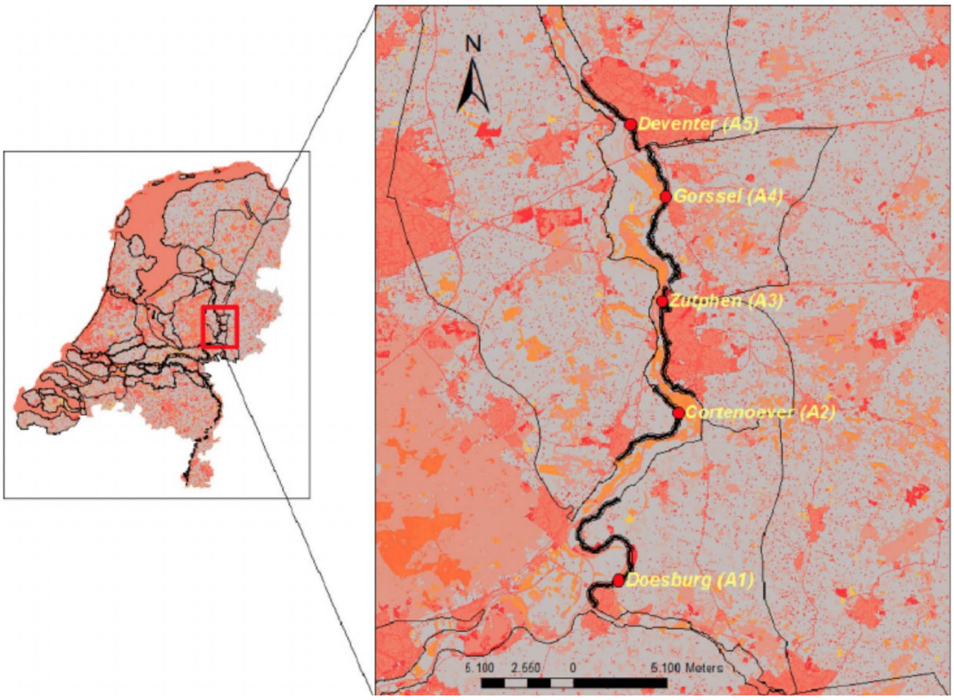

Figure 1. Five locations of interest (Ciullo et al., 2019)

For these locations of interest the different trade-offs for flood management will be defined. Different methods and techniques for flood management exist. Such as strengthening dykes, depoldering or riverbed excavations (UNESCO-IHE, 2012).

1.3 The Multi Actor Arena

However, these five locations are all elements within the larger system arena, of which Rijkswaterstaat is also a component, as can be seen in figure 2. Between the different stakeholders, numerous relations exist. Rijkswaterstaat, the provinces and the municipalities are all part of a hierarchical structure.

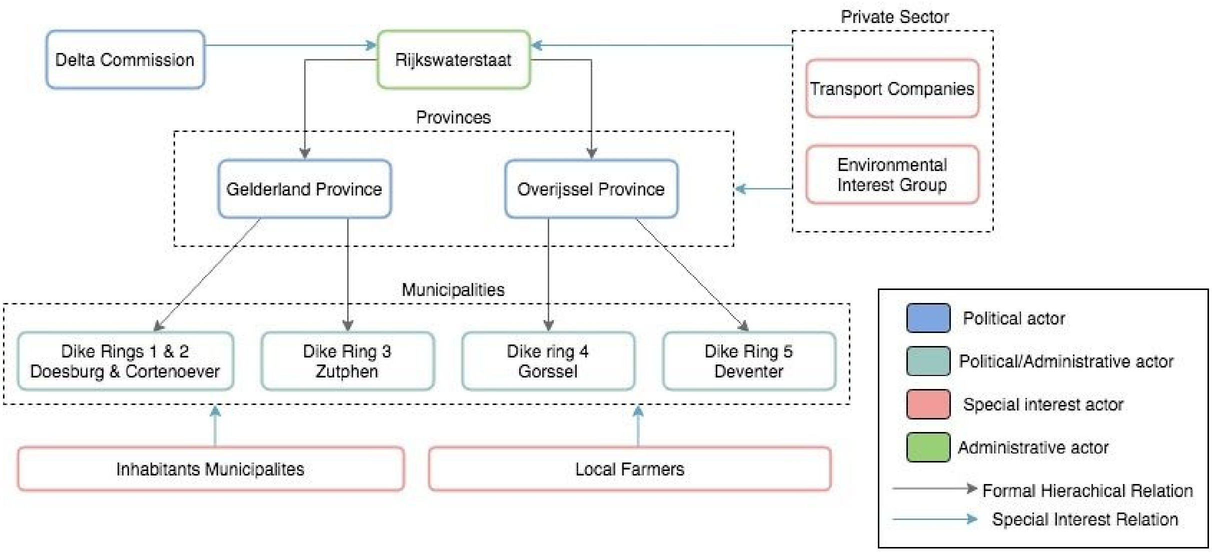

Figure 2. Multi-Actor Arena IJssel river Flood Risk Management Project

The traditional government functionality is largely top-down. However, the project plan proposed by Rijkswaterstaat needs to resonate both with the provinces as well as the municipalities in order to become a success. Not only because of the desire of Rijkswaterstaat to develop a plan agreeable for all parties involved, but also because of the formal power held by the Delta Commission, which is able to veto all project proposals not addressing the needs and interest of key stakeholders. Therefore, the solution should be acceptable for all parties involved. One of the ways to attain this is through involving all stakeholders throughout the entire decision-making process. In order to achieve long term success, listening to the values and objectives of important stakeholders, is important in any organisation (Wheeler & Silanpa, 1998).

The aim of this approach is to also prevent outcomes in which there are clear winners and losers. As de Bruijn (2015) noted, modern societies are often a network of interdependencies, meaning that potential 'losers' can seek to sabotage or block the decision making process. This means that, for the development of the flood risk management plan, a shift from traditional top-down governance, to a more network form of governance is needed.

Appendix A. shows an elaborate analysis of the interest and objectives off all the involved actors. The key takeaways are as follows. Gelderland proposed a policy they coined as 'IJssel all together', which is in favour of a joint effort made by all the involved actors. Within this proposed policy, safety is a key concern as well as that the selected policy is affordable and robust. In addition, it should have a minor impact on the land and economy as well as a minor impact on the shipping industry, as Gelderland is dependent on these. Therefor, they don't prefer a room for the river policy.

For Overijssel the policy should not be at the expense of the economic position of Overijssel's rural and urban areas. Furthermore, the policy should allow Deventer to flourish into a prominent city of Overijssel. In other words, the spatial quality of the region is very important. However, this is a very poorly defined concept and not quantifiable (Klein et al. 2013), making it hard to reach a consensus on in a debate.

In addition, research has pointed out that the room for the river measures could negatively impact the flow of commercial cargo shipping on the Ijssel, as it will lead to more bottlenecks (Smienk, 2003). Therefore, the transport companies will seek to leverage their economic importance for the region, in the debate for potential flood risk management policies.

1.4 Dealing with Uncertainty

De Bruijne (2015) noted that the concept of resilience is not merely technical, but has a large political aspect to it: in a situation with many actors that all have conflicting interests, everyone has a different idea to what dealing with these uncertainties concretely means. The presence of different stakeholders, multiple possible solutions but no 'right answer' and the profound consequences of making the wrong decision, all contribute to the 'wickedness' of the problem (Kwakkel et. al, 2016). Furthermore, the system as it is, is exposed to high levels of uncertainty. Besides the political aspect of the problem and the uncertainty it entails, the probabilistic nature of the issue need also be addressed. When examining flood risk management numerous definitions are relevant. A flood can be defined as the (temporary) submergence of land underwater, by water outside its normal confines. The actual 'flood hazard' is the probability that a flood will occur. The resulting damage of the exposed elements is the 'vulnerability' (Schanze, 2006). The probability of a flood and how this reacts to different interventions, under different scenarios, results in a highly uncertain model. Therefore, it is not feasible to try and anticipate. Instead, a range of possible futures needs to be considered (Maier et al. 2016). Using optimization and scenario discovery it is possible identify the best possible policies, across these different uncertain futures.

1.5 Problem Formulation

The aim of the flood management project is that the entire region of the IJssel river benefits from it fairly. This translates to the project aiming to reduce flood risks evenly across the country, generate economic benefits for the entire region, and distribute the costs and / or 'nuisance' evenly. However, the diversity in preferences and objectives lead to different preferred policies amongst the stakeholders. It is, therefore, key that the solution should be acceptable for all parties involved. For potential outcomes of the flood risk management project, Rijkswaterstaat looks to achieve the following goals:

- Reduce flood risks evenly across the region
- Generate evenly distributed economic benefits
- Spread costs and/or 'nuisance' evenly across the region

In order to achieve this, Rijkswaterstaat will need open communications and a clear understanding of the needs and objectives of the different stakeholders, to allow them to shape a policy beneficial for all. As discussed in the previous paragraph, instead of a traditional hierarchical top-down form of governance, a more network centered governance approach is needed. Nevertheless, Rijkswaterstaat will be extremely receptive to empirical evidence for the project outline. Looking for an analytically proven solution that it is maximally effective and at the same time very robust. The deep uncertainty that has been explained above, due to lack of certain knowledge, means that many different futures might happen. This project needs to be maximally beneficial in all of them. All in all, this forms some interesting dilemmas across different dimensions.

Political Dilemma
While Rijkswaterstaat wants everything to benefit equally, the different parties have different interests, and giving everyone something they want means that another party sometimes cannot get what they want.

Political vs. Scientific Dilemma
While Rijkswaterstaat wants everybody to approve their policy, they also want it to be scientifically sound. This does not always align.

Effectiveness vs. Robustness Dilemma
Effectiveness in a specific scenario is usually opposed to being robust over many different scenarios. Robustness is considered more important than effectiveness in the base scenario, because of the explained deep uncertainty. Policies that are effective in a robust way are however preferred.

Based upon the above defined dilemma's, the following problem definition for Rijkswaterstaat can be defined:

How can a flood risk management policy be implemented on the Ijssel river in such a way that it is maximally acceptable for all the parties involved, and at the same time robust and effective for different deep uncertainties?

In this problem formulation, 'maximally acceptable' relates to the extent to which all the parties concur with the policies. Rijkswaterstaat has a very neutral role and wants what is best for all the stakeholders, therefore it has to find a policy which also finds common ground amongst the stakeholders. It is also necessary to understand the policy under 'deep uncertainty'. But, what is 'deep uncertainty'? One refers to deep uncertainty in a situation when stakeholders or decision-makers do not agree on appropriate models to describe interactions, the expected future developments and the desirability of the outcomes, and the system of interest being studied (Maier, Guillaume, Van Delden, Riddell, Haasnoot & Kwakkel, 2016). In the case of the Ijssel river, each stakeholder will have a different evaluation of the impacts of different policies. Combine this with the fact that there is uncertainty in future developments, we can then conclude that the system under study should be analysed under deep uncertainty

1.6 Report Structure

This report aims to follow a roadmap towards forming a recommendation for Rijkswaterstaat. Chapter 2 operationalizes the problem formulation and describes the method choices and steps taken to answer the research question. Chapter 3 describes the findings from the different analysis steps, which will then be transformed into a policy recommendation in chapter 4. Chapter 5 discusses the implications of our choices and assumptions.

2. Methodology

The analysis on the Ijssel river was performed using the Exploratory Modeling Workbench in Python created by Kwakkel (2017). The workbench is a library that allows users to access various exploratory modeling techniques using Python. This chapter discusses what methods of the workbench were used, why, and how.

2.1 Operationalization

An important step before performing analyses is to translate the problem into model terms. In this report this was done according to the XLMR framework (see figure 3) (Kwakkel, 2017; Lempert, Popper, Bankes, & RAND Pardee center, 2003). An elaborate explanation of all the aspects of the model in light of the framework can be found in appendix B.

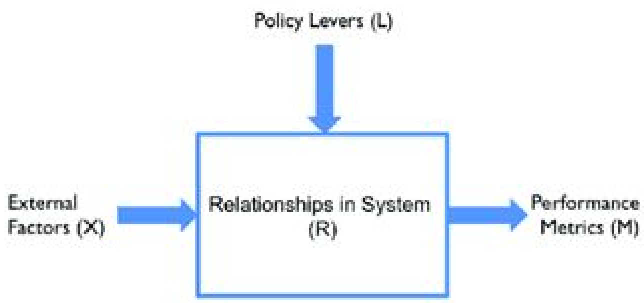

Figure 3. XLMR-framework

Since the main goal of Rijkswaterstaat is to find a robust solution which redounds to the interest of all stakeholders, a high level of aggregation was chosen which also takes into account low level influences. Therefore, based on this goal, the following outcomes of interest were chosen: (1) the expected number of deaths, (2) the total expected annual damage, (3) total of non-RfR related costs (i.e. dike investment costs + evacuation costs), and (4) the variance of costs between locations[1]. These outcomes of interest are influenced by both the values of the uncertainties in the model and policies. In this model, policies can be implemented every 66 years and are made up of combinations of the levers. The levers considered in this model were heightening dikes, making room for the river, and warning the citizens. Next to this, as heightening dikes is favoured over broadening the rivers by many stakeholders, the total RfR costs was used as a constraint. As more RfR costs indirectly mean that more dike broadening will take place, a constraint aims to reflect that preference.

[1] In the model, this variance will be calculated using the standard deviation.

2.2 Modelling Cycle

In order to create a well-argumented proposal for Rijkswaterstaat, it is important to find policies that will work independent of the possible scenario. In this report this was done in 5 steps. Figure 4 shows an overview of these steps and the order in which they took place. The approach that we took in this report is by looking at the system in a pessimistic way. This approach was first introduced by Abraham Wald (1945), the concept of this approach is to minimize the effects in the worst case scenario. Since not intervening in the system of the Ijssel river could lead to great damages and lives lost, it is of utmost importance not to underperform. Therefore, it is important to find a policy which has benefits in the worst case scenario. Assuming that policies are also accepted and effective in average or good scenarios, this maximin approach is a logical choice. Hence, the used method focuses on finding policies that perform best in the worst-case scenario. After that, to ensure the policies are not scenario dependent, the policies were tested on a broader range of scenarios.

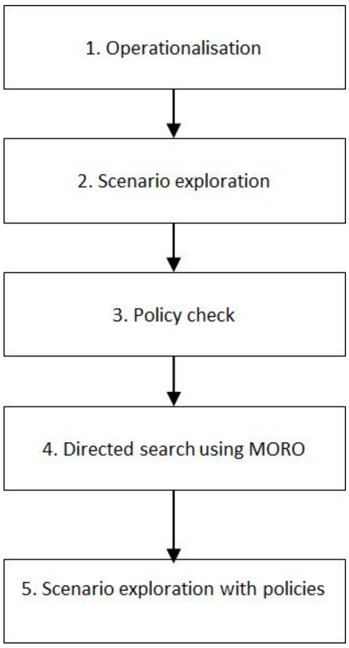

Figure 4. Steps taken in this report

2.3 Used Methods

For the different steps, different available methods were used. First, the problem had to be operationalized (which has already been discussed in the previous section), uncertainties had to be explored, and then the worst case scenarios had to be found. Exploration of the uncertainties was done by running the model without any policies over 5000 scenarios using Latin Hypercube Sampling (LHS). Patient Rule Induction Method (PRIM) was used to find the scenarios that are classified as 'the worst'. Originally designed by Friedman & Fisher (1999), PRIM is a technique that iteratively narrows down the uncertainty space until boxes are found that form a good trade-off between coverage (what fraction of the total outcomes of interest are in the box) and density (what fraction of all cases in the box are actually of interest). While PRIM may be imperfect, possibly restricting too many dimensions, it is more easily interpretable than its alternative Classification and Regression Tree (CART) (Lempert, Bryant & Bankes, 2008). In this case, 'the worst' was defined as scenarios that are simultaneously in the worst 33.3% of their range for the KPIs; 'Expected annual damage', 'Expected number of deaths, and 'Variance expected annual damage'[2]. Section 3.2 will further elaborate on PRIM's results.

After retrieving the subset of worst-case scenarios, this subset was used as the point of departure for finding the policies. However, before finding the policies, random policies were tested on the model, to determine whether policies even work at all. After having checked whether policies work, which they did, Multi-Objective Robust Optimization (MORO) was performed to find the ideal set of policies. MORO was chosen as this is considered the most promising method when looking at Rijkswaterstaat's goals for two reasons. Firstly, MORO searches along the entire uncertainty space instead of a select few scenarios. This is in line with what Rijkswaterstaat would like, since they are responsible for the well-being of the general population and are rather safe than sorry. Secondly, the involved uncertainties cannot reasonably be guessed, therefore it is better to already include robustness early on in the optimization. Given these points, MORO is considered the most suitable method.

The result of a directed search using MORO is a set policies that are both robust and are able to deal with worst-case scenarios. MORO searches through a defined uncertainty space and searches for policies that are least sensitive to changes in scenarios, i.e. policies that are most robust. . For this, MORO requires robustness metrics to optimize. In this analysis the robustness metric 'signal-to-noise' was chosen. Subsequently, it is to be noted that the MORO was run on a constraint. As mentioned in the multi actor arena, most of the stakeholders favour heightening dikes. Therefore, in order to take this into account while performing the MORO, a restraint was set on the RfR costs. A more detailed explanation on what the MORO method is, why this method was chosen and what values we have used is given in appendix C under section 'Directed search using MORO'.

After MORO, the identified policies were run across the whole uncertainty space again, to find the policies that are not only optimally robust for the small set of scenarios that MORO considers, but for the entire uncertainty space. Afterwards, the trade-offs were analyzed, visualized and explained, to give Rijkswaterstaat the tools to determine which policy they feel fits the needs of all stakeholders and is desirable.

[2] Total policy costs is not considered in this analysis: these would be 0, as no policy is implemented in the base case.

3. Results

In this chapter, the results from the analyses will be detailed, starting with the open exploration. Secondly, the scenario discovery will be elaborated on, from which we will draw the effects of the policy in general. Finally, the search for suitable policies will be presented.

3.1 Open Exploration

By doing open exploration, the question of how different KPIs perform over a large range of different scenarios can be answered. Consequently, it will be possible to identify which KPIs perform badly, before policy is implemented. The results of the run for 5000 different scenarios are shown in figure 5, 6 and 7. All these results can also be found in the '1 - Exploration.ipynb' notebook. Note that expected annual damage is taken into account in this case, as this is the only type of 'cost' involved when no policy is implemented yet.

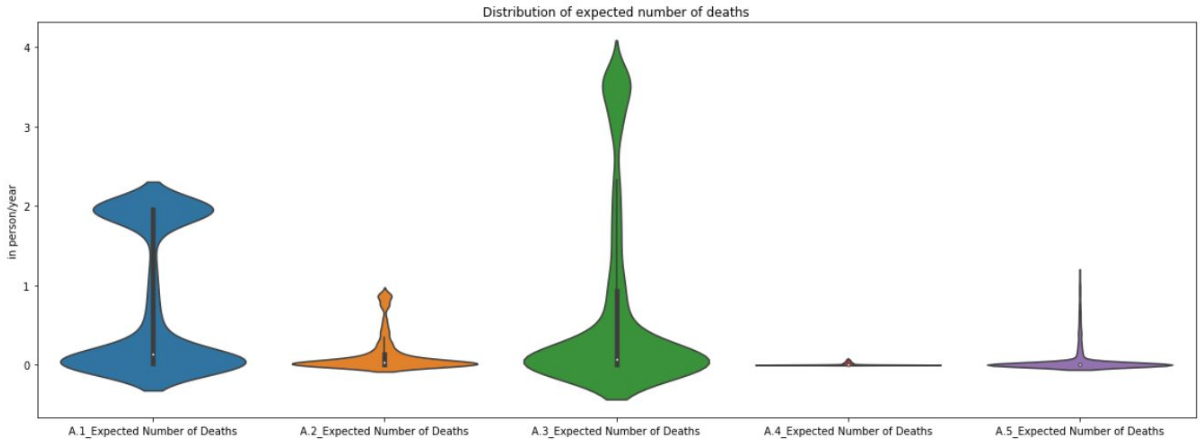

Figure 5: Open exploration - distribution of expected number of deaths

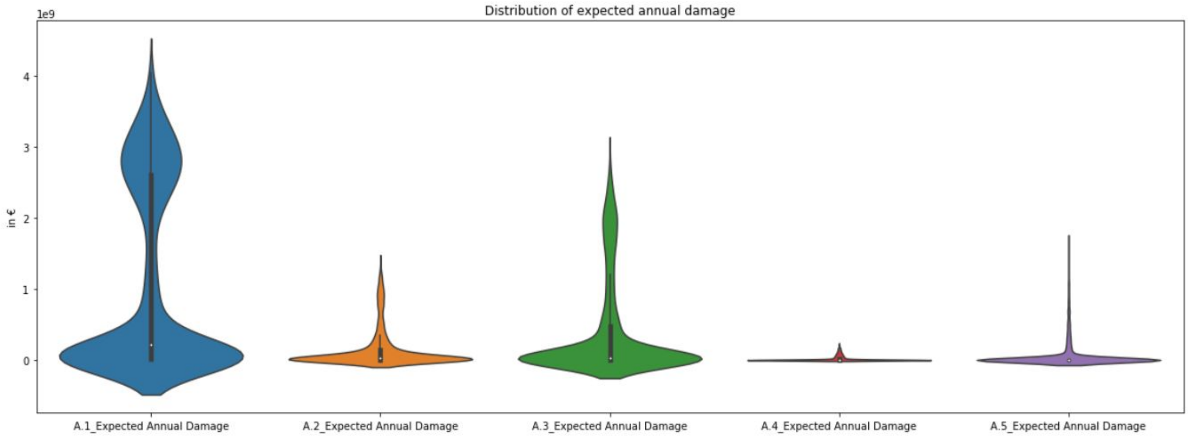

Figure 6: Open exploration - distribution of expected annual damage

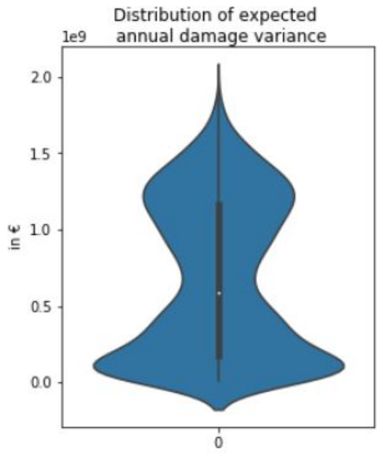

Figure 7: Open exploration - distribution of expected annual damage variance

Figures 5 and 6 show that for most scenarios the expected number of deaths, as well as the total costs (which in this case only consists of expected annual damage), are expected to remain low. However, for locations A1 and A3, there are quite some scenarios for which this is not the case. For A1, a peak can be seen of scenarios in which the expected number of yearly deaths rises to 2, and the annual damage to 3 billion euros; for A3, this peak has a higher expected number of deaths are higher, around 3.5, whereas the expected annual damage is lower, around 2 billion euros. In other words, when implementing no policy, and thus keeping the base case, Doesburg and Zutphen are most vulnerable to damage and deaths. Their KPIs are least robust in possible future scenarios.

Figure 7 shows the variance of expected annual damage between the locations, i.e. to what extent are the damages evenly distributed between the locations.From this graph, it can be concluded that while most scenarios have an expected variance of below 500 million damage, there are quite some scenarios in which there is around 1.25 billion or even higher variance. Based on the insights from figure 5 and 6, it can be said that this is mostly due to Doesburg and Zutphen getting more damage than the others. It is therefore advisable for Rijkswaterstaat to take this variance into account, especially when looking for candidate solutions, as in many scenarios Doesburg and Zutphen have more to lose than others, which might hinder their policy's acceptability.

3.2 Scenario Discovery

Now that a general exploration of the data has been carried out, it is useful to identify the scenarios in which the outcomes are undesirable, as has been explained in section 2.3. These analyses can once again be found in the '1 - Exploration.ipynb' notebook. As one of the KPIs taken into account deals only with policy costs, this one is not considered yet, as policy implementation is not yet taken into account. For the other three important outcomes, being expected number of deaths, expected annual damage and variance of total expected costs, we are interested in the uncertain futures in which their resulting values are undesirable, given that no policy is implemented yet.

By searching for the scenarios that simultaneously are in the 33.3% of worst outcomes for expected deaths, expected annual damage *and* variance between location-specific costs, 879 of 5000 scenarios (=17.5%) are considered as being of interest. Figure 8 below shows the results of the box found by PRIM, with 56% coverage and 70% density.

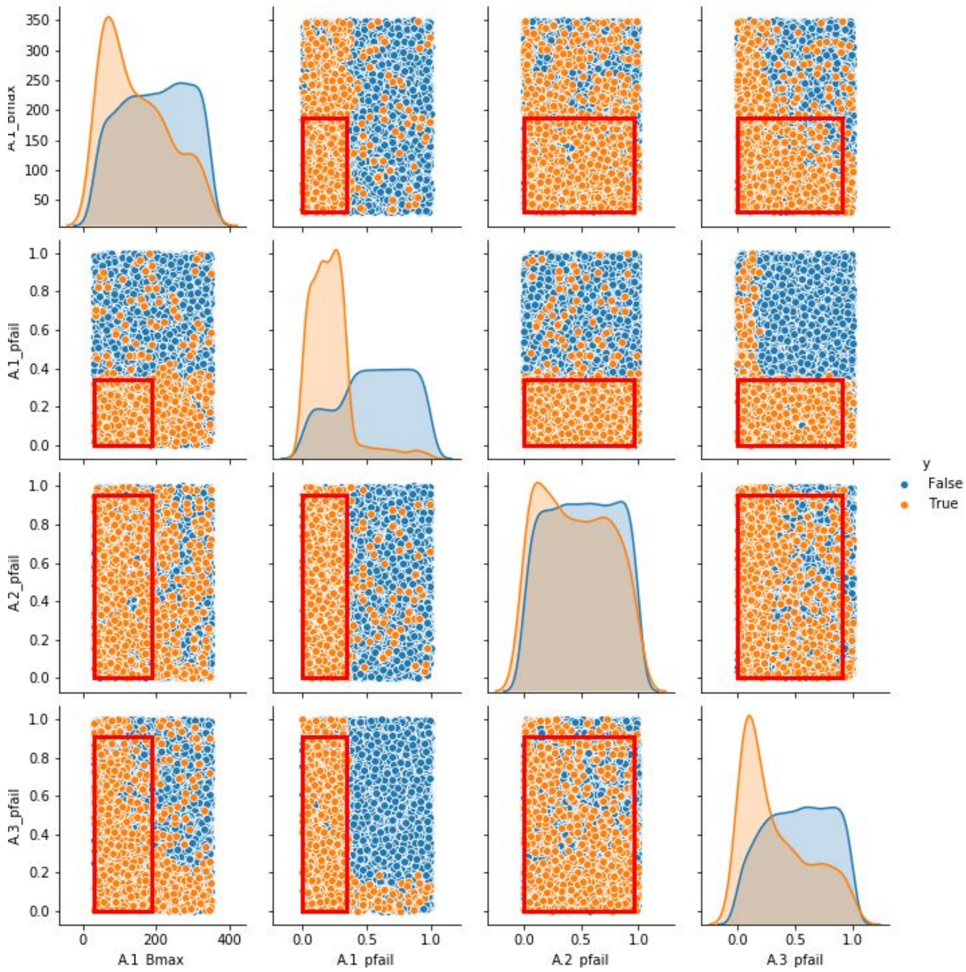

Figure 8: Results of scenario discovery by PRIM

As illustrated by figure 8, there are four uncertainties that contribute to these undesirable outcomes. Outcomes are often undesirable if: the width of a potential dike breach at location A1 (Doesburg) is on the low side, i.e. between 30 and 190 decimeters; the probability of dike failure at location A1 (Doesburg) is on the low side, i.e. between 0 and 0.34; the probability of dike failure at location A2 (Cortenoever) is between 0 and 0.96 and the probability of dike failure at location A3 (Zutphen) is on the low side, i.e. between 0 and 0.96.

These results are in line with the first exploration (see figure 5 and 6): the probability of having high annual damage and a high expected number of deaths was most variable for location A1 and A3, with some scenarios resulting in quite high numbers. Of the other 3 locations, A2 was the most vulnerable as well. Therefore, it is not strange that the uncertainties of probability of failure and Bmax of these locations affect the desirability of outcomes the most. As a low value for this variable implies a higher discharge and therefore a higher probability of damage, this would then result in a bad desirability of outcomes.

Based on the results of open exploration and scenario discovery, it has become evident that Doesburg and Zutphen are the most vulnerable locations. In the subsequent MORO analysis, the uncertainty space will be constrained to the identified ranges presented above, in order to consider the worst possible scenarios only. This method will contribute to finding a policy that performs well under the worst circumstances, and therefore, maximizes the robustness of the policies.

3.3 Effect of policy in general

The results of the 100 random policies for 375 scenarios are shown in figure 9, and can also be found in the '2- Comparison.ipynb' notebook.

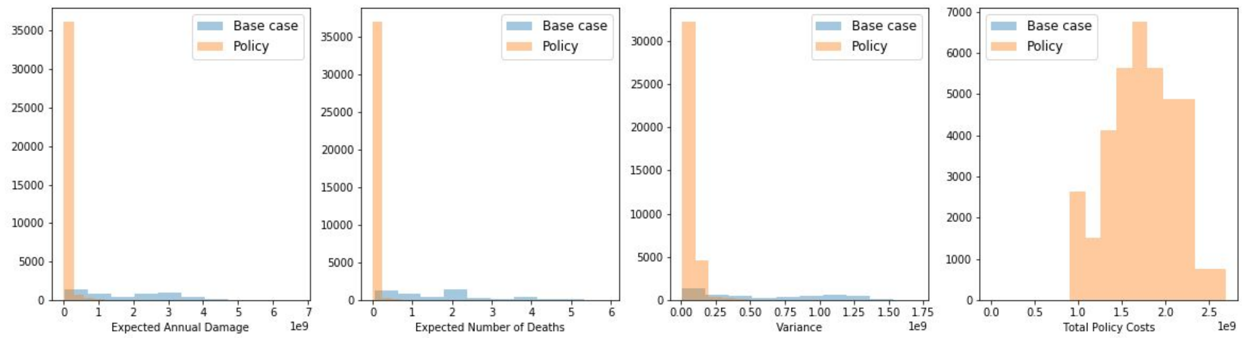

Figure 9: Comparison of the base case and random policy distributions

Apart from the policy costs[3], all indicators give more desirable outcomes when policy is implemented, as can be seen in table 1. This is the case for the maximum, average *and* variance of all other KPIs, i.e. expected annual damage, expected number of deaths and variance in costs per location. These numbers tell us that yes, implementing policy costs money (on average 1.8 billion euros, with a maximum of 2.7 billion), but it will have immense positive effects. A huge part of the money is already won back by having less annual damage (on average, 1.12 billion euros is won back, although this has quite a large variance), and the rest will be worth it, given the reduction in expected number of deaths, and the better distribution of costs over the different locations.

Table 1: Comparison of the base case and random policy values

Indicator	Variable	Base case value	Value with policy
Maximum	Expected annual damage	6.71*10^9	3.35*10^9
Maximum	Expected number of deaths	5.91	1.99
Maximum	Variance in costs per location	1.70*10^9	9.67*10^8
Maximum	Total policy costs	0	2.7*10^9
Average	Expected annual damage	1.85*10^9	7.32*10^8
Average	Expected number of deaths	1.77	0.017
Average	Variance in costs per location	6.08*10^8	8.29*10^7
Average	Total policy costs	0	1.75*10^9
Std	Expected annual damage	1.32 E9	1.73 E8
Std	Expected number of deaths	1.30	0.07
Std	Variance in costs per location	4.59*10^8	4.72*10^7
Std	Total policy costs	0	3.82*10^8

[3] Note that the total policy costs are now considered as well, because they are now a non-zero number. For now, this includes dike investment costs, evacuation costs and Room for the River costs (RfR costs), to get a general picture.

3.4 Searching for policy solutions

Now that it has been concluded that implementing policy is very desirable, the question remains *what* policy is best to implement. The MORO method aims to answer this, for which the Python code used is visible in the Python notebook '3 - MORO.ipynb'. As explained in section 2.3, signal-to-noise was chosen as a robustness metric. Also, based on the scenario discovery results (section 3.2), the 4 important uncertainties were constrained to the values for which the outcomes were found to perform the worst, so that the model is optimized for the worst possible scenarios. Furthermore, the used values for the MORO method can be found in Appendix C.

Whereas up till now, all policy costs have been aggregated, RfR costs is now separated to form a constraint. This is because RfR costs will be the same for every scenario within a policy, so its signal-to-noise value would always be zero. Moreover, it reflects many actors preferring dyke heightening over dike broadening, which will now be incorporated due to this constraint. Additionally, dike investment costs and evacuation costs are run separately in MORO, so that their difference in order of magnitude does not make one insignificant. They will however be combined in subsequent analyses, but optimizing over them separately will achieve lowering the robustness value of each of these.

3.4.1 MORO

Using the epsilon values given in table 6 in appendix C, MORO has been run for 30 scenarios with 20,000 function evaluations[4]. The Python notebook '4 - Optimal policies.ipynb' is used for further MORO analysis. The convergence metrics can be seen in figure 10. These graphs illustrate how the epsilon progress metric shows that converge has been reached (i.e. the gradient approaches 0). This improves our faith in the found policies, as it shows that sufficient function evaluations were run to form a consistent Pareto set of solutions. The hypervolume progress shows an almost constant value of 1. Apparently, after few function evaluations, a Pareto set of solutions was already found that covers the entire Hypervolume space. This could be a sign that the ranges have been set too small. This metric can therefore not be used to conclude about convergence of the algorithm.

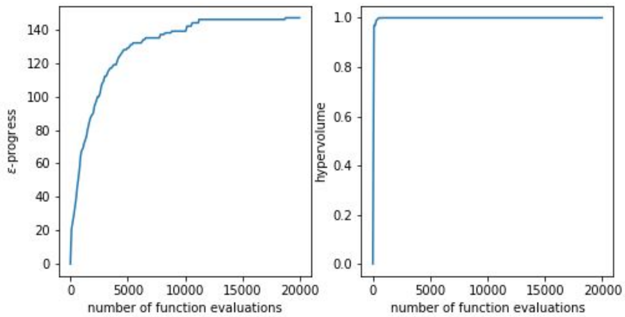

Figure 10: MORO convergence metrics

MORO has found 6 solutions, which is a suitable number for further analysis. The lever values of which are shown in table 2. Figure 11 shows the tradeoffs between the robustness scores for these policies, based on the 30 scenarios for which MORO was run.[5] Note that lower is better, because the robustness scores are to be minimized. These results show that implementing Room for the River for locations A1 to A4 is often favoured, leading to robust results. In contrast, heightening the dikes at location A1 is not favourable at all. Looking at the trade-offs, it is clear how MORO has done its job selecting policies that make different trade-offs for the robustness. In general, policies that robustly minimize the dike investment and evacuation costs, perform badly for robustly minimizing the expected deaths and annual damage. For the rest, the 6 policies all clearly make different tradeoffs, favoring one KPI over the others.

[4] See '3 - MORO.ipynb' for the MORO process itself, and '4 - Optimal policies.ipynb' for the further analysis

[5] The actual values for the levers of these 10 policies can be found in the '4 - Optimal policies.ipynb' notebook. They are not included here, as some policies will still be eliminated in section 5.4.3.

Table 2: Combinations of policy levers found by MORO

Policy (unit)	**Heighten the dikes** (decimeters)					**Implement Room for the River** (% of timesteps that this is done)					**Early Warning System** (days)
Location	**A.1**	**A.2**	**A.3**	**A.4**	**A.5**	**A.1**	**A.2**	**A.3**	**A.4**	**A.5**	
Policy 1	0	10	6	10	7	100%	100%	100%	100%	100%	3
Policy 2	0	4	1	0	1	100%	100%	100%	100%	66.7%	0
Policy 3	0	6	4	0	0	100%	100%	100%	100%	33.3%	2
Policy 4	0	5	7	0	0	66.7%	100%	100%	100%	0%	3
Policy 5	0	6	2	0	0	100%	100%	100%	100%	0%	0
Policy 6	0	10	6	12	7	100%	66.7%	100%	100%	0.33%	3

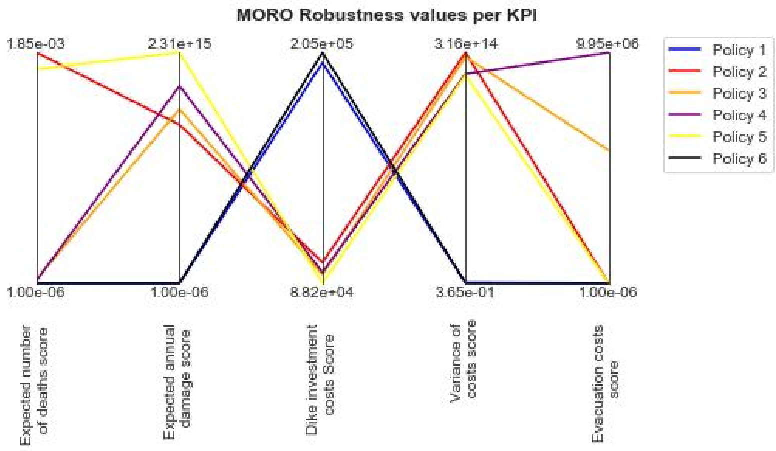

Figure 11: Robustness tradeoffs for the 6 found policies
(lower is better)

3.4.2 Re-evaluation under deep uncertainty and tradeoff analysis

MORO has taken into account a relatively small set of scenarios. To see how the candidate policies perform across all uncertain futures, their performances were evaluated over 1000 scenarios per policy. The different policies' distributions for each of the KPIs are shown in figure 12 to 15. Note that, in order to make these figures better interpretable, outliers have not been included in this plot. In order to incorporate the fact that some policies might have many outliers, figure 16 shows a parallel coordinate plot in which the revised robustness values for the 4 KPIs are shown.[6]

[6] Figure 11 shows different robustness values, as these are calculated for the 30 scenarios that MORO took into account, instead of the 1000 that are now considered. The revised values in figure 16 will be used for interpretation.

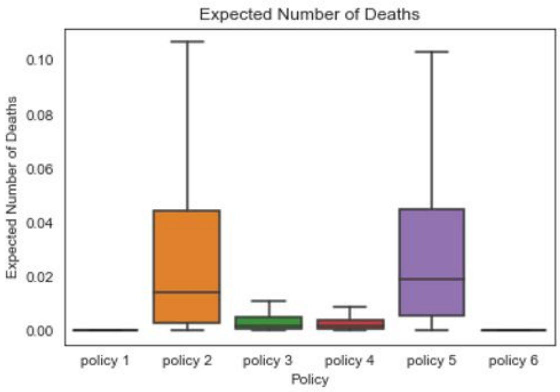

Figure 12: Expected number of deaths for the 6 policies

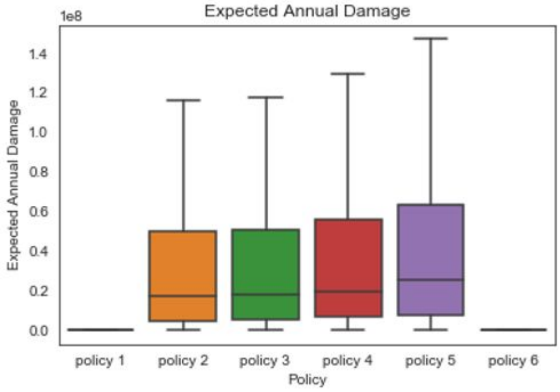

Figure 13: Expected annual damage for the 6 policies

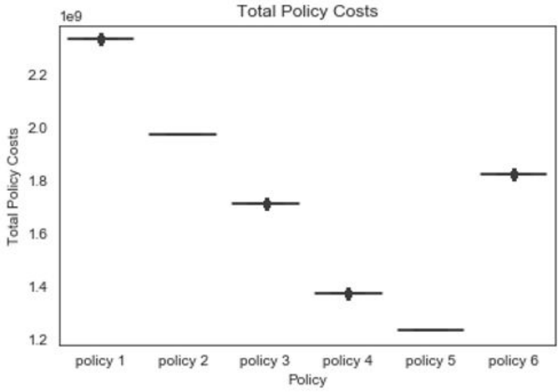

Figure 14: Total policy costs for the 6 policies

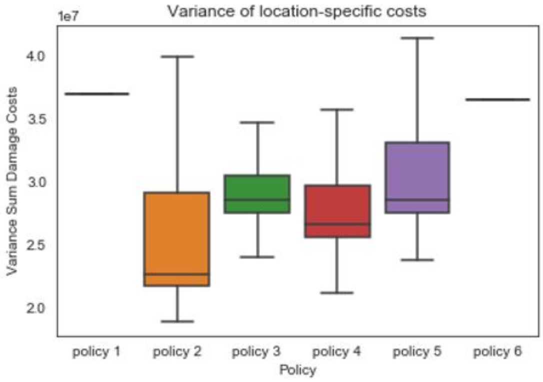

Figure 15: Variance of location-specific costs for the 6 policies

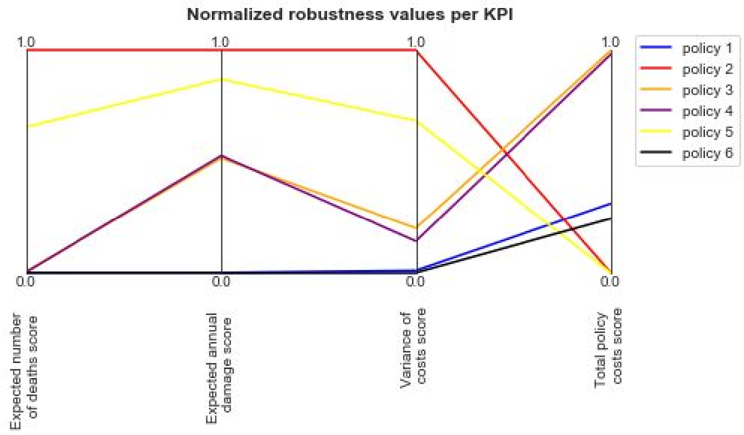

Figure 16: Normalized robustness scores per KPI, after re-evaluation (lower is better)

These plots together provide the means to form a well-considered decision that is in line with the problem formulation of Rijkswaterstaat. All these 6 policies can be considered robustly effective in their own ways, and the choice for one specific policy depends on what KPI is considered most important. If minimizing the expected deaths and damage is goal number one, then policy 6 would be best: this policy achieves this most, for the least amount of costs and a slightly better robustness. Minimizing costs as prime goal would lead to policy 5, but this policy cannot be considered as robust as the others. If a fair distribution of costs is the prime goal, there is no real winner: policy 2, 3 and 4 do this well in their own ways. As policy 3 and 4 are however more robust, these would be preferred. Finally, in a situation where all KPIs are considered equally important, policy 4 or policy 6 would score best, where policy 4 favors low and fairly distributed costs over expected damage and deaths, and policy 6 the other way around. Note that these considerations are very arbitrary. Moreover, it has some ethical considerations, which will be discussed in chapter 5.

4. Conclusion

This report has aimed to find an optimal set of policies that mitigate the flood risk in the IJssel delta, for Rijkswaterstaat to implement. Rijkswaterstaat is an organization which operates at a high level of aggregation; that is, Rijkswaterstaat prefers a solution which distributes the costs and benefits evenly across all stakeholders and is therefore acceptable for all actors involved. The problem Rijkswaterstaat is facing can be captured in the following problem statement:

How can a flood risk management policy be implemented on the Ijssel river in such a way that it is maximally acceptable for all the parties involved, and at the same time robust and effective for different deep uncertainties?

To successfully answer the problem statement and provide Rijkswaterstaat with a well-informed advice, the political side of the problem - in which there are conflicting interests among the stakeholders - should be reflected with regard to the retrieved results. Among the stakeholders, there is a consensus that the suggested policy should be safe, robust and economically viable. This means that the policy should not be too expensive to implement, nor should it negatively impact the regions' economy. The key takeaways from the actor analysis (Appendix A) are that neither Gelderland nor Overijssel wishes to lose land in terms of square surface, as a result of a "Room for the River" policy, since this will negatively impact urban real estate or rural farming land. Furthermore, the transport companies will also be negatively influenced by the "Room for the River" implementation since it will limit the possibility to transport cargos through the river.

By diving in the results, the model has been able to conclude that without any policies the upstream regions will be affected the most by the floods. The costs for these regions can reach up to 3 billion, while a total of four expected deaths could also be possible. Moreover, while looking at the variance of expected annual damage between the locations, it can be concluded that Doesburg and Zutphen are the more vulnerable locations.

Policy-wise, we have found 6 different robust policies, i.e. policies that perform well in any scenario, especially in the worst-case scenarios. They will therefore mitigate the flood risk in the most effective way. These policies are shown in table 3. Generally, the identified policies seem to steer in a direction in which "Room for the River" has to be implemented in order to successfully mitigate the flood risks; especially for Doesburg, heightening the dike will not mitigate the risks enough. Therefore, we advise Rijkswaterstaat to convince the regions that implementing the "Room for the River" policies is inevitable in order to mitigate the flood risks. However, arrangements should be made with the duped regions in order to prevent the regions from turning their back on the to be implemented policy.

Table 3: Combinations of policy levers found by MORO

Policy (unit)	**Heighten the dikes** (decimeters)					**Implement Room for the River** (% of timesteps that this is done)					**Early Warning System** (days)
Location	**A.1**	**A.2**	**A.3**	**A.4**	**A.5**	**A.1**	**A.2**	**A.3**	**A.4**	**A.5**	
Policy 1	0	10	6	10	7	100%	100%	100%	100%	100%	3
Policy 2	0	4	1	0	1	100%	100%	100%	100%	66.7%	0
Policy 3	0	6	4	0	0	100%	100%	100%	100%	33.3%	2
Policy 4	0	5	7	0	0	66.7%	100%	100%	100%	0%	3
Policy 5	0	6	2	0	0	100%	100%	100%	100%	0%	0
Policy 6	0	10	6	12	7	100%	66.7%	100%	100%	0.33%	3

While all 6 identified policies will mitigate the flood risk, they make their own trade-offs between the KPIs "Expected Number of Deaths", "Expected Annual Damage", "Variance of costs between locations" and the "Total Policy Costs". It is up to Rijkswaterstaat to consider which trade-offs they value the most. Based on our interpretation, we advise the following policies:

- **Policy 6**. If a policy should focus on minimizing the "Expected Number of Deaths" and "Expected Annual Damage", while "Total Policy Costs" is not a hurdle.
- **Policy 5**. If the policy should focus on the fewest costs. It has to be noted that also policy 5 minimizes the "Expected Number of Deaths" and "Expected Annual Damage" absolutely, while relatively seen it is not the best performer.
- **Policy 3 or 4**. If the policy should focus on evenly distributing the costs between the locations.
- **Policy 4**. If the policy should focus on minimizing the "Room for the River" levers and keeping the stakeholders more satisfied.

All in all, policy 4 and 6 seem to be the best fit. Policy 4 focuses a bit more on fewer costs and the least amount of "Room for the River" levers, while policy 6 focuses a more on minimizing the "Expected Number of Deaths" and "Expected Annual Damage". It is up to Rijkswaterstaat what they find most valuable and what trade-off seems appealing to them.

5. Discussion

While the chapters above have managed to give quite specific policy recommendations, it is important to understand the assumptions and limitations that underlie these recommendations, so that the quality of the recommendation can be transparently assessed.

Firstly, this report was written with the aim of providing Rijkswaterstaat's with relevant analytical insights and possible policy measures. In order to be able to reason from their point of view, interviews between both us and Rijkswaterstaat were conducted. Using investigative questions, our aim was to identify their needs and objectives as accurately as possible. However, miscommunication and bias can always play a role, which means making certain assumptions was inevitable. However, these were well-argued assumptions and based on literature. There are 3 key moments in the analysis during which these assumptions have been made: during the problem formulation (i.e. the chosen outcomes of interest and constraints); during the choice of signal-to-noise as robustness metric; and during the trade-off and selection of the 'optimal' policies. While we have tried to transparently report about them, taking different assumptions would inevitably have led to different conclusions, which limits the validity of our recommendations. Further research could get these values and interests more explicit. Specific to the robustness metrics, signal-to-noise has the limitation that values that have an undesirable mean, but have this value consistently (low noise), are seen as relatively desirable. Involving and comparing the results of multiple robustness metrics could have made this limitation less significant.

Secondly, the used method of MORO comes with its limitations. MORO is a computationally expensive method, and given the project's time constraints, the number of possible scenarios and function evaluations was limited. Because of this, the number of KPIs and constraints taken into account had to be limited. Moreover, this prevented us from doing seed analysis, which can be considered important for MORO, as the underlying algorithm relies on stochastic processes (as also mentioned by Kasprzyk, Reed & Hadka, 2016, pp. 9). Lastly, the specified hypervolume ranges turned out to be too low, which made the hypervolume convergence metric unusable. This could not be iteratively changed due to the long runtime. While the epsilon convergence metric showed convergence, faith in the results would have been higher if the second metric could have been used. Together, these points makes the recommendations less valid, and could easily be improved in further research with less time constraints.

Thirdly, there are multiple model properties that could limit the conclusion's validity. While the chosen time step of 66.67 years allows the model to give insight in the long-term performance of the dikes, it is somewhat unrealistic that decision revision can only take place after so many years. In reality, such decisions could be made more often, meaning that this model underestimates the potential of adaptive policy. More importantly, because not all relevant outcomes for the different actors have been defined in this model, these have not been taken into account while finding an 'optimal' solution in this paper. The 3 main examples that were out of the model scope are: the loss of land area, environmental considerations and the effect of river broadening on ship transport companies. While we aimed to overcome this by taking the variance of costs over locations, so that these are at least properly distributed, it might be that some actors' wishes are not fulfilled in the proposed policies.

Finally, there are some ethical considerations to the use of this model. It namely implies a consequentialist view to decision-making. In that sense, it shares many ethical considerations with performing a social cost benefit analysis. As Hansson (2007) explains, loss of human lives and monetary costs of a project might be incommensurable. Bias (not taking all consequences into account) and interpersonal aggregation (implying that a disadvantage for one can be fully compensated by advantage for another) are 2 other aspects that make the use of this model ethically questionable. While these issues have been considered during tradeoff analysis, by keeping options open, the tradeoff remains subjective and should be taken with caution. This aspect could be more explicitly considered in further research.

References

Bryant, B.P., & Lempert, R.J. (2010). Thinking inside the box: A participatory, computer-assisted approach to scenario discovery. *Technological Forecasting and Social Change, 77(1), 34–49.* doi:10.1016/j.techfore.2009.08.002

CBS (2009, November 11). Nederlandse vaarwegen belangrijk voor goederentransport. Retrieved June 12, 2020, from: https://www.cbs.nl/nl-nl/nieuws/2009/48/nederlandse-vaarwegen-belangrijk-voor-goederentransport

Ciullo, A., de Bruijn, K. M., Kwakkel, J. H., & Klijn, F. (2019). Accounting for the uncertain effects of hydraulic interactions in optimising embankments heights: Proof of principle for the IJssel River. *Journal of Flood Risk Management, 12(S2), e12532.* doi:10.1111/jfr3.12532

Desouza, K. C., & Flanery, T. H. (2013). Designing, planning, and managing resilient cities: A conceptual framework. Cities, 35, 89-99. doi:10.1016/j.cities.2013.06.003

De Bruijn, J. A., De Bruijne, M. L. C., & Ten Heuvelhof, E. F. (2015). The Politics of Resilience in the Dutch 'Room for the River'-project. *In Procedia Computer Science, 44, 2015; Conference on Systems Engineering Research. Elsevier.* doi:10.1016/j.procs.2015.03.070

Delta Commissie. (2008). Doel. Consulted on June 10, 2020, from http://www.deltacommissie.com/commissie/doel

Friedman, J. H., & Fisher, N. I. (1999). Bump hunting in high-dimensional data. *Statistics and Computing*, 9(2), 123–143. https://doi.org/10.1023/a:1008894516817

Huizinga, F. (2012). The economics of flood prevention, A Dutch perspective. Centraal Plan bureau documents. Retrieved June 9, 2020, from http://www.cpb.nl/en/publication/economics-flood-prevention.

Kasprzyk, J. R., Reed, P. M., & Hadka, D. M. (2016). Battling Arrow's Paradox to Discover Robust Water Management Alternatives. *Journal of Water Resources Planning and Management*, 142(2), 04015053-1-04015053–12. https://doi.org/10.1061/(asce)wr.1943-5452.0000572

Klijn, F., de Bruin, D., de Hoog, M. C., Jansen, S., & Sijmons, D. F. (2013). Design quality of room-for-the-river measures in the Netherlands: role and assessment of the quality team (Q-team). *International Journal of River Basin Management*, 11(3), 287-299. doi:10.1080/15715124.2013.811418

Kwakkel, J. H., Walker, W. E., & Haasnoot, M. (2016). Coping with the wickedness of public policy problems: approaches for decision making under deep uncertainty. doi:10.1061/(ASCE)WR.1943-5452.0000626

Kwakkel, J.H. (2017). The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environmental Modelling & Software*, 96, 239–250. doi:10.1016/j.envsoft.2017.06.054

Lempert, R.J., Popper, S.W., Bankes, S.C., & RAND Pardee Center. (2003). Shaping the Next One Hundred Years: New Methods for Quantitative, Long-term Policy Analysis. Santa Monica, CA: Rand Corporation. doi:10.7249/MR1626

Lempert, R. J., Bryant, B. P., & Bankes, S. C. (2008, March). *Comparing Algorithms for Scenario Discovery* (WR-557-NSF). Retrieved from https://www.rand.org/pubs/working_papers/WR557.html

Maier, H. R., Guillaume, J. H., van Delden, H., Riddell, G. A., Haasnoot, M., & Kwakkel, J. H. (2016). An uncertain future, deep uncertainty, scenarios, robustness and adaptation: How do they fit together? *Environmental Modelling & Software*, 81, 154-164. doi:10.1016/j.envsoft.2016.03.014

McPhail, C., Maier, H.R., Kwakkel, J.H., Giuliani, M., Castelletti, A., & Westra, S. (2018). Robustness Metrics: How Are They Calculated, When Should They Be Used and Why Do They Give Different Results? *Earth's Future*, 6(2), 169–191. doi:10.1002/2017EF000649

McVeigh, T. (2014, February 16). The Dutch solution to floods: live with water, don't fight it. *The Guardian*, 2014. Retrieved June 6, 2020, from https://www.theguardian.com/environment/2014/feb/16/flooding-netherlands

Rijke, J., van Herk, S., Zevenbergen, C., & Ashley, R. (2012). Room for the River: delivering integrated river basin management in the Netherlands. *International journal of river basin management*, 10(4), 369-382. doi:10.1080/15715124.2012.739173

Rijkswaterstaat (2020). Maatregelen voor de scheepvaart. Retrieved June 12, 2020, from https://www.rijkswaterstaat.nl/water/waterbeheer/droogte-en-watertekort/maatregelen-voor-de-scheepvaart/index.aspx

Rijkswaterstaat. (2020). Onze Missie. Retrieved June 10, 2020, from https://www.rijkswaterstaat.nl/over-ons/onze-organisatie/onze-missie/index.aspx

Sterman, J.D., 1994. Learning in and about complex systems. *Syst. Dyn. Rev.*, 10, 291–330. http://dx.doi.org/10.1002/sdr.4260100214.

Schanze, J. (2006). Flood risk management–a basic framework. I*n Flood risk management: hazards, vulnerability and mitigation measures (pp. 1-20)*. Springer, Dordrecht. doi:10.1007/978-1-4020-4598-1_1

Smienk, H. (2003). Verbeteren van de Beneden-en Midden-IJssel als scheepvaartweg. Retrieved June 13, 2020, from http://resolver.tudelft.nl/uuid:e63b74de-2159-4ee8-b6f6-778c89edf0a5

UNESCO-IHE (2012). Room for the River Brochure, Retrieved June 4, 2020, from https://www.un-ihe.org/sites/default/files/13270-rvdr-brochure-governance-engels_def-pdf-a.pdf

Wald, A. (1945). Statistical decision functions which minimize the maximum risk. *Annals of Mathematics*, 265-280. doi:10.2307/1969022

Appendix

Appendix A. Tailor Made Collaboration: A Multi Actor Arena

The developments around flood risk management, and its impact on the spatial design of the region, are very much still driven by economic and social factors (Rijke et al, 2012). The room for the river project has two main goals. To both create a safer river catchment area by decreasing flood risk, as well as simultaneously improving the spatial quality of the catchment areas (UNESCO-IHE, 2012). Nevertheless, the project aims to achieve this will creating equal opportunity for all stakeholders involved and by distributing the costs or nuisances evenly and fairly. The multi actor arena in which the room for the river project takes place, forces Rijkswaterstaat to create an overall consensus within the decision making process. In order to achieve this, the following actor analysis has been developed, based on the different rounds of debate on June 4th and June 11th. During these debates, the different stakeholders voiced both their goals and concerns for the project, ultimately trying to move towards and acceptable policy with a majority support.

A.1 Rijkswaterstaat

Rijkswaterstaat is part of the Ministry of Infrastructure and waterstate as its executive branch. The organisations main goals is to create and sustain a safe, habitable and accessible environment (Rijkswaterstaat, 2020). The Room for the River project is of course no exception. Rijkswaterstaat is charged with executing the project objectives, while maintaining the support from the numerous stakeholders. This will inevitably result in trade offs between stakeholders and locations, with regards to the aforementioned economic and social factors, as well as of course the flood risk and thereby general safety of the region. Based upon the analysis conducted in this report, Rijkswaterstaat will be equipped to choose a robust yet efficient policy that will ensure a maximal profitability for the entire region.

A.2 Delta Commission

The Delta Commission exists to advise the Dutch kabinet and express the urgency of water management safety (Delta Commissie 2008). Within the current actor arena and decision making process, the Delta Commission is tasked with protecting the different stakeholder interests. The commission has the formal power to veto any policy, regardless of the voting process, of which they feel it neglects their standards on water management or if it fails to meet the interests of the stakeholders involved. Their goal is to find a long term solution.

A.3 Gelderland Province

As illustrated in figure 1. in the first chapter, Gelderland is an upstream province, meaning they're more vulnerable for potential flooding, and their interventions will also have downstream consequences. Therefore, during the debate the Province of Gelderland proposed a policy they coined as 'IJssel all together', which is in favour of a joint effort made by all the involved actors. Within this proposed policy, Gelderland put special emphasis on their safety concerns for dike ring 1, 2 and 3. Furthermore, the wish that the selected policy is affordable and robust. In addition, it should have a minor impact on the land and economy as well as a minor impact in the shipping industry, as Gelderland is dependent on that. Therefor, they don't prefer a room for the river policy.

A.3.1 Doesburg & Cortenoever (Dike ring 1 & 2)

Doesburg and Cortenoever are part of Gelderland and the first two cities upstream of the river. In accordance with the proposed policy by Gelderland, Doesburg and Cortenoever will support a policy that is both safe and robust, while having little economic impact on the region.

A.3.2 Zutphen (Dike ring 3)

Zutphen is a part of Gelderland and the third city along the IJssel. In accordance with the proposed policy by Gelderland, Zutphen will support a policy that is both safe and robust, while having little economic impact on the region.

A.4 Overijssel Province

Based on a meeting held with the delegates of the Overijssel Province, the following can be said. Overijssel would like to avoid a winner takes all scenario. Instead, the decision making process should focus on a cooperative strategy that ensures the safety for the people of Overijssel. The Province sees cooperation as the primary goal and feels a strong responsibility towards the safety of its citizens. However, the policy should not be at the expense of the economic position of Overijssel's rural and urban areas. Furthermore, the policy should allow Deventer to flourish into a prominent city of Overijssel. In other words, the spacial quality of the region is very important. However, this is a very poorly defined concept and not quantifiable (Klein et al. 2013), making it hard to reach a consensus on in a debate.

With regard to dikering 4, it is important to maintain enough land (m^2), in order to grow organic products. Secondly, the water should remain a sufficiently deep level, otherwise the transport companies in the region are not able to keep using it for their transport, which adds economic and social benefits.

Overall, Overijssels seeks to find a fair result, in which not only the stakeholders with most power win the most, but everyone is satisfied with the solution. From their side, this also means that they are willing to give some, to gain some. This is a mentality they expect from the other involved stakeholders as well, stating it should be a joint effort. In conclusion, they want the proposed solution to be as natural as possible. The main starting point for good alternatives is that the current state of nature should be compromised as little as possible. This result in Overijssel preferring a policy that allows room for the river in dike ring 1 and which heightens the dikes everywhere else.

A.4.1 Gorssel (Dike ring 4)

Gorssel is almost exclusively dependent on farming, selling sustainable products. Therefore, their long term insurance is very important. This results in Gorssel being extremely reluctant to give up land to make room for the river, as they prefer to use this land for farming.

A.4.2 Deventer (Dike ring 5)

Deventer is a heavily urbanised area meaning it contributes economically to Overijssel. This means it is very hesitant to expand their river, as this will negatively impact the available land for real estate. Their believe is that if dike ring 4 expends their river bed, this could keep the river within comfortable limits within their city, without having to implement unfavorable policies themselves within the city. Furthermore, Deventer likes to use their importance to the region as leverage to not take more responsibility within the project.

A.5 Environmental interest group

The environmental group is invested in protecting the environment in the region. For the IJssel river flood risk management plan, this means they heavily favour room for the river as a policy option, as this will result in the best possible outcome for the nature.

A.6 Transport companies

Out of all European countries, the Netherlands transports the most cargo across rivers and waters on the mainland. Within this transport network, the Ijssel is an important artery (CBS, 2009). In order to be able to carry heavy cargo on the ships, the depth of the river needs to be substantial. If the depth decreases, either through a continued draught or through water management measures, ships aren't able to carry as much cargo (Rijkswaterstaat, 2020). The current requirements for the Ijssel are that two ships should be able to pass each other, at a minimum river depth of 2,5 meters (Smienk, 2003). Research has pointed out that the room for the river measures could negatively impact the flow of commercial cargo shipping on the Ijssel, as it will lead to more bottlenecks (Smienk, 2003). Therefor, the transport companies will seek to leverage their economic importance for the region, in the debat for potential flood risk management policies.

Appendix B. Operationalization of the problem formulation

This Appendix gives an in-depth explanation of the operationalization of the problem formulation. The operationalization is an important part as it translates the problem in real life into computer-terms such that quantitative simulation can be done. In this case, quantitative simulation is this case is optimal as it is almost impossible to simulate these kinds of problems mentally (Sterman, 1994).

The model used in this case report is made by Alesso Ciullo (Ciullo, de Bruijn, Kwakkel & Klijn, 2019). It is a model which is able to calculate the costs of failure at different aggregation levels given certain relevant, but uncertain factors. For a more detailed description of the model, please refer to the article written by Ciullo et al. (2019).

Translating the problem to terms which can be interpreted by computers is done using the XLMR framework (see figure 3) (Kwakkel, 2017; Lempert, Popper, Bankes, & RAND Pardee center, 2003). The problem formulation that is the foundation of this analysis is, as previously mentioned; *How can a flood risk management policy be implemented on the Ijssel river in such a way that it is maximally acceptable for all the parties involved, and at the same time robust for different deep uncertainties?* Each part of the problem formulation will be elaborated on in the following few paragraphs.

B.1 Aggregation level

There are multiple locations where the dikes can either be heightened or where river sections can be expanded. In this case, the locations are: Doesburg, Cortenoever, Zuthphen, Gorssel, and Deventer, as visible in figure 1. In the model they are respectively labelled as A.1 - A.5. The different locations also have different properties, meaning that they each have different profitabilities. As Rijkswaterstaat wants a robust solution and redounds to all the stakeholders' interests, it is important to gain knowledge of the relative profitability of the possible policies for each of the stakeholders and to get them all on board, the provinces in particular, as their land will be used for creating room for the river. Therefore, it was chosen to use a higher level of aggregation while also taking into account lower level influences to make sure no actor carries the heavy load. How this is measures is explained in more detail in the 'outcome' section of this appendix

As regards time, the model runs for 200 years and there are 3 separate moments which allow for decisions to be made. This implies that every 66 years decisions can be made whether to implement certain policies or not.

B.2 Uncertainties

In this model five uncertainties are taken into account. Table 3 gives a clear overview of the uncertainties, what they mean, their ranges and their units. The uncertainties in the model may be able to point out the worst case scenarios.

Table 4: Overview of the uncertainties present in the model

Factor	Description	Range	Unit
Flood wave shape	Describes the discharge at the most upstream location	0 - 132	
Dike failure probability (per location)	The higher this probability, the lower the chance that the dike will fail	0-1	
Final breach width (per location)	Indicator of the total volume of water that enters through a breach	30 - 350	m
Breach growth model	Growth rate of the dike breach width over time	1, 1.5, 10	m / day
Discount rate (per timestep)	Interest rate used to calculate the net present value	1.5, 2.5, 3.5, 4.5	

B.3 Levers

In this model, there are a few ways to intervene, but in general, an intervention takes place at a specific location, at a specific time. An intervention can either be Room for the river, heightening the dikes, or implementing a warning system. From the perspective of Rijkswaterstaat, the levers should be chosen in such a way that the costs and benefits are evenly distributed amongst the stakeholders. An overview of the levers is given in table 5.

Table 5: Policy levers in the model

Lever	Description	Range	Unit
Room for the River (per location per and timestep)	RfR lowers the water levels to a given level by widening the river bed. RfR can be implemented at the 5 locations (indicated by either 1 or 0, where 1 is implemented and 0 is not implemented). Each project corresponds to a profile of water level reductions across locations.	0 or 1	
Heightening Dikes (per location and timestep)	Total increase in dike height. The higher the dike, the higher the hydraulic loads it can withstand.	0 - 10	dm
Early warning	Early warning systems anticipate threats and therefore limit damage and casualties. The earlier the alarm is raised the more effective the response will be. However, this also implies that when it may raise a false alarm. False alerts can be costly and undermine trust in authorities. Waiting too long is also problematic as efficacy decreases the later the alarm is raised. The model allows the modeller to choose how much time in advance the alarm is raised.	0 - 4	Days

B.4 Outcomes

The outcomes which this model contains can be grouped into two categories. First, there are the costs of implementation of protecting and mitigating measures. These are proxied in the model by costs for RfR, dike heightening, and the warning system. Secondly, the category which represent the damage in case of a flood; the number of deaths and damage done to the properties. Table 6 shows an overview of the outcomes.

As written in the problem formulation, Rijkswaterstaat is to find a solution which is acceptable for all involved stakeholders. Therefore, the expected death, expected annual damage, total of non RfR related costs (e.g. dike investment costs + evacuation costs), and the variance of costs between locations, as this will make sure the costs are distributed evenly, were chosen as outcomes of interest. Subsequently, as mentioned in the actor analysis, actors have stated that they prefer heightening dikes over Room for the River, which is why a constraint was implemented as well. In our variant of the model, This constraint is defined by the median value of RfR and functions as a means to ensure that policies which heighten dikes more than they give the river space are favoured.

Table 6: Model outcomes present in the model

Outcome	**Description**	**Unit**
Expected annual damage (per location and timestep)	Expected annual value of flood damage over the planning period. The lower the value, the better.	€
Expected number of deaths (per location and timestep)	Expected number of deaths over a planning period. The lower the value, the better.	
Dike investment costs (per location and timestep)	Costs of raising dikes.	€
Evacuation costs (per timestep)	Function of the number of people evacuated and the number of days they have to stay away from home. This is based on the 1995 evacuation in the Netherlands.	€
Room for the River costs (per timestep)	Investment costs of the implemented Room for the River project.	€

Appendix C. Detailed description of the roadmap of the analysis

This appendix gives an in depth explanation of the roadmap of the analysis. It is important to note this appendix does not include the operationalization as this is explained extensively in the previous appendix as well as in the main text in section 2.1.

C.1 Open exploration

The first two steps to finding the set of desirable policies is to perform scenario discovery- and analysis. First, there is the Scenario analysis. Scenario analysis is used to determine how the important outcomes for Rijkswaterstaat, or key performance indicators (KPIs), perform over different scenarios. In this research, It was decided to run the model over 5000 scenarios using Latin hypercube sampling to get an overview of the uncertainty space and how the model may behave.

After having retrieved information about how the KPIs behave, scenarios can be identified in which the KPIs behave in an undesired fashion (e.g. scenario discovery). These scenarios then become the scenarios of interest.

Scenario discovery is a way of using statistical tools to look at the entire scenario space, and find regions that are relevant for policy, for example because the outcomes would perform poorly in that region (Bryant & Lempert, 2010). By using threshold values for the outcomes (i.e. values that the outcomes certainly should be able to exceed), uncertainty can be explored in an easy-to-interpret way. Poor performance in this analysis is defined as the scenarios that are simultaneously in the worst 33.3% of their range for the KPIs 'Expected annual damage', 'Expected number of deaths, and 'Variance expected annual damage' were used as the outcomes of interest. As concrete information about undesirability is lacking, this is an arbitrary number that has been chosen as a trade-off between good algorithm performance and usefulness of the interpretation. By no means does this imply that scenarios with costs/deaths just below this threshold are very desirable and should be fully disregarded (Bryant & Lempert, 2010).

C.2 Checking whether policies even work

An intermezzo before searching for actual policies is to check whether policies even work. This was done by running 100 different policies over 375 scenarios and comparing the results with the base case from the scenario analysis (5000 scenarios, no policies, using latin hypercube). These will then be compared using pair plots and histograms.

C.3 Directed search using Multi-Objective Robust Optimization

There are multiple methods available that can be used to search for candidate solutions that are robust. Robust decision-making aims to find solutions that can withstand uncertainty in the best way possible. This robustness can be defined in many different ways, and which one is most suitable depends on the decision context, the preferred level of risk aversion and a preference towards maximizing performance, minimizing variance or some combination (McPhail et al., 2018).

Two of the most promising directions currently are the so-called 'Multi-Scenario Many Objective Robust Decision-Making (Multi-Scenario MORDM) and Many Objective Robust Optimization (MORO). Bartholomew & Kwakkel (2020) have compared the two, and concluded that MORO is computationally more expensive and pays a higher 'price for robustness' (i.e. it is more likely that robust solutions are not in the Pareto set of specific scenarios), because multi-scenario MORDM at least finds the optimal solution in some scenarios. However, as MORO directly optimizes for robustness, it makes 'scenario selection' less of a problem.

In this report, MORO has been chosen as the algorithm to find promising policies, for two reasons. Firstly, it is argued that robustness in all uncertain futures is more important than optimization for a select few futures. Rijkswaterstaat needs to take into account the interests of many different actors and is accountable for the well-being of the general population; a 'better safe than sorry' mindset therefore seems more than suitable. Secondly, the involved uncertainties cannot reasonably be guessed: they are mainly technical, unknown factors, and if robustness is optimized for in the search phase already, then it is guaranteed that they are equally taken into account.

A MORO analysis consists of different steps. First a suitable robustness measure is chosen, for which the optimization algorithm needs to optimize. Then, using a multi-objective evolutionary algorithm (MOEA), a Pareto set of candidate solutions is found, for which the robustness is optimized. Then, for each of these candidate solutions, the robustness performance over the entire scenario space is analyzed, by taking samples of the uncertainties. Lastly, a tradeoff analysis is performed, to look at what solutions provide the most desirable tradeoff between the different KPIs. In this way, a recommendation can be put forward what policy or policies might best be implemented.

One important aspect of MORO is to define robustness metrics as this is the foundation over which the algorithm will optimize. The preferred method depends on the decision context, the preferred level of risk aversion and a preference towards maximizing performance, minimizing variance or some combination (McPhail et al., 2018). In this case, signal-to-noise has been chosen, a metric that seeks to maximize average KPI performance, and minimize the variance of this performance simultaneously. The metric seeks for optimizing system performance instead of satisfying constraints, and it takes into account the absolute values (McPhail et al., 2018). This is argued to most directly reflect Rijkswaterstaat's wish to find the solution that performs best in many different uncertain futures. It is seen as a metric that is medium risk-averse, which is assumed to reflect a Rijkswaterstaat that wants to be 'better safe than sorry' on one hand, but not so risk-averse that the more risky options for one KPI are directly ruled out if they do perform well on another KPI (reflecting the idea to find a solution that is maximally acceptable for different stakeholders, who each value different KPIs differently). Optimizing the mean reflects searching for the best possible solution, optimizing the variance reflects searching for one that will perform well in different futures. As this choice is largely based on assumptions, its implications will be further discussed in chapter 5 (discussion).

Another important aspect of MORO is defining constraints. In this case, there was only one constraint which was touched upon in the operationalization. As explained before, this constraint was chosen in such a way that heightening the dikes is favoured over Room for the River, following multiple actors' wishes.

Last but not least, before MORO can be implemented, first, the epsilon values, that determine the grid size within which MORO maintains one solution, had to be determined. Based on the resulting robustness values for random policies and iterative (small) MORO runs, the values shown in table 7 are chosen, in order to aim for around 10 solutions. Second, the hypervolume convergence metric needs expected ranges for the robustness metrics. Using the results of section 3.3 (the run with random policies), a rough estimate has been made of these, the values of which can be seen in the Python notebook ‘3 - MORO.ipynb’.

Table 7: Epsilon values used for MORO

KPI	Epsilon value
Expected number of deaths	1 * 10^-2
Expected annual damage	1 * 10^9
Dike investment costs	1 * 10^5
Evacuation costs	1 * 10^4
Variance of location-specific policy costs	1 * 10^9

C.4 Open exploration of MORO based policies

To make sure that the found policies also perform in average and best scenarios, each of the policies will be examined across the whole scenario space. This helps strengthen the position of the policies in terms of vulnerability and profitability (Bryant & Lempert, 2010). It is possible that the policies are not optimal for all possible scenarios. However, as stated before, the solution should also be acceptable next to performing optimally in the worst cases. Hence, why it is important to show their respective performance across the whole space.

As the simulation model is central to formulating advice for the Rijkswaterstaat, it is of utmost importance to translate their goals into the properties of the model. This chapter will guide the reader through the set up of the goal and how each part is related to Rijkswaterstaat’s goals. The whole setup of the analysis is based on the fact that Rijkswaterstaat wants to find a policy measure that is both robust and accepted by the different political parties.