Model-based Decision-making (EPA1361)
Faculty of Technology, Policy and Management

Flood Risk Management Strategy for the Municipality of Zutphen

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Part I

Model-based Analysis and Advice

Summary

In order to create Dutch resilient flood protection, the extensive 'Room for the River'(RfR) project has been brought into existence. The project stresses the importance of making room for the river, rather than only building more and higher dikes. The RfR initiative consists of multiple smaller projects along the river IJssel. This report focuses on the municipality of Zutphen, which is located amidst a few of these projects and has the task to maintain safety and well-being for its citizens. The projects requires Zutphen to make choices affecting expected deaths, damages and a variety of costs and (temporary) inconveniences. Moreover, as the river is connected to more municipalities and other stakeholders, the choices are also highly political.

The objectives, as well as the constrains for Zutphen, are formalized in the following research question: ***'What are the most robust and feasible policies to ensure minimized expected deaths, annual damage, dike investment- evacuation costs for Zutphen given the potential policy levers dike heightening, early warning and RfR-projects and all uncertainties of the model?'***

To be able to answer this question, an analysis is conducted employing multi-scenario, multi-objective robust decision-making (MS-MORDM). A main reason for employing this approach is that the issue at hand suffers from deep uncertainty, which is partly caused by climate change playing a role. Deep uncertainty implies that there are many potential futures and disagreement between actors on multiple levels. MS-MORDM is useful to detect robust solutions even in deep uncertain issues, making it suitable for this problem. To aid the decision-making process, scenario discovery is used. More specifically, the patient rule induction method (PRIM) is employed.

From the analysis, it can be concluded that Zutphen is dealing with two major trade-offs. The first one being, making a choice between damage/deaths and evacuation costs. The second trade-off is that for every policy chosen, a dike will suffer great damage on either monetary or physical level. It is highly recommended that Zutphen moves forward with the RfR strategy. Simultaneously it is advised to push for dike increase strategies for dike rings 1, 2, 4 and 5. In this manner, the Gelderland dikes will be spared damage and at the same time harm is minimized for Zutphen.

Though, it has to be taken into account that these recommendations are created from a theoretical model and therefore have to be critically examined by the receiving party. Moreover, MS-MORDM has a bias in favor of the poorly performing solution from the first search and scenarios are hand-picked by the analyst. This causes the modeling process to be imperfect. Lastly, the model suffers from s lack of information and computing power inherent to every modeling technique.

Chapter 1

Problem Framing

This report concerns the Room for the River project and focuses on the perspective of the municipality of Zutphen. This chapter will introduce the project and discuss the political arena within which a policy has to be developed. This section will also introduce the interests and constraints of Zutphen, as well as the policies, uncertainties and outcomes of interest considered in the analysis. Lastly, a research question will be introduced to guide the analysis.

1.1 Room for the River

Room for the river (RfR) is an innovative series of projects aimed at protecting the Dutch inhabitants and land from the increasing flow of water. The project goes beyond traditional approaches by employing innovative measures such as relocating dikes, riverbed excavation and depoldering (Zevenbergen et al., 2013). Figure 1.1 shows the total stretch of the project.

Zutphen is a municipality located in the province of Gelderland. It is situated in the center-East of the Netherlands on the upper branch of the IJssel river, as can be seen in Figure 1.1. Several parts of the river surrounding Zutphen are taken into consideration in the RfR project. In the past, Zutphen has taken the initiative to improve the safety of its inhabitants while simultaneously ensuring a comfortable and natural living environment (Zevenbergen et al., 2013). Within RfR the municipality of Zutphen has many stakes: the safety of its citizens, the quality of the living environment but also potential costs for measures as well as relocation.

1.2 Political Arena: Zutphen's Objectives and Constraints

In this section, the objectives and constraints of Zutphen as well as its position in the political arena are formalized. The municipality of Zutphen has an elected council that is dependent on the favour of its citizens for re-election. Zutphen has little financial power

Figure 1.1: A map of the Room for the River project (Zevenbergen et al., 2013).

but does have a strategically crucial location at the center of the RfR-project. Its needs and desires are advocated by the province of Gelderland and Rijkswaterstaat, who determine a final policy for the region in collaboration with the province of Overijssel and actors like the Delta commission, transport companies and environmental groups. Generally speaking, these can be split into two groups. Provinces which advocate the needs of dike-rings mainly focusing on their own safety, and all other aforementioned actors which focus more on financial, environmental and logistic reasoning.

The voice of Zutphen is important and definitely heard at times but this actor is also a mere single dike ring in a multi-stakeholder project. To enable Zutphen to successfully advocate for their interests and preferred policy, the policy proposals should be in line with the desires of other actors, to make implementation feasible. Therefore, the aim of this analysis is to focus not merely on what is best for Zutphen but rather to also include an analysis of what is best for all other parties (and therefore feasible). Thereby a strategy can be proposed which will increase Zutphen's chances of advocating successfully for a policy. This will avoid the likelihood and disapproval of the 'passing the hot potato'-strategy, where the problem is solved in one location but elicits the same problem in other locations. This is a strategy that most certainly will be opposed by other, disadvantaged actors. In definite terms, it simply passes on an increased flood risk. If Zutphen's strategy was only to heighten dikes, thus increasing the safety of its citizens, all upstream townships would not benefit from this policy and would be less likely to concede with such a proposal. The following objectives and constraints by Zutphen are considered:

- High priority on safety of inhabitants and land, which is non-compromisable. Concessions are acceptable in other fields.
- Minimize flood risk, mainly for Zutphen's dike ring given its highly populated area in relative terms.
- Re-location of inhabitants should be heavily compensated.

The objectives and constraints are formalised into a set of outcomes of interest in the subsequent section. These outcomes of interest for Zutphen focus on the financial and societal costs of potential strategies.

1.3 Research Question

The analysis aims to provide a **robust strategy** for the municipality of Zutphen to achieve **minimized expected deaths, damages, dike investment and evacuation costs**, preferably including options that seem **feasible in collaboration** with other actors. A second aim is to gain insight into the working of the system in collaboration with the client.

In this project, the decision-makers are confronted with deep uncertainty: they are faced with a problem that is highly tied to climate change. This makes it extremely difficult to predict the exact outcomes of the current decisions. To best tackle this uncertainty, robust decision-making can be deployed to run the analysis 'backwards' (Bartholomew and Kwakkel, 2020). This will be explained more thoroughly in section 3.3.

Two rivaling problem formulations are analysed. To start, the issued model (Kwakkel, 2021a) will be optimized for specific outcomes of interest, which lie within Zutphen's focus. These are determined to be annual damage, number of casualties and evacuation costs, given Zutphen's main focus on safety of its citizens. Of note, given technical restraints of the model, optimisation for evacuation costs in not only for Zutphen's population but on a global aggregated level (for the full upper branch of the IJsel). Since there is an option of compensating for relocating citizens if the river has have to be widened, RfR costs are not optimised. As a second problem formulation, to ensure dikes are not endlessly heightened in Zutphen, dike investment costs are minimised. This refrains from proposing a policy which would focus mainly on dike heightening, undermining the cost-effectiveness (safety versus costs) and thus feasibility of a project where money is a limited resource. Additionally, the robustness of a solution where dikes are solely and continuously heightened is questionable in light of prospective climate change effects.

Since Zutphen is not combating this complex problem alone, an overview of the effects of the found pareto front of optimal solutions on other dike rings is given. This provides a realistic understanding of the effects in the political arena. Here, the issued model is optimised for all aforementioned outcomes for all dike rings, displaying the full political arena of dike rings.

All potential policies will be simulated and analysed. The policies are a selection of combinations of levers: dike heightening, early warning systems and RfR-projects. Several uncertainties also occur in the model, such as the flood wave shape, dike failure probability and final breach width. For a full description of levers, uncertainties and model specifications, see Appendix A.

The combination of these problem formulations and model specification constitutes in the following formal research question: ***'What are the most robust and feasible policies to ensure minimized expected deaths, annual damage, dike investment- evacuation costs for Zutphen given the potential policy levers dike heightening, early warning and RfR-projects and all uncertainties of the model?'***

Chapter 2

Approach

The approach chosen for this analysis is multi-scenario, multi-objective robust decision-making (MS-MORDM). After a brief exploration of the model to understand its basic inner workings, a motivation for the chosen approach and a description of the steps taken are presented.

2.1 Exploration

Some preliminary analyses are run in order to identify the most important inputs and uncertainties as well as some trade-offs and correlations in the outputs. The goal of these preliminary analyses is to gain a basic understanding of the inner workings of the model and to manage expectations for future analyses.

Figures 3.1-3.3 show the impact of four randomly created policies, visualised by color. Their specifications are listed in Appendix B, a brief overview is provided here:

- In the blue policy, seven RfR-projects are conducted, one of which in Zutphen. The dikes are heightened by 56 decimeters along the entirety of the IJssel and by 7 decimeters in Zutphen. The early warning system is set to zero days.
- In the purple policy, seven RfR-projects are conducted, one of which in Zutphen. The dikes are heightened by 75 decimeters along the entirety of the IJssel and by 8 decimeters in Zutphen. The early warning system is set to three days.
- In the yellow policy, ten RfR-projects are conducted, three of which in Zutphen (the maximum number). The dikes are heightened by 64 decimeters along the entirety of the IJssel and by 19 decimeters in Zutphen. The early warning system is set to two days.
- In the green policy, five RfR-projects are conducted, one of which in Zutphen. The dikes are heightened by 108 decimeters along the entirety of the IJssel and by 26 decimeters in Zutphen. The early warning system is set to four days.

Figures 3.1 - 3.3 show that the green policy, in which dike heightening is carried out in combination with a few RfR-project seems most beneficial for Zutphen's outcomes of interest. The purple policy however, which poses the second most dike heightening, results in the largest number of expected deaths and damages. The blue policy, which is the cheapest, has relatively low damages but resulted in high deaths in some cases. Finally, the yellow policy is on the higher side in terms of costs but also seems to have quite some risks in terms of both damages and deaths. Overall, these results show that a large amount of dike heightening in combination with some RfR-project is the most beneficial for Zutphen.

A few more visualisations were made to show the outcomes of interest in the worst-case scenarios regarding expected deaths for each dike. Figure 3.4 shows the number of deaths and the annual damage in Zutphen as well as the overall evacuation costs in these scenarios. The annual damage is fairly high, whereas the number of expected deaths is still at a relatively low level for a worst-case scenario. Figure 3.5 shows the expected damage in all five dike rings in these scenarios. It becomes clear from this visualisation that who bears the highest strongly differs per scenario. The highest potential costs are born by dike ring 1, followed up by 3, 5, 2 and 4. Zutphen ranks the second-highest, which is worrisome. Finally, Figure 3.6 shows the expected deaths in all dike rings over these scenarios: dike ring 3 clearly ranks the highest. This is an unfortunate position for Zutphen because it means they risk the most casualties. This relatively high risk should be taken into consideration in further analysis.

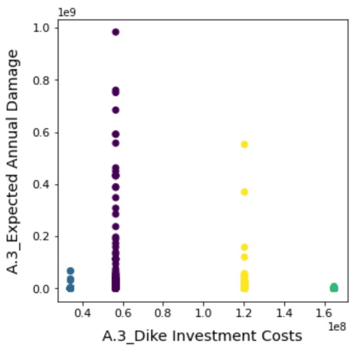

Figure 2.1: Expected annual damage versus dike investment costs for Zutphen, 250 scenarios, 4 policies

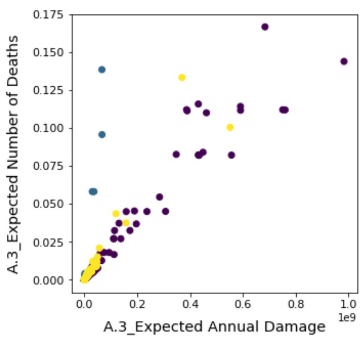

Figure 2.2: Expected deaths versus expected annual damage costs for Zutphen, 250 scenarios, 4 policies

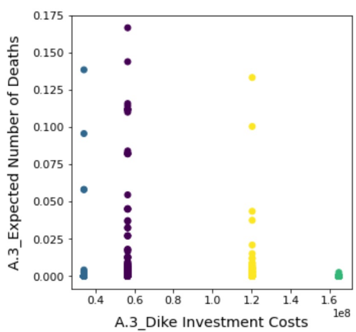

Figure 2.3: Expected deaths versus dike investment costs for Zutphen, 250 scenarios, 4 policies

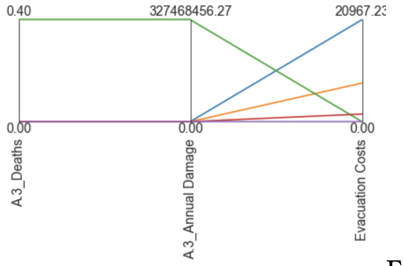

Figure 2.4: Expected annual deaths and damages for Zutphen and general evacuation costs for the worst-case death-wise scenario of each dike.

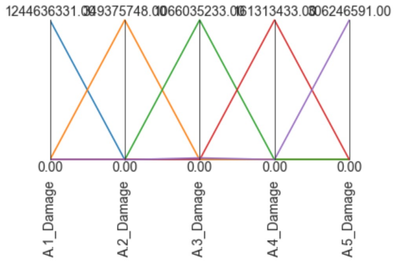

Figure 2.5: Annual damage per dike ring for the worst-case death scenario of each dike. The top numbers are: (A1) 1 244 636 331€ (A2) 349 375 748€ (A3) 1 066 035 233€ (A4) 161 313 433€ (A5) 306 246 591€

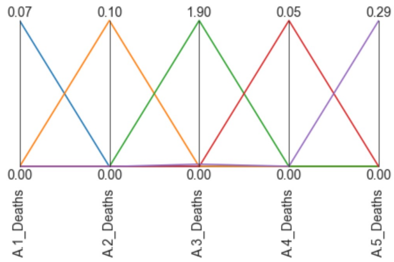

Figure 2.6: Expected deaths for all dike rings for the worst-case death scenario of each dike ring.

2.2 Choosing the approach

The presented problem faces a variety of objectives and constraints from a range of actors. It is highly intertwined with environmental issues, specifically that of climate change, which gives rise to the element of deep uncertainty: many potential futures exist and there is disagreement between actors on the technical feasibility and necessary scope of the project as well as on the ranking of outcomes of interest. (Eker and Kwakkel, 2018; Walker et al., 2013). A potential way to deal with this deep uncertainty in an environmental problem is Robust Decision Making (RDM), Multi-Objective RDM (MORDM) and Multi-scenario MORDM (Bartholomew and Kwakkel, 2020). These approaches aim to detect solutions characterized by robustness even in deeply, uncertain cases (Eker and Kwakkel, 2018), making them fit for the problem at hand.

One of the challenges of MS-MORDM is that base cases have to be chosen (Bartholomew and Kwakkel, 2020). This especially poses a challenge because climate change, a deeply uncertain and multi-faceted process, places a significant role in the RfR-project. Therefore, there are no prevalent base cases and the decision options should be examined under as many base cases as possible. Multi-scenario MORDM specifically is able to handle this wide range of plausible future by repeating the search for several alternative scenarios (Bartholomew and Kwakkel, 2020). MORO was also considered as a potential approach. In addition to the benefits of Multi-Objective MORDM, MORO optimizes robustness over a set of scenarios. Nonetheless, the large computational costs make MORO the appropriate solution only when our sole focus would be on robustness (Bartholomew and Kwakkel, 2020). In this report, a solution for Zutphen is desired that will both be robust across a set of scenarios (since there are many factors that Zutphen cannot control), but also as close as possible to the optimal one. Taking this into account, MS-MORDM is considered to be an adequate method to follow.

2.3 MS-MORDM

This section discusses the steps taken in the analysis following the MS-MORDM framework presented in Kwakkel and Bartholomew's work (2020). The map presented in the aforementioned work begins with a model specification, followed by a MORDM, which will result in a reference scenario selection and a policy alternative determination. The last part constitutes of uncertainty analysis followed by scenario discovery, whereas at the same time it should be noted that the process is iterative and should be repeated multiple times, but due to computational power and time constraints, the process was only implemented once.

Model Specification

This phase has already been covered in the form of the selection of the model and the outcomes of interest to prioritise as explained in section 1.3 and Appendix A.

Finding candidate solutions (MORDM- part 1)

During the search for candidate solutions, many multi-objective evolutionary algorithms could be chosen. The final selection was based upon the prevalence and therefore Non-dominated Sorting Genetic Algorithm was selected. The search for candidate solutions is done by optimizing over all possible combinations of individual policy actions such as dike heightening or RfR using 5000 evaluating functions and an epsilon value of 0.01 to ensure that as many solutions as possible are being detected on the pareto front in terms of deaths, one of our outcomes of interest. Convergence is monitored with epsilon progress and hyper volume. The candidate solutions found must then be evaluated under uncertainty.

Re-evaluating the candidate solutions under uncertainty (MORDM- part 2)

The candidate solutions were pre-filtered to only keep those that yield an expected annual damage in Zutphen below 100M€. This number is chosen quite arbitrarily: it should be low enough to reduce the number of policies analysed but high enough to not prematurely remove policies that could be the most robust. The uncertainty analysis consists of running experiments using 100 scenarios and the pre-filtered policies. Their performance in the experiments is measured using a signal-to-noise robustness metric. Given that the outcomes should be minimized, a low signal-to-noise ratio is desirable. A visualization of the results of the experiments allows for an estimate of the policies' performance.

Scenario Discovery with PRIM to find vulnerabilities (MORDM- part 3)

Scenario discovery aims to find the conditions under which the candidate policies do not yield desirable results. The scenario discovery method that is being used in this analysis is the most frequent one, the Patient Rule Induction Method (PRIM). PRIM identifies regions in the model input space that gathers the strongest potential to produce outcomes of interest. One drawback is that PRIM can only be used for binary classifications (Kwakkel & Jaxa-Rozen, 2015). The scenario discovery in this step aims to find scenarios in which damages in Zutphen are over 1M€.

Reference scenario selection and repeating previous steps

The scenarios found in the previous are filtered for the five worst cases regarding deaths and damages for Zutphen. This is done to find a better policy proposal for Zutphen's interests. Since Zutphen is a small actor in the decision-making arena and even small decisions might affect the municipality heavily, a conservative approach with high risk aversion is proposed. Worst cases are considered to be adequate for this type of analysis (McPhail et al., 2018). These scenarios are then used as reference to find alternative solutions following the same procedure as described under "finding candidate solutions" above.

The alternative solutions found are re-evaluated under uncertainty in the same way as above, but using a maximum regret robustness metric instead of a signal-to-noise ratio. This new metric is introduced to further limit the number of alternate solutions that should be considered. The consequences of the outcomes under study are deemed to be catastrophic for a community as small as Zutphen, both in terms of deaths and in terms of annual damage. Therefore, a rather 'conservative' set of robustness metrics is considered to be appropriate (McPhail et al., 2018). The results of this re-evaluation allow for the selection of a proposed policy.

The last step in this analysis is to perform another scenario discovery following the same procedure as above, but focusing on another outcome of interest which is determined by the results of the re-evaluation of the alternative solutions.

Chapter 3

Results

The results of the experiments are presented in accordance with the approach discussed in the previous section.

3.1 Finding Candidate Solutions

The results after the optimization process for the MORDM is being depicted in Figure 3.1. It must be noted that, due to the low number of evaluating functions, the algorithm did not converge. This leads to sub-optimal solutions.

Reflecting on Figure 3.1, despite the fact that there are several solutions that can be considered desirable in general, in the vast majority of the cases trade-offs have to be made. In various cases, it is achievable to minimize damages and deaths in Zutphen, but that comes at a significant cost in terms of evacuations. Although a large part of these costs is being covered by the Central Government, such an incident might have far-reaching ramifications on the budget allocated to the municipalities and in the long-term might constitute a blow to Zutphen's financial status.

3.2 Re-evaluating candidate solutions under uncertainty

In order to measure robustness, a signal-to-noise ratio analysis is performed. Our goal is to minimize all of the variables under study, since they are mostly financial and physical damage which we want to restrict close to zero. Taking that into consideration, our main focus on the cases in which the signal-to-noise ratio scores are low, since in order to minimize these outcomes we need a very low mean and a relatively higher standard deviation.

Figure 3.2 portrays the signal to noise score for all solutions. It can be claimed that the vast majority of the solutions cannot score low on signal to noise ratio in all three expected outcomes of interest. This highlights, once again, the trade-offs that ought to be made for the municipality of Zutphen.

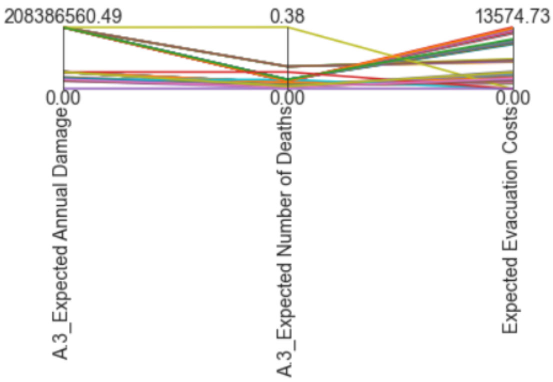

Figure 3.1: Candidate solution search based on outcomes of interest

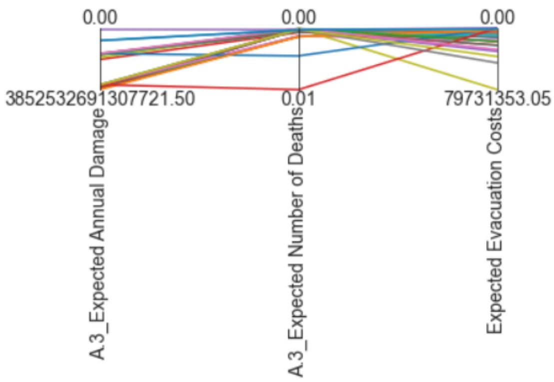

Figure 3.2: Signal to noise scores for all solutions

Taking the aforementioned into account, it is crucial to further examine the possible solutions and choose the scenarios that are deemed to be most of interest, in order to have a better understanding of the system and examine whether the proposed policy is robust.

3.3 Scenario discovery with PRIM

This scenario discovery aims to find scenarios in which candidate solutions fail to keep damages in Zutphen under 100M€, as well as the range of inputs that lead to them.

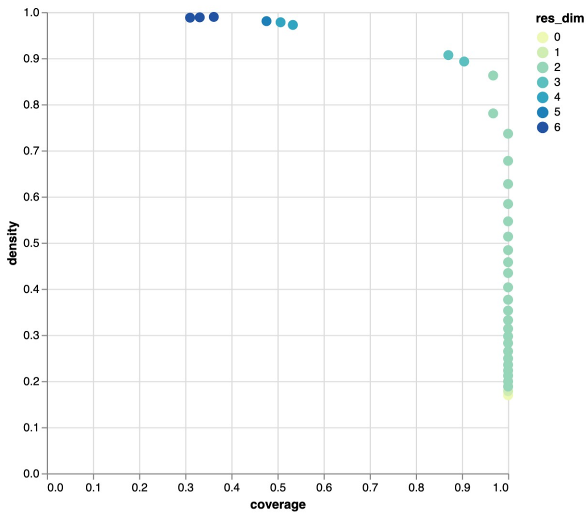

Figure 3.3: Scenario Discovery Results for Outcomes of Interest

Figure 3.3 portrays the scenario discovery results. The trade-off between coverage (proportion of scenarios of interest covered) and the density (proportion of covered scenarios that are of interest) is apparent. Therefore, a choice where both density and coverage are adequate has to be made for further examination. The box chosen has a density of 90% and a coverage of 87%, which makes it yield a highly suitable set of scenarios.

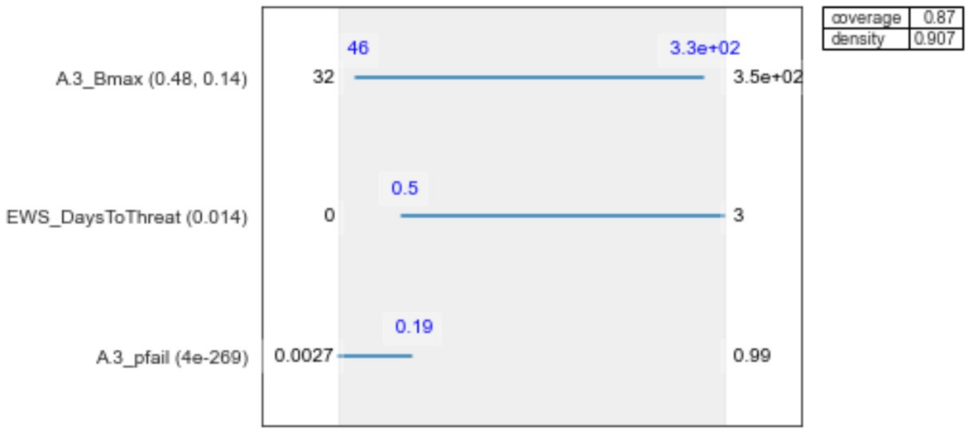

Figure 3.4: Examination of the box under study

Figure 3.4 shows the the ranges of values in the inputs that lead to the scenarios within box 28, which constitute the result of the scenario discovery. Reflecting on the graph, it is important to assert that the aforementioned coverage and density values for box 28 can only exist if the values presented in Figure 3.4 can be achieved.

3.4 Reference scenario selection

The set of scenarios covered in the results of the scenario discovery is too large for the following steps, so a selection must be made. To this aim, the cases with the highest 2% of expected annual damage and the 2 % of the expected number of deaths at the same time are selected. These numbers were found through trial and error, until only five scenarios fit the criteria.

The selected scenarios produce the outcomes shown in blue in Figure 3.5. Interestingly, the chosen scenarios present the worst outcomes in terms of damage and deaths, but not for evacuation costs. The high number of deaths may be due to a faulty evacuation policy that failed to evacuate all citizens, resulting in a higher death count.

3.5 Re-evaluating alternative solutions under deep uncertainty

This time around, the robustness of the solutions is evaluated through the maximum regret. The main aim is to minimize regret across all possible variables. Nonetheless, that is again a largely challenging task and it is paramount to assess the trade offs that are being presented in the regret analysis. Regret is only analyzed for the outcomes of dike rings 1, 2 and 3 due to their geographical relevance. Given the high number of alternative solutions found, only those that yield the lowest 10% damage in dike ring 3, the lowest 20% of damage in dike

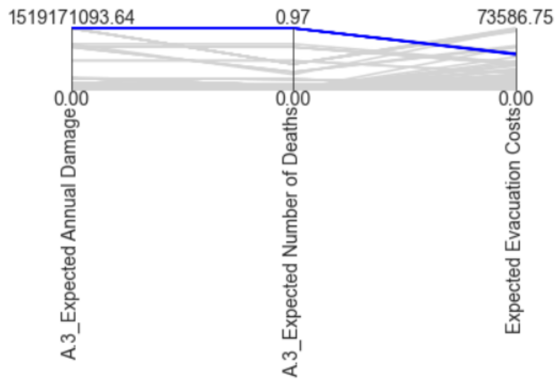

Figure 3.5: Scenario Selection

ring 2, the lowest 60% in dike 1, and the lowest 50% number of deaths over all dike rings are being taken into account.

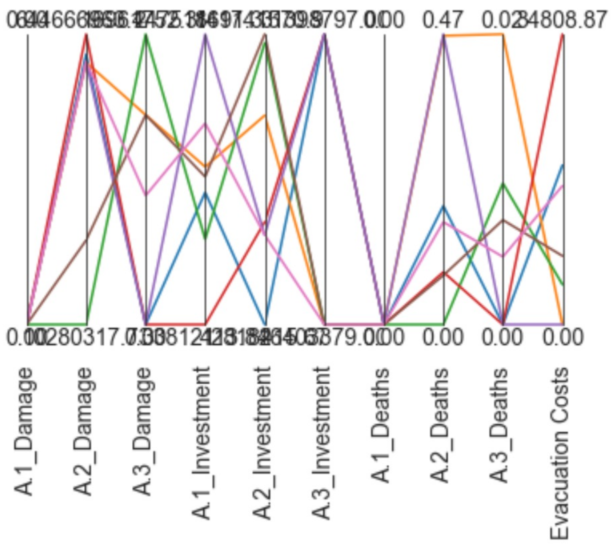

Figure 3.6: Maximum regret graph for the policies that are considered best for Zutphen

The results of the maximum regret analysis are shown in Figure 3.6. The graph clearly maps all the sets of trade-offs that have to be made between the different dike rings. A low regret scenario for Zutphen might have catastrophic consequences (high regret) for dike ring 1 or 2, leading to a clear conflict of interests. Having in mind the mandate of Zutphen about safety and minimizing damage and deaths, but also keeping a relatively low damage for the other dike rings in Gelderland, a selection of the policy that are considered best is made. Overall, the policy in red seems to generate the results with the lowest regret in the outcomes of interest. The aforementioned policy consists of a full Room for the River implementation for dike rings 3, 4 and 5, as well as a dike heightening in dike rings 1, 2, 4 and 5. For this policy, the majority of citizens of the dike rings in Gelderland seem to suffer the minimum damage possible. A drawback would be the relatively high investment costs that will be necessary for Zutphen, namely around 31M€, as a somewhat high maximum regret is being shown. They are seemingly, however, the only road to safety, since policies that lower that investment also expect a higher damage on Zutphen. This policy formulates an alignment of interest across virtually all Gelderland dike rings, so that they can build a unified front to pursue their demands on a province level.

Second Scenario Discovery

The results of the final scenario discovery can be depicted in Figure 3.7. It can be seen that there is almost no scenario that is particularly of interest. PCA preprocessing before actually running PRIM could have been conducive into finding cases of interest. However, due to time constraints, this was not performed.

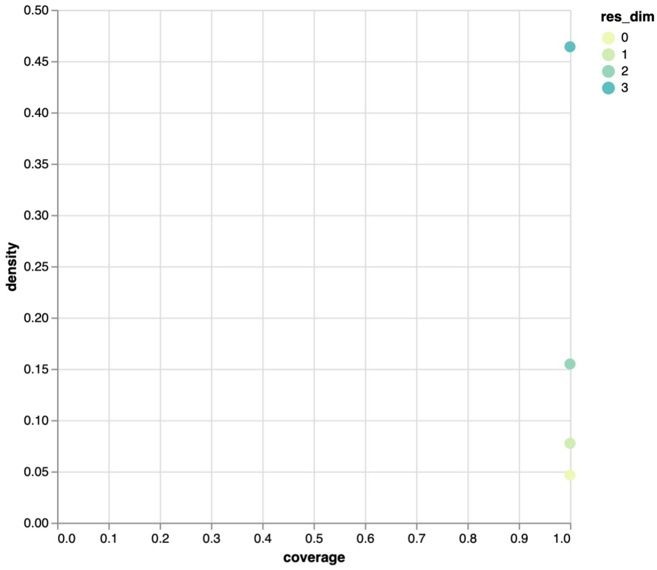

Figure 3.7: Scenario discovery after re-evaluation

CHAPTER 4

DISCUSSION

This section describes the key threats to the validity of the conclusion of this report. It also presents several suggestions for further improvement of the analysis.

4.1 Limitations

It can be widely understood and accepted that *'All models are wrong, but some are useful'* (Box, 1976). The analysis presented in this report comprises of an imperfect implementation of the model, largely due to constraints in time and computing capacity. The main setback of this implementation is the limited number of function evaluations during optimization and scenarios, giving little room for convergence and a complete and diverse set of solutions and scenarios.

Secondly, the use of this model in itself was based on an interpretation of the interests, constraints and political position of the dike ring Zutphen, which is characterized by bounded rationality and limited resources. Materials provided within the course and digital resources were used to investigate the position of Zutphen. No interviews or in-depth investigation were conducted to shed more light on this position. For this reason, the analysts might be missing information that would have supported decision-aiding.

Included in this flawed perception of Zutphen is the flawed perception of its position in the political arena, its relation with other actors and the interests and constraints of these other actors. Knowledge of these positions and relations were acquired to a degree through the course material, digital resources and the debate that was conducted. Knowledge of real-life relations however is very difficult, even though it is extremely relevant to the political game (De Bruijn et al., 2008).

Thirdly: MS-MORDM was a very useful approach to use in this report because it strikes a balance between robustness and optimality (Bartholomew and Kwakkel, 2020). However, a potential limitation of this methodology is that it, as well as MORO, is challenged in the selection of the scenarios to use. MS-MORDM intrinsically has a bias towards solutions that performed poorly in the first search (Bartholomew and Kwakkel, 2020). This leads to a possible deletion of policies that could be very robust very early on in the MS-MORDM process. In the context of this report, this bias leads to solutions that are advantageous to Zutphen, but may heavily affect other dike rings.

Another limitation is the selection of reference scenarios. This analysis picked the worst-case scenarios in order to reproduce Zutphen's high risk aversion, but this is done at the cost of diversity. A more diverse ensemble of scenarios could lead to even more robust albeit less optimal solutions.

The choice of sampling methods and robustness metrics also leads to a certain bias, which may limit the quality of the results. For sampling, latin hypercube was chosen due to its ability to better cover the entirety of the input space. However, this approach is not as risk oriented as for example Monte Carlo sampling. Regarding the robustness metrics, signal to noise and maximum regret were considered to be adequate, but a selection in diversity could have been highly efficient to detect the most relevant policies (Eker and Kwakkel, 2018). Finally, PCA-preprocessing before performing scenario discovery with PRIM, especially for the last step of the anlaysis, could have improved the coverage and density ratios of the boxes found. PCA is known to improve scenario quality and also to increase interpretability (Dalal et al., 2013).

Finally, the approach fails to address the limitations and needs of other actors, especially beyond the limits of Gelderland, taking them only into consideration during the calculation of the evacuation costs. This is due to prioritising the needs and issues of Zutphen and to the computational limits of the machines used. Nevertheless, since the overall budget of the Central Government is allocated in both regions, among all others within the Netherlands, it would be wise given a much larger computational power and wider time limits to examine the financial and physical damages of the dikes in Overijssel (dike rings 4, 5 and 6 in the model) as well.

4.2 Future Research

A few clear suggestions can be given to further improve this analysis:

- Larger computing power and more time could be made available to run the model, enabling a wider scope of scenarios and higher number of function evaluations. This could allow for optimization on more metrics, including metrics that might not seem relevant at first but might make the policies more feasible nonetheless. A wider time frame would also allow for testing of different sampling techniques.
- A second set of improvements concerns stakeholder involvement. Stakeholder involvement is a very important part of any decision aiding process/model. Stakeholder involvement could be carried out efficiently and beneficially in several ways. Participatory modelling could be introduced during several stages of the project, both with policy-makers from Zutphen and with several other actors (Moallemi et al., 2020). Interviews could be carried out to enable a more sound understanding of the roles and interests of the different actors, and to generally improve the credibility of the results of the analysis in the stakeholder's eyes.

- The bias in the MS-MORDM methodology could be prevented by optimizing for all dike rings and involving all stakeholders in the model formulation process. However, it is unclear whether the model would yield solutions that are both robust and optimal for all outcomes in all dike rings at the same time.

Chapter 5

Conclusion

Considering the results and reflecting on the limitations before and during the model analysis, numerous points are asserted to be useful. Among these, the most important is that Zutphen sits at the intersection between two major trade offs:

- On one hand, there ought to be a choice between damage/deaths and evacuation costs, namely to choose either safety and security or prosperity. Increasing evacuation costs will undoubtedly put further pressure on the overall budget of the Central Government, which will hinder investment in the region. Despite the fact that, according to the mandate, Zutphen's primary focus is safety, it is not its sole purpose. Therefore, there should be further consideration to which extent Zutphen is willing to opt for safety in the aforementioned trade off.

- In addition, it can be clearly understood, that, for every possible policy, there will be a dike that will take severe damage, either on a monetary or on a physical level. In the policy proposal below, dike 2 suffers severe damage. This generates difficulties in achieving cooperation between the different dike rings within the region, with the ultimate goal of presenting a unified front on the region and make their claims and demands heard on a national level. The analysis conducted aimed at finding the policy that would generate the lowest possible damage across all dike rings, quantified through the maximum regret function. The second part of the process involves communicating the results of this analysis to the whole region, in order to continue with coordinated action.

Reflecting on the whole analysis, it is strongly suggested that Zutphen moves forward with pursuing a room for the river strategy, while at the same time advocating in favor of dike increase strategies in the rest of the dikes, which are dike rings 1, 2, 4 and 5. A useful strategy would be to cooperate with municipalities that share the same interests and are affected in a similar way by the proposed policy, in this case dike ring 1, in order to unify and approach the head of province, with the aim of moving along with the proposed projects. This is believed to lead to lower damage for the Gelderland dikes, while minimizing the damage for Zutphen. It is clear, however, that the damages incurred by dike ring 2 are unacceptable and that the final policy agreed upon by all actors of Gelderland will differ in some ways from the one proposed here. The proposed policy still provides insights in what can be achieved and may nourish discussions surrounding the protection of the IJssel river banks.

Overall, a vast increase on the river flow is expected to generate damages in the communities that reside along its banks. This report aims at providing an initial map of action for the municipality of Zutphen. This comes in the shape of the potential figures on the outcomes of interest for various different scenarios. It also presents several potential outcomes that are of interest to the other actor, so that Zutphen can plan an initial strategy and make an endeavour to find possible collaborations, but also pitfalls during negotiations and debates. For a more concrete plan to be constructed on the long-term, however, further analysis is strongly recommended.

Part II

Political Reflection

Chapter 6

Reflection

Real-world decision making does not solely rely on model predictions and scientific findings. Diverging values, disputed knowledge and conflicting interests are at play in the real-world, messy political decision-making. As an analyst, it is of the utmost importance to be aware of this political arena and employ a strategy to ensure that your findings are used in an appropriate way. In this reflection, tensions and challenges will be addressed that can hinder the impact of the analysis and strategies to deal with the tensions are provided.

The Dutch RfR-project has proven to be more than an interesting arena for water management research. The multi-actor, multi-level governance policy creation showed to be a valuable research domain for investigating the interaction between science and politics. Previously, large-scale projects such as RfR were hindered by governance issues, but these issues have been successfully addressed and navigated within RfR (Rijke et al., 2012). On a basis of leadership, public engagement and collaborative research, a successful integrated approach was developed. Research was mobilized selectively by different stakeholders, leading to contesting research claims (Schut et al., 2010). Stakeholders enrolled on a political process of devaluing research of other stakeholders, often attacking models on the assumptions made.

As George Box used to say: "All models are wrong, but some are useful" (Box, 1976). It is up to the analysts to be transparent about the assumptions that underlie and the expected usefulness of their model. A clear example of a political process in which science was blown away occurred in the recent student debates of the EPA1361 course, in which knowledge about river management was completely swept away by a transportation company representative stating: "Room for the river? No, we need room for the farmers!" These examples show that thinking strategically about the interface of research and politics is of utmost importance to have adequate impact on society with the conducted research.

6.1 Tensions and Challenges

Tensions and challenges have been established through closely watching, and taking part in, the student debates of the EPA1361 course, but also through analysing the state of the art literature. During the process of establishing a desired policy for the student debate, the municipality of Zutphen had trouble understanding in-depth model workings and questions like “What would a good threshold be for variable X?" were difficult for them to grasp or seriously answer. Robustness came up mainly when talking about climate change. A question often asked was: “We can take these measures now, but what if?" The conflicting interests were clear from the start, in which the transport company had no interest in safety, whereas municipalities had little interest in talking about transportation possibilities. Finally politicizing is often used to put away analyses in a matter that is difficult for an analyst to respond to. Once framed as the enemy, it is difficult to escape that frame (de Bruijn, 2011).

There are four main tensions and/or challenges in the political arena as an analyst, identified by the analyst team: communicating about uncertain and complex predictions with clients that have limited knowledge, ensuring a robust solution, handling conflicting interests in the actor field and preventing politicizing of scientific findings.

6.2 Communicating about Uncertain and Complex Predictions

The client is the municipality of Zutphen. The city council of the municipality of Zutphen consists of elected members, with limited knowledge on modeling and simulation. This gives rise to risks such as misinterpretation of model results, oversimplifiction of model results and deliberate misuse of the model results. A conflict with the actor about modeling could lead to distrust, limiting the impact of the analysis.

A frequently mentioned issue at the science-policy interfaces is the so-called “operational misfit between demand and supply of knowledge" (Van Enst et al., 2014). In short, that means that the information a scientist gives is not enough for the policymakers to have a clear sense of which direction to go in the policy arena. To account for this issue, the goals of the model have been set up in cooperation with the municipality during the debate cycle. Moreover, it is important to stay in talks with the municipality during the analysis, keeping the process iterative, instead of only delivering a report at the end of the process. This will retain a bond of trust, keep the municipality informed on modelling choices and the usability of the model.

A big danger is to simplify complex analyses to make them understandable for the municipality. This should be avoided, and instead the focus should be on collaboratively understanding of incomplete knowledge and implications (Stirling, 2010). Although the municipality may want easy, confident outcomes that tell them what to do, that is simply impossible for the type of complex issues. Therefore exploratory, collaborative modelling can be used to gain insights in the behaviour of the system and can form a strong base for building knowledge about the system with the client (Moallemi et al., 2020). In section 2.1 this exploratory modelling has been performed.

An important final note is that in all communication with the client, the analyst needs to account for the lack of modelling knowhow by the client. "The analyst should speak in a language that policymakers can understand" (Kettl, 2016). Instead of using terms like "thresholds" analysts should speak about acceptable ranges for instance.

6.3 Robustness

For a model outcome to be robust, it should have performance above a certain threshold in the uncertain future, with all plausible scenarios taken into account. This entails coming up with solutions that do not only hold if a specific set of events happen in the future, but are strong and resilient.

Throughout the modelling cycle, robustness has been central. Therefore, the MS-MORDM (multi-scenario, multi-objective, robust decision-making) approach was taken for this analysis. MORDM enables a robust analysis by testing each solution under a bulk of future states (Kasprzyk et al., 2013). Thereafter, scenario discovery methods can be used to discover influential assumptions and system conditions. Eventually, MS-MORDM was chosen in favor of MORDM as it performs well in terms of computational costs, robustness considerations and optimality (Bartholomew and Kwakkel, 2020).

Alternatively, Watson and Kasprzyk 2017 presented an approach in which multi-objective evolutionary algorithm (MOEA) optimization is used in a multi-scenario context. In this case, multiple plausible scenarios are separately optimized, and their resulting trade-off sets are compared to determine how solutions' properties change based on scenario assumptions (Watson and Kasprzyk, 2017). Optimization under severe conditions may create solutions that are better suited for a wide range of conditions than sole optimization under a baseline assumption. This approach could be a suggestion to apply in further analysis.

Finally, an adaptation plan could enhance the robustness of the analysis and proposed strategy as well. In such a plan, it is clarified how the decision-makers should respond to changing events and conditions. This could make for an even robuster decision-aiding tool (Kwakkel et al., 2015, Haasnoot et al., 2013). Dynamic adaptive policy pathways are therefore another suggestion to apply in further analysis.

6.4 Actor Field

In the actor field, conflicting interests are at stake. Policies that might be perfect for our client, can be devastating for other actors. It is unrealistic that such a policy would become the approved solution at the end of a decision-making process.

In the model, not only parameters that affect Zutphen are taken into account, but also those that concern other dike rings and the overall outcomes. This provides the municipality with a clear overview of solutions that work for other actors as well, instead of having a tunnel vision on its own interests. Furthermore, before the final policy strategy can be decided on, multiple meetings and debates take place in which information can be gathered on the resources, interests and constraints of other actors. Through this process, a clear perspective can be established on what a solution that will satisfy other actors looks like. Additionally, these sessions can lead to negotiated knowledge, which grants easier pathways to suitable solutions most actors will agree on (Schut et al., 2010).

It is computationally very demanding to evaluate the exact outcomes for every single actor in the field. To help the client in the messy debate, the client should thus mainly get insights into how the system works. This can grant the client room in the political process to play the political game, deviate from set-in-stone pre-defined scenarios and establish a policy strategy that satisfies everyone's needs. In the end, the model is not there to come up with an optimal solution, but rather to give insight into the inner workings and trade-offs of the system.

6.5 Politicizing Science

A risk when applying models to complex, political issues is politicizing science (Sarewitz, 2004). In working with a client as analyst, your findings are inherently subject to becoming politicised to some extent(Sarewitz, 2004). It is also a threat in this case, as multiple actors have their own team of analysts, thus supplying contesting parties with their own bodies of relevant findings. The analysts will thus be directly hired by a political actor who will demand information suiting their political objectives. Politicizing science can be destructive in the long term, as it can lead to questions about the legitimacy of scientific research (Rayner et al., 2021).

As analysts, it is important to try and stay away from the political frame of the client. To avoid politicizing as much as possible, Sarewitz suggests being very clear about value positions from the beginning onwards (Sarewitz, 2004). Furthermore, available policy options should be broad to have broad political support. For this reason, additional to previously mentioned reasons, not only parameters relevant for the Zutphen municipality have been taken into account when evaluating solutions. This gives a clear overview of what a certain measure would mean for other actors, and whether it would thus have a broad base of support.

6.6 Strategy Risks

The real-world decision-making process remains relatively unstructured and difficult to grasp. In previous paragraphs, for all challenges and tensions, strategies have been suggested to reduce the tensions. However, even with the addressed tensions and challenges, some risks will remain.

A first risk stems from the strategies of taking a broad view on the problem, striving for common knowledge rather than providing simple solutions to the client. This strategy can frustrate the process for the client, as they have limited resources and want advice to be as concrete as possible. To address these concerns, clear expectations have to be set at the start of the project, in consultation with the client. This will provide the client with a clear view of the method and abilities of the analysts, granting clear expectations on the form of the results from the analysis.

A second risk of the proposed strategy is that by analyzing broad and focusing on shared system knowledge, the analysis will remain vague and will therefore have less impact compared to direct, simple advice. It is difficult to address this matter since it is a deliberate choice to not go for simple truths (Stirling, 2010). However, being clear about uncertainties should not be confused with talking in riddles. Therefore to adapt to the risk, the analysts need to explain the model and outcomes in a clear manner, using words that are understandable to policymakers in the actor field (Kettl, 2016).

The last risk is that computationally, the analysis will be so heavy that the analysts run out of time and cannot quickly respond with new outcomes when a minor perspective change is requested by the client. Although the deliberate choice was made to use MS-MORDM instead of MORO, which would be more robust but computationally more expensive, MS-MORDM remains a computationally heavy method (Bartholomew and Kwakkel, 2020). As this is difficult to solve, clear communication with the client is again key. Clear communication about flexibility of the analysis can set expectations to a reasonable level, preventing disputes between analysts and client. Furthermore, this communication can prevent the analysts from having to rerun the model over and over again to account for new questions by the client.

6.7 Conclusion

Acting on the interface of modelling and politics remains a challenge that should be addressed with caution. By identifying the main tensions and challenges and implementing solutions to these, the problems are mitigated, but the risks have not completely disappeared. As analysts, we should stay aware of the complex political arena in which we operate throughout the process, stay up-to-date with the way our insights are used and play an active role in bringing insights to the decision arena.

Bibliography

Bartholomew, E., & Kwakkel, J. H. (2020). On considering robustness in the search phase of robust decision making: A comparison of many-objective robust decision making, multi-scenario many-objective robust decision making, and many objective robust optimization. *Environmental Modelling & Software*, *127*, 104699.

Box, G. (1976). Science and statistics. *Journal of the American Statistical Association*, *71*(356), 791–799.

Dalal, S., Han, B., Lempert, R., Jaycocks, A., & Hackbarth, A. (2013). Improving scenario discovery using orthogonal rotations. *Environmental modelling & software*, *48*, 49–64.

De Bruijn, J. A., de Bruijn, H., & ten Heuvelhof, E. (2008). *Management in networks: On multi-actor decision making*. Routledge.

de Bruijn, H. (2011). *Framing: Over de macht van taal en politiek*. Bariet ten Brink.

Eker, S., & Kwakkel, J. H. (2018). Including robustness considerations in the search phase of many-objective robust decision making. *Environmental Modelling & Software*, *105*, 201–216.

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global environmental change*, *23*(2), 485–498.

Kasprzyk, J. R., Nataraj, S., Reed, P. M., & Lempert, R. J. (2013). Many objective robust decision making for complex environmental systems undergoing change. *Environmental Modelling & Software*, *42*, 55–71.

Kettl, D. F. (2016). Making data speak: Lessons for using numbers for solving public policy puzzles. *Governance*, *29*(4), 573–579.

Kwakkel, J. H. (2021a). Epa1361_open, final assignment.

Kwakkel, J. H. (2021b). Model-based decision making course schedule 2020-2021.

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2015). Developing dynamic adaptive policy pathways: A computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change*, *132*(3), 373–386.

McPhail, C., Maier, H., Kwakkel, J., 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.

Moallemi, E. A., Kwakkel, J., de Haan, F. J., & Bryan, B. A. (2020). Exploratory modeling for analyzing coupled human-natural systems under uncertainty. *Global Environmental Change*, *65*, 102186.

Rayner, S., Lefty, D. W., Sarewitz, D., & is Co-Director, D. S. (2021). Policy making in the post-truth world. *Breakthrough Journal*, *13*.

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.

Sarewitz, D. (2004). How science makes environmental controversies worse. *Environmental science & policy*, *7*(5), 385–403.

Schut, M., Leeuwis, C., & van Paassen, A. (2010). Room for the river: Room for research? the case of depoldering de noordwaard, the netherlands. *Science and Public Policy*, *37*(8), 611–627.

Stirling, A. (2010). Keep it complex. *Nature*, *468*(7327), 1029–1031.

Van Enst, W. I., Driessen, P. P., & Runhaar, H. A. (2014). Towards productive science-policy interfaces: A research agenda. *Journal of Environmental Assessment Policy and Management*, *16*(01), 1450007.

Walker, W. E., Marchau, V. A., & Kwakkel, J. H. (2013). Uncertainty in the framework of policy analysis. *Public policy analysis* (pp. 215–261). Springer.

Watson, A. A., & Kasprzyk, J. R. (2017). Incorporating deeply uncertain factors into the many objective search process. *Environmental Modelling & Software*, *89*, 159–171.

Zevenbergen, C., van Tuijn, J., Rijke, J., Bos, M., van Herk, S., Douma, J., & van Riet Paap, L. (2013). Tailor made collaboration: A clever combination of process and content. *Rijkswaterstaat Room for the River.*

Appendix A

Model Specifications

The model that was used for this analysis (Kwakkel, 2021a) has the following specifications, as defined in (Kwakkel, 2021b):

External factors:

- Flood wave shape: a normalized curve describing the way discharges at the most upstream location change over time. There are 140 possible wave shapes and therefore 140 possible values for this factor.
- Dike failure probability: the probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dike, this factor can take up a value anywhere between 0 and 1.
- Final breach width: the final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain, this value can be between 30 and 350 meters and differs per location.
- Breach width model: the way the breach width develops over time, with the uncertainty being the growth rate. This input can take up the values 1, 1.5 and 10, corresponding to 5, 3 and 1 days.
- Discount rate: the present value of future expected damage, it can take up the values 1.5, 2.5 3.5 or 4.5.

Policy levers:

- Dike heightening: the number of decimetres with which the dike is heightened, ranging from 0 till 10 and differing per location.
- Early warning (systems): the amount of days in advance in which the early warning alert is given, can range from 0 till 4 days. False alarms can damage the public's trust and cause high costs.

- Room for the River (projects): there are 5 potential projects that can either be implemented or not, defined by a 0 or 1.

Performance metrics:

- Expected annual damage: annual value of flood damage, defined per location in euros.
- Expected number of casualties: annual number of casualties, defined per location.
- Dike investment costs: defined per location in euros.
- Evacuation costs: defined based on the number of people that need to be evacuated and for how long they have to be, defined for the entirety of the IJssel.
- Room for the River costs: costs per project, defined per location in euros.

Appendix B

Exploratory Analysis Specifications

0_RfR 0	1
0_RfR 1	1
0_RfR 2	1
1_RfR 0	0
1_RfR 1	1
1_RfR 2	0
2_RfR 0	1
2_RfR 1	0
2_RfR 2	1
3_RfR 0	0
3_RfR 1	0
3_RfR 2	1
4_RfR 0	0
4_RfR 1	0
4_RfR 2	1
A.1_DikeIncrease 0	9
A.1_DikeIncrease 1	6
A.1_DikeIncrease 2	5
A.2_DikeIncrease 0	8
A.2_DikeIncrease 1	7
A.2_DikeIncrease 2	2
A.3_DikeIncrease 0	0
A.3_DikeIncrease 1	4
A.3_DikeIncrease 2	4
A.4_DikeIncrease 0	9
A.4_DikeIncrease 1	1
A.4_DikeIncrease 2	1
A.5_DikeIncrease 0	2
A.5_DikeIncrease 1	9
A.5_DikeIncrease 2	8
EWS_DaysToThreat	3

Figure B.1: Details of exploratory policy 1, purple.

0_RfR 0	1
0_RfR 1	1
0_RfR 2	0
1_RfR 0	0
1_RfR 1	1
1_RfR 2	0
2_RfR 0	0
2_RfR 1	1
2_RfR 2	1
3_RfR 0	1
3_RfR 1	0
3_RfR 2	0
4_RfR 0	1
4_RfR 1	0
4_RfR 2	0
A.1_DikeIncrease 0	1
A.1_DikeIncrease 1	3
A.1_DikeIncrease 2	9
A.2_DikeIncrease 0	3
A.2_DikeIncrease 1	3
A.2_DikeIncrease 2	10
A.3_DikeIncrease 0	7
A.3_DikeIncrease 1	0
A.3_DikeIncrease 2	0
A.4_DikeIncrease 0	1
A.4_DikeIncrease 1	4
A.4_DikeIncrease 2	3
A.5_DikeIncrease 0	6
A.5_DikeIncrease 1	5
A.5_DikeIncrease 2	1
EWS_DaysToThreat	0

Figure B.2: Details of exploratory policy 2, blue.

0_RfR 0	0
0_RfR 1	0
0_RfR 2	0
1_RfR 0	1
1_RfR 1	0
1_RfR 2	1
2_RfR 0	0
2_RfR 1	1
2_RfR 2	0
3_RfR 0	0
3_RfR 1	1
3_RfR 2	0
4_RfR 0	0
4_RfR 1	1
4_RfR 2	0
A.1_DikeIncrease 0	5
A.1_DikeIncrease 1	8
A.1_DikeIncrease 2	5
A.2_DikeIncrease 0	2
A.2_DikeIncrease 1	10
A.2_DikeIncrease 2	8
A.3_DikeIncrease 0	10
A.3_DikeIncrease 1	8
A.3_DikeIncrease 2	8
A.4_DikeIncrease 0	5
A.4_DikeIncrease 1	6
A.4_DikeIncrease 2	9
A.5_DikeIncrease 0	9
A.5_DikeIncrease 1	8
A.5_DikeIncrease 2	7
EWS_DaysToThreat	4

Figure B.3: Details of exploratory policy 3, green.

0_RfR 0	0
0_RfR 1	0
0_RfR 2	1
1_RfR 0	1
1_RfR 1	0
1_RfR 2	1
2_RfR 0	1
2_RfR 1	0
2_RfR 2	0
3_RfR 0	1
3_RfR 1	1
3_RfR 2	1
4_RfR 0	1
4_RfR 1	1
4_RfR 2	1
A.1_DikeIncrease 0	5
A.1_DikeIncrease 1	0
A.1_DikeIncrease 2	0
A.2_DikeIncrease 0	7
A.2_DikeIncrease 1	1
A.2_DikeIncrease 2	4
A.3_DikeIncrease 0	3
A.3_DikeIncrease 1	9
A.3_DikeIncrease 2	7
A.4_DikeIncrease 0	4
A.4_DikeIncrease 1	9
A.4_DikeIncrease 2	6
A.5_DikeIncrease 0	3
A.5_DikeIncrease 1	2
A.5_DikeIncrease 2	4
EWS_DaysToThreat	2

Figure B.4: Details of exploratory policy 4, yellow.