Regional Water Management

A model-based advice for Water Board Rijn & IJssel within the IJssel River Case Study

(*Het Werkgebied van Waterschap Rijn en IJssel*, z.d.)

EPA141A Model-based decision-making
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Recommendations

We advise the Rijn & IJssel Water Board to implement two possible policies, mainly because of their extensive willingness for Room for the River (RfR) investments, as this is the most beneficial for the environment and long-term protection. The first policy focuses on moderate dike investments and moderate RfR costs. Specifically, the policy recommends implementing RfR in dike ring 3 at a later stage and slightly raising the dikes in dike rings 2, 3 and 5 as soon as possible. This policy costs 234 million euros in total. The second policy prioritises low dike investments with high RfR investments. More precisely, the RfR is to be implemented in Dike Ring 2 at a moderate to late stage and in Dike Ring 3 as soon as possible. The dikes in Dike Ring 2 and 5 are to be raised slightly in early stages. This policy costs 460 million euros in total. In order to be effective, these policies require a high level of cooperation with other water authorities, significant financial resources and the support of local residents.

We have optimised these policies to protect dike rings 3 and 4, all of which result in relatively low, considering the scenarios, to no expected damage and no expected fatalities. They differ in the trade-offs between investing in RfR and strengthening dikes. Implementing RfR is more expensive and significantly alters the landscape. Raising existing dikes is less expensive and requires less cooperation, but is also less beneficial for the environment and long-term protection. With more funding, more RfR can be implemented due to its higher cost. High resistance from local residents, especially farmers, requires policies that minimise RfR implementation. Both policies require high cooperation with other water boards and organisations, high availability of funding and high cooperation with residents. In addition, these policies delay the implementation of RfR, which reduces resistance and allows time for farmers to be bought out and relocated.

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1. Problem Framing

1.1 Introduction

More than a quarter of the Netherlands' territory lies below sea level, and a staggering 60% is vulnerable to flooding from the North Sea, rivers, or lakes (van Alpen et al., 2022). As a result, the Netherlands has been combating water issues for centuries. Despite the extensive expertise in water management, the rapidly increasing effects of climate change are intensifying the need for solutions.

The "Room for the River" project is an innovative flood management program initiated by the Dutch government in response to the increasing risk of flooding due to climate change, land subsidence, and rising sea levels (Ministry of Infrastructure and Water Management, 2022). It represents a significant shift from traditional flood defence strategies that primarily focused on heightening dikes to a more holistic approach that enhances the natural capacity of river systems to manage high water levels.

This research aims to find a set of potential policies that are tested over several scenarios inclined to make them robust against high uncertainty. The policies aim to find balance between dike strengthening and Room for the River interventions, considering financial trade-offs, landscape use, and damage prevention. To achieve this, Chapter 1 clarifies the problem framing. Chapter 2 explains the research approach, detailing the various models used. The results are presented in Chapter 3. Conclusions and discussions follow in Chapters 4 and 5, respectively. A political reflection is also included, significantly enhancing the conclusion by offering insight into the political landscape during the implementation of the advised policies.

1.2 Problem owner: Water Board Rijn & IJssel

The Rijn & IJssel water board is responsible for ensuring a safe, clean and sufficient supply of water originating from the Rijn & IJssel in the eastern part of Gelderland and a small part of the southern part of Overijssel. They monitor dikes, ditches, brooks and rivers on a daily basis and also manage wastewater treatment (Waterschap Rijn & IJssel, n.d.). Due to the variability of the weather and climate change, continuous adaptation is necessary.

The Rijn coming from the Swiss mountains, flowing through Germany to the Netherlands, divides the east of the Netherlands into two important rivers, the Waal and the IJssel. The Rijn & IJssel water board is an organisation mostly concerned about the status of the IJssel. They monitor the river and maintain it in case of drought or flooding. This is very crucial, as the river is important for overall water supply and the quality of drinking water.

In recent years, the riverbeds of both the Waal and the IJssel have deepened due to erosion. The Waal, being deeper, attracts more water, as water follows the path of least resistance. This process is self-perpetuating, resulting in a lower water level in the river. This problem is exacerbated during periods of drought. The reduction in water leads to a worsening of drought conditions in regions such as Twente and the Achterhoek B (Unie van Waterschappen, 2022), as the canals that feed these areas do not receive enough water. In

addition, persistent low water levels in the IJssel can affect the quality of drinking water. With less clean, flowing water, there is an increased risk of salt intrusion from the North Sea, leading to salinisation of the IJsselmeer on the North Holland side (Eikelboom, 2022).

As well as drought, the water board is also concerned about the risk of flooding. Due to climate change, periods of increased rainfall and snowmelt are more frequent. The accelerated melting of snow in the Swiss mountains means that more water flows into the Rijn. In addition, increased rainfall in the Rijn and IJssel regions contributes to a higher water flow in the Dutch IJssel. Combined with rising sea levels, this will significantly increase the risk of flooding.

The water board uses several strategies and resources to manage water effectively and protect the region from floods and droughts. In the past, one of its main methods has been to strengthen dikes. By increasing the stability and height of these barriers, they can prevent flooding from major rivers and ensure the safety of surrounding areas. Following the extremely high water levels between 1993 and 1995, it became clear that many of the dikes were not strong enough, potentially leading to flooding. In response, not only were the dikes strengthened, but a new approach, Room for River (RfR) was adopted to allow large rivers such as the IJssel to carry more water during high water. This new strategy involved creating more space for the rivers through methods such as moving dikes further inland, creating side and widened channels and lowering excavation sites. Figure 1 below illustrates the potential options for RfR.

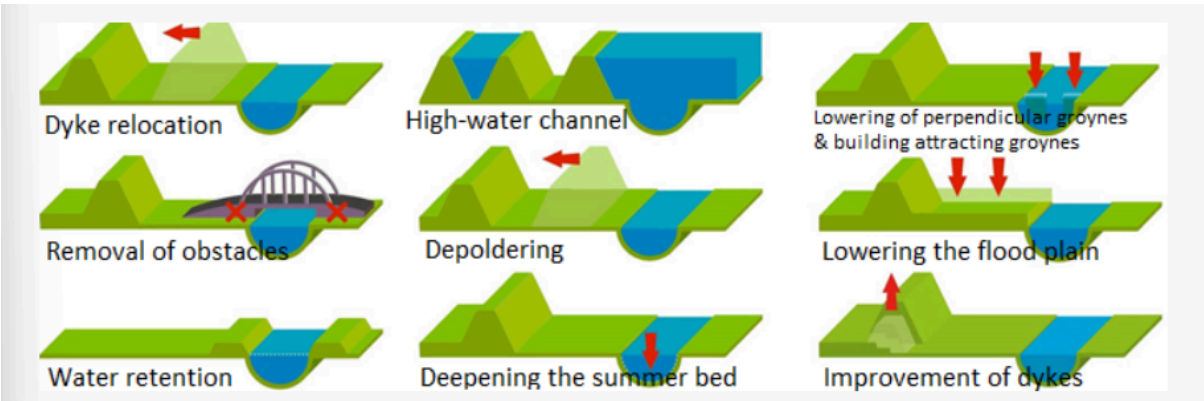

Figure 1, (Rijkswaterstaat, n.d.)

In addition, to manage excess water from rain, ditches and streams, these RfR plans could also function as temporary water storage areas known as 'reservoirs'. These storage areas allow water to slowly soak into the ground and be released gradually after the highest peak has passed the river or during periods of drought. This approach not only helps manage heavy rainfall by preventing immediate downstream flooding, but also ensures water availability during dry periods.

Through these methods of strengthening dikes, managing heavy rainfall and creating temporary water storage, the water board can effectively protect the region from floods and droughts. These strategies enable the water board to adapt to the challenges of variable weather and climate change. The implementation of RfR seems to be more effective in

tackling the problems, but this approach is more costly and has a much greater impact on the use of the landscape by residents such as farmers.

The Rijn & IJssel water board receives tax money from the citizens of the region, but this is not enough to make major interventions in the landscape to manage the water levels of the Rijn & IJssel. Additional funding from umbrella organisations and cooperation with other stakeholders is therefore required (Waterschap Rijn & IJssel, n.d.) in order to find an optimal solution that balances the strengthening of dikes and the implementation of RfR, taking into account financial trade-offs, landscape use and damage prevention.

1.3 Political arena

Different stakeholders are involved in the political arena of the "Room for the River" initiative. Understanding this arena provides insights into the goals and objectives of these actors, which is crucial when formulating a strategy for the Rijn & IJssel water board. A simplified overview of this arena can be seen in Figure 2.

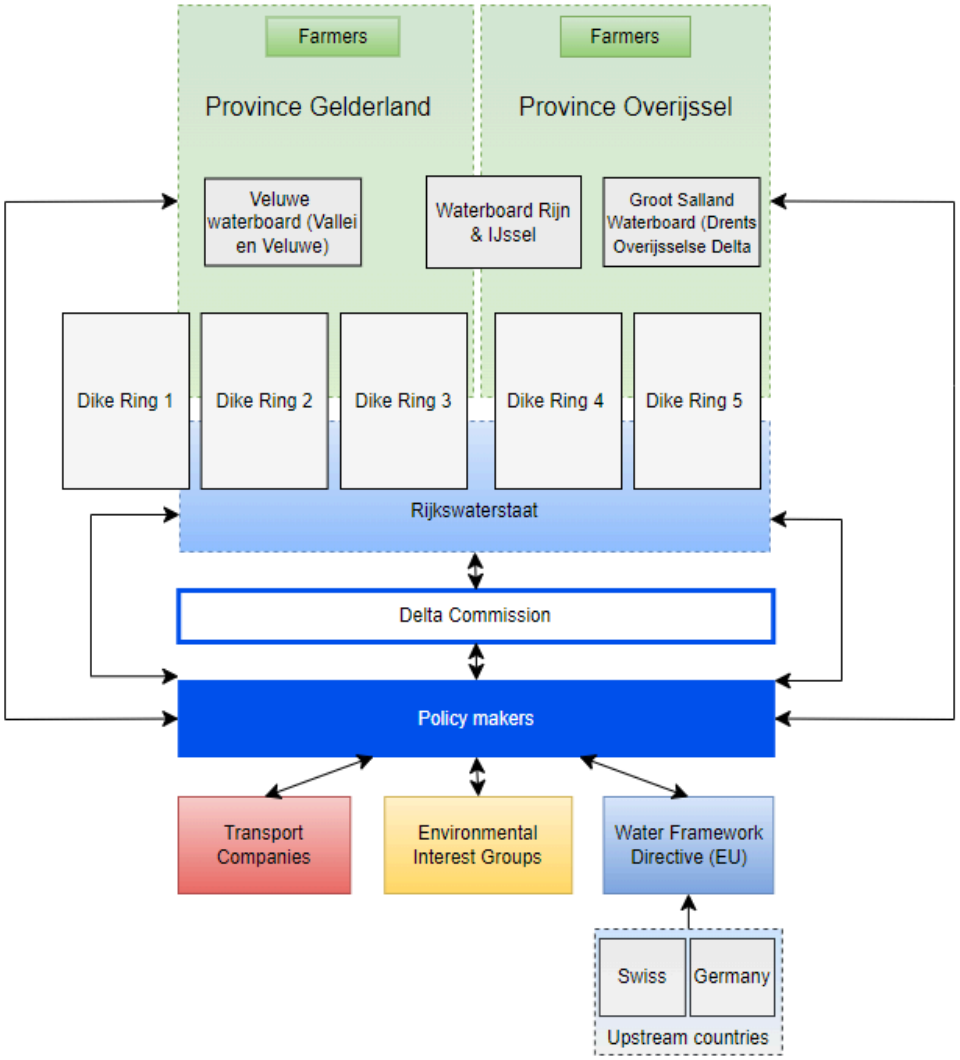

Figure 2: Visualisation of the political arena

Each actor has its own interests and objectives, shortly described in this paragraph and also listed in appendix A. Every stakeholder will endeavour to pursue policies that align with their individual best interests. While a common goal among stakeholders is to prevent river flooding, opinions on how to achieve this vary.

Rijkswaterstaat aims to include all stakeholders and remains neutral regarding dike heightening versus the Room for the River (RfR) approach. Their primary concern is minimising costs while being open to multiple solutions. As well as Rijkswaterstaat the Delta Commission focuses on long-term solutions to meet the Delta Programme's targets (Glas, 2023), proposing a hybrid solution of dike heightening and RfR, with a slight preference for the latter.

The five dike rings along the river have different priorities. Urban dike rings in cities like Zutphen and Deventer aim to protect the city and its inhabitants, while rural dike rings prioritise protecting agricultural land to ensure year-round farming activities. The provinces of Overijssel and Gelderland, which include both rural and urban areas, face a complex consideration regarding where to place RfR and/or strengthen the dikes.

The water boards, including Rijn & IJssel, play a crucial role in managing water levels and ensuring regional water safety. Their strategies must balance flood protection, environmental sustainability, and economic interests. While water board 3 and water board 2 are more concerned with flood protection than drought protection as they are further upstream, water board 1 is more concerned with drought protection given the risk of salt intrusion as it is further downstream.

Transport companies need deep rivers to facilitate the transportation of goods along the IJssel, making high water levels essential for their operations. This need for high water levels often conflicts with the RfR approach, which can lower water levels to create more space for rivers.

Lastly, environmental interest groups advocate for biodiversity and nature conservation, which aligns well with the positive side effects of the RfR approach.

Stakeholders have opposing views on how to prevent river flooding. Rijkswaterstaat and the Delta Commission prefer a long term hybrid approach with an emphasis on the RfR strategy. Urban and rural dike rings prioritise protecting cities and agricultural land, respectively, while transport companies need high water levels for navigation, conflicting with the RfR approach. Environmental groups support the RfR strategy for its benefits to biodiversity and nature conservation.

By understanding these diverse perspectives and interests, water board Rijn & IJssel can better navigate the political landscape and develop strategies that address the varied needs of all stakeholders involved.

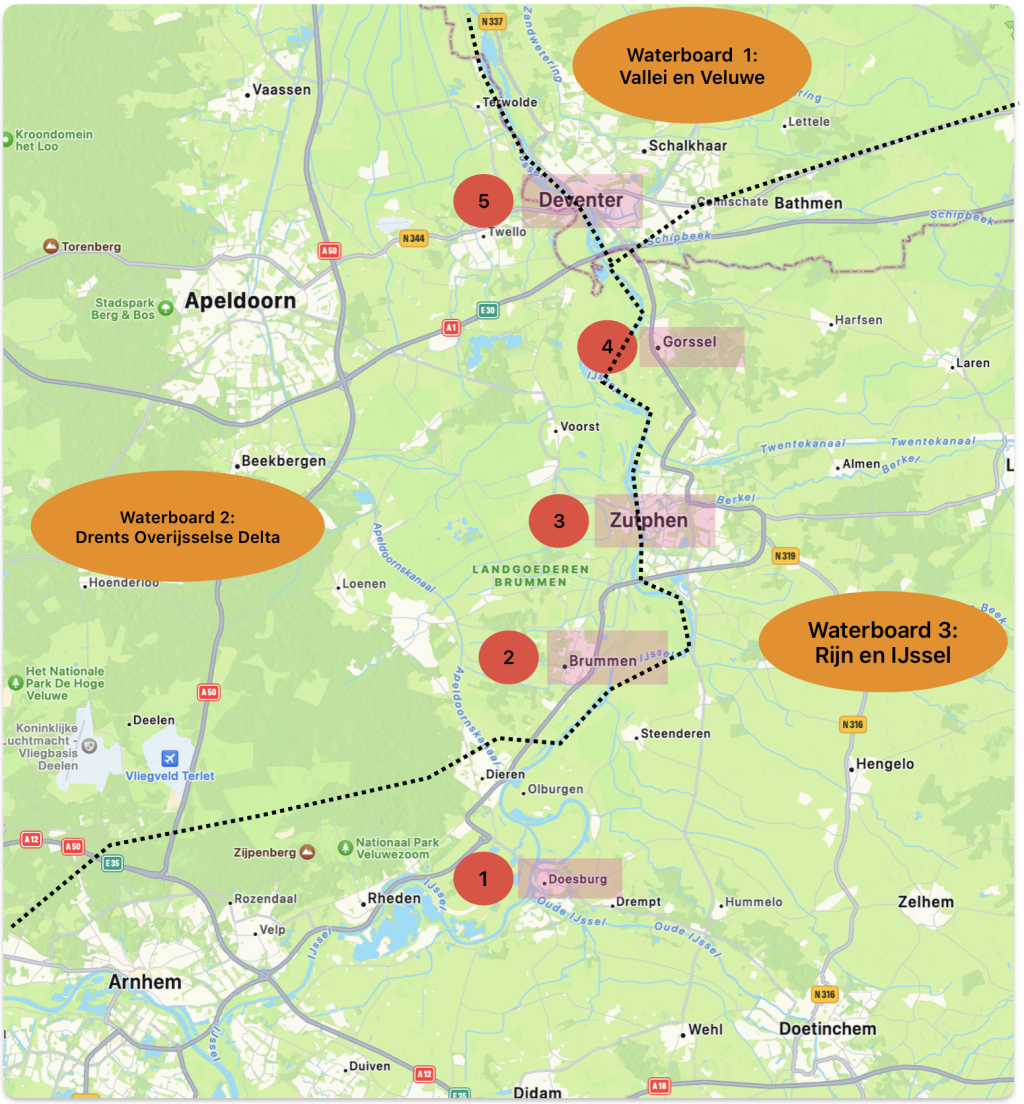

Figure 3: visualisation of positioning of dike rings and water boards

2. Approach

2.1 Model Explanation

The simulation model that is used, evaluates economic damage and casualties at various locations along the IJssel River. It simulates flood progression and assesses the dike system's response, including potential dike failure and breach expansion. If a dike fails, the model estimates the resulting flood damage and casualties. By applying different flood risk management measures, the impacts on risk reduction and distribution can be explored. The model follows the XLRM framework, which is listed below. In appendix B, a more detailed description of this framework can be found. The model includes pre-specified problem formulations, offering various ways to aggregate and analyse the outcomes.

- **Uncertainties (X)**
  The uncertainties affect the system's performance without direct control.

- **Levers (L)**
  Policies under study (decision variables).

- **Relationships (R)**
  Rules or mathematical expressions linking X and L to compute outcomes.

- **Outcomes (M)**
  These indicators assess the performance of policies.

2.2 Exploring the uncertainties

Open exploration is a method to get an overview of model uncertainty and model behaviour, for which the EMA workbench will be used. Experiments will be generated using the **Latin Hypercube Sampling method**. This method is chosen because it reduces randomness in sampling, providing more certainty that the uncertainty space is thoroughly sampled. This structured approach minimises the risk of missing important sets of uncertainties (Dutta & Gandomi, 2020). Experiments are defined as a combination between a scenario (sampled values for X) and a policy (sampled values for L). The experiments used for open exploration will be based on a zero-policy and 100.000 sampled scenarios. A zero policy means that no investment is made. This is not of interest in scenario discovery. We want to explore the uncertainty space in the absence of prior action. The **Patient Rule Induction Method** (PRIM) is used for scenario discovery and exploratory modelling. This method is designed to find the optimal input space of experiments in a model to address a specific problem (Bryant & Lempert, 2010).

Next, only a part of the scenarios simulated during open exploration will be taken into further account. These are the scenarios that comply with high constraints set for expected annual damage and expected number of deaths. **K-means clustering** is then used to group similar experiments into five clusters, simplifying the analysis of the numerous scenarios generated. This helps identify representative scenarios and understand the model's behaviour under uncertainty, facilitating more focused and effective decision-making. By clustering, we can

reduce complexity and highlight key patterns within the data (Ikotun et al., 2023).

Additionally to the open exploration, a global sensitivity analysis will be executed. **Feature scoring** and **SOBOL sensitivity analysis** will serve as quantitative methods that examine how the system's outputs are connected to and affected by its inputs (Razavi, S. et al., 2021). Feature scoring evaluates the importance of each individual input variable, while Sobol is used to find the contribution of each variable and their interaction effects. It helps to understand which input variables have the most significant impact on the model outcome, to assist in model validation and eventually the decision making.

2.3 Search for possible solutions

To find the best policies the **Multi-Objective Robust Decision-making** (MORDM) method will be used. This involves searching for policies under various scenarios, which emerged from the open exploration step, using a large number of function evaluations (NFEs) to ensure convergence of the solutions (i.e. policies). To ensure the robustness and reliability of our results, we will repeat the optimisation process with five random seeds. Furthermore, to ensure that the policies found are sufficiently diverse, the epsilon values will be adjusted. The epsilon values are set in such a way that it balances solution diversity and computational efficiency.

Next, the **Many Objective Evolutionary Algorithms** (MOEA) method is implemented. This method involves testing the policies found during MORDM across all five scenarios. It will help us identify robust policies that are resilient across the sampled scenarios. Afterwards, the amount of policies are narrowed down to Pareto optimal outcomes. This can help determine the optimal value of policy levers to maximise preferred outcomes (Kwakkel, 2023). Finally, out of the Pareto optimal outcomes, a few policies are chosen that align with the objectives of water board Rijn & IJssel and the policy landscape.

Within the directed search, the following outcomes were selected to align with the water board's primary goal to ensure a safe, clean and sufficient supply of water originating from the Rijn & IJssel:

- "Room for the River Costs"
- "Dike Investment Costs" (summed for dike rings 3 & 4)
- "Expected Annual Damage" (summed for dike rings 3 & 4)

The focus is only on dike rings 3 and 4, as they are the responsibility of the Rijn & IJssel water board.

Dike increasement and the RfR project are two primary methods to prevent flooding. Monitoring the costs associated with these investments is essential for budget planning and for evaluating the feasibility and sustainability of long-term flood protection measures. Besides, understanding the financial impact of floods on an annual basis helps in prioritising investments and interventions.

"Expected evacuation costs" and "expected number of deaths" are important considerations, but they are secondary to the primary objective of minimising flood damage. Damage is a more effective measure of success because it occurs in every flood event and can be significantly reduced. In scatterplot C1 in Appendix C, there are scenarios where the annual number of deaths is negligible (less than 1) despite significant damage costs of 2 billion. Conversely, scenarios with low damage costs also have minimal annual fatalities. So while low expected damage costs generally lead to low expected annual deaths, it's important to note that low expected annual deaths can still coincide with high damage costs.

Furthermore, the focus remains on implementing long-term solutions that reduce the need for evacuation, rather than simply managing evacuation processes. This approach ensures sustainability and resilience in flood management strategies.

3. Results

This chapter delves into the results of our analysis. First, we show the results of the open exploration with scenario discovery and global sensitivity analysis. This will show the main variables and scenarios that we will use in the directed search. Afterwards we show the results of the directed search, i.e. the search for possible solutions.

3.1 Exploring the uncertainties

3.1.1 Scenario discovery

As mentioned in Chapter 2, we used PRIM to execute the scenario discovery. The analysis focused on identifying scenarios that represented the top 10% of expected annual fatalities and top 15% annual damages in each scenario. The constraints for expected annual fatalities are set slightly higher. We have chosen to do so because, as said before, floods are rarely heavy enough to cause fatalities. We therefore only consider the real worst-case scenarios. By combining these criteria, scenarios with high damage and mortality rates were isolated. From this subset, a selection of scenarios was made based on coverage and density, ultimately defining a specific scenario box.

Coverage refers to the proportion of scenarios of worst-case outcomes (top 15% annual damage and top 10% deaths) that are included in the scenario box. A coverage value of 0.725 means that 72.5% of these high-risk scenarios are captured within the defined box.

Density indicates the proportion of scenarios within the scenario box that belong to the worst-case outcomes. A density value of 0.610 means that 61.0% of the scenarios in the box are among the highest risk cases.

We chose these specific values of coverage (0.725) and density (0.610) to balance the inclusion of a significant number of high-risk scenarios (coverage) while maintaining a focus on scenarios that are predominantly within the top 15%/10% of worst-case outcomes (density). This ensures that our scenario box is both comprehensive and concentrated on the most critical cases.

The specific box contains uncertainties within a certain range, meaning that all scenarios (under policy-zero) where the uncertainties fall within this range are included. Appendix D Figure D3 shows the range of the uncertainties. A large portion of these scenarios are in the 15% worst cases of expected annual damage and worst 10% of expected deaths. These scenarios are of interest because they represent the situations with high potential for trade offs. It are these scenarios on which we want to test the policies.

The box obtained from the PRIM analysis contained 6259 experiments (also referred to as scenario since we used a zero-policy). The PRIM box however solely serves as a narrative descriptor, meaning that it can help as a qualitative explanation for a scenario of interest associated with bad outcomes. The box also contains experiments that are not supposed to be in there. We therefore used the conditions for PRIM on the entire dataset which resulted in 5270 experiments of interest. We plotted these experiments and used k-means clustering to create 5 clusters. From each cluster, we selected the experiments closest to the centroids

(the centres of the clusters), ensuring that each experiment was optimally different. As these experiments are carried out with no policies implemented, these 5 scenarios are considered to be the most important scenarios to explore in order to determine the most robust policy outcome.

The scenario clusters are shown in Figure D2 in the Appendix. This figure shows that all the clusters are distinct, allowing us to use these different scenarios for further analysis to identify the best policy. Note that the probability of failure for both Dike Ring 3 and Dike Ring 4 contributes significantly to the clustering of the scenarios.

Figure 4 below shows a subset of the data, focusing on the sensitivities of dike ring 3 and dike ring 4, as these are located within the Rijn & IJssel water board region. The uncertainty parameter B_max represents the breach width; a wider breach results in a larger volume of water entering the floodplain, increasing the likelihood of flooding. The parameter B_rate refers to the rate at which the breach expands over time. A rapid increase in breach width indicates a higher probability of more frequent flooding in the future. P_fail is the probability that the dike will withstand the hydraulic load, with lower values indicating a higher probability of dike failure. Appendix B table B1 also explains the uncertainties.

For us, these scenarios mean the following:

<u>Scenario 1 (cluster 0): High probability of dike failure with varied sensitivity on breach characteristics.</u>
This scenario suggests that while the probability of dike failure is very high for dike ring 3 and average for dike ring 4, the sensitivity to the width of the breach is low in dike ring 3 but high in dike ring 4. The growth of the breach, however, shows very low sensitivity in both dike rings.

<u>Scenario 2 (cluster 1): High probability of dike failure in Dike Ring 4 with varied sensitivity on breach characteristics.</u>
This scenario highlights a very high probability of dike failure for dike ring 4, with both the breach width and growth showing average sensitivity. For dike ring 3, the probability of failure is very low, but there is high sensitivity to breach growth and relatively low to average sensitivity to breach width.

<u>Scenario 3 (cluster 2): General low probability of dike failure with moderate sensitivity to breach growth.</u>
This scenario indicates a very low probability of dike failure for both dike rings 3 and 4. However, there is moderate sensitivity to breach growth, with dike ring 3 showing average to high sensitivity and dike ring 4 showing high sensitivity. The sensitivity to breach width is relatively low for both dike rings.

<u>Scenario 4 (cluster 3): General High probability for dike failure in dike ring 4 with high sensitivity to breach growth.</u>
This scenario highlights a very high probability of dike failure for dike ring 4, with both breach width and growth showing high sensitivity. For dike ring 3, the probability of failure is average to low, but there is high sensitivity to breach growth and relatively low average sensitivity to breach width.

Scenario 5 (cluster 4): Moderate probability of dike failure with high sensitivity to breach characteristics.

This scenario indicates a moderate probability of dike failure for dike ring 4, with high sensitivity to breach growth and average to low sensitivity to breach width. For dike ring 3, the probability of failure is low, but there is relatively high sensitivity to breach width and high to average sensitivity to breach growth.

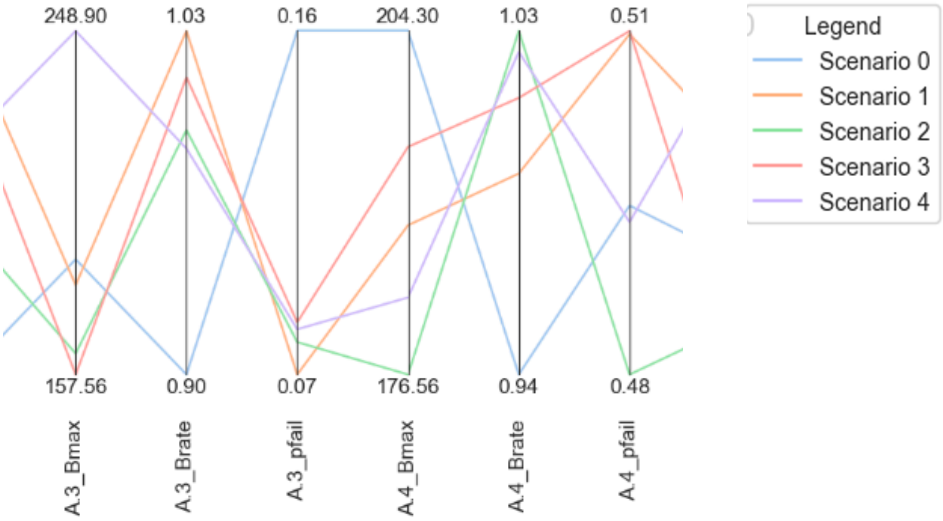

Figure 4: Slice of scenario clusters

3.1.2 Global sensitivity analysis

As mentioned in Chapter 2, Feature Scoring and SOBOL sensitivity analysis have been executed to investigate for which uncertainties the outcomes are the most sensitive. The result of this analysis shows that the outcome 'Expected Annual Damage' is the most sensitive for variable A.1_pfail, which can be seen in Figure 5. Within the SOBOL analysis the outcome is summed for all dike rings. This indicates that the probability of failure for dike ring 1 has a significant impact on the overall damage. This suggests that any changes in the failure probability of dike ring 1 will greatly influence the annual damage estimates. Feature Scoring gives the same result. Appendix D7 provides the results of Feature Scoring.

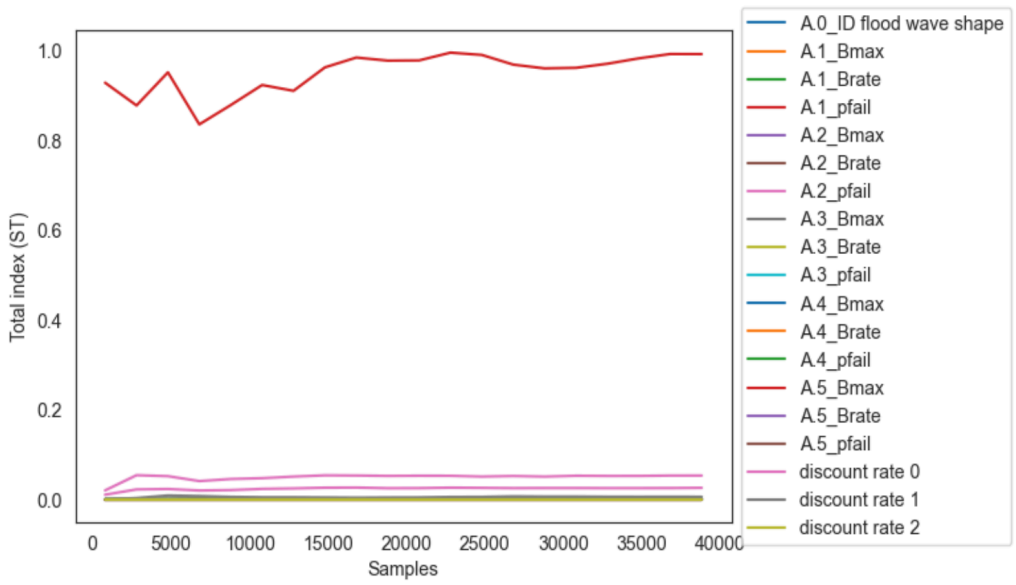

Figure 5: Result of global sensitivity analysis - SOBOL

3.2 Search for possible solutions

3.2.1 MORDM and MOEA for policy optimisation

To identify the optimal policies, we use the Multi-Objective Robust Decision-Making (MORDM) method. This approach involves running the five scenarios obtained from the open exploration and searching for possible policies that minimize the costs and damage under the conditions of these scenarios. To optimise these policies, we use 20.000 NFEs (Number of Function Evaluations), a measure that represents the total number of times the objective functions are evaluated. Higher NFE allows for thorough exploration of the solution space, increasing the chances of finding optimal solutions but requiring more computational resources. The appropriate NFE is determined by whether the algorithm has converged, meaning further evaluations do not significantly improve solutions. Appendix D5 presents the corresponding convergence metrics, which clearly show this convergence.

The NFE optimization in combination with epsilon value is of real importance. Epsilon values are set in such a way that it finds the balance between a diverse set of solutions while still narrowing down the amount of total policies. They manage solution diversity by imposing a grid on the objective space, with grid granularity defined by epsilon values. Smaller epsilons create a finer grid, capturing more details but requiring more computation. Larger epsilons create a coarser grid, simplifying the process but potentially missing nuances. The right epsilon values balance exploration and exploitation. The epsilon value chosen for our optimization is 0.1 for all three outcomes RfR costs, dike investment costs and expected annual damage.

The optimization resulted in 857 policies. When calculating the Pareto front, it is important to keep in mind that certain scenarios might be more favourable for the desired outcomes, resulting in Pareto Optimal solutions based on just those scenarios. A key component is therefore to create scenario robust policies, which is part of the MOEA method. We have

ensured this by simulating the optimised policies over all the five scenarios obtained from the scenario discovery. This resulted in 4285 experiments which we reduced back to 857 scenario robust policies by getting the median values for each policy over all five scenarios. We chose the median for data aggregation due to its robustness against outliers, providing a more reliable measure of central tendency.

After calculating the Pareto optimal solutions for the 857 scenario robust policies a Pareto front of 34 policies remained. Of these, we analysed those that are most relevant to our objectives and our policy landscape as the Rijn & IJssel water board. As a result, five policies were picked for further investigation on robustness and for final recommendations. Figure 6 shows the relation between the expected annual damage, and the investment in either one or both dikes and RfR costs. The reduction process from 34 to the final 5 policies is further explained in Appendix D4. The policy levers belonging to each of the 5 policies are presented in Appendix D6. A distinction is also made between the time steps in which a particular policy lever is implemented. There are three time steps: early, moderate and late.

The five final policies resulting from directed search are explained below.

<u>Policy 1 - Long term RfR and dike increase balanced (blue line):</u>
This policy has the lowest possible values for all outcomes and the smallest absolute difference between investing in dikes and RfR. It proposes to implement RfR in Dike Ring 3 in time step 2 (later stage), to slightly raise dikes in Dike Ring 2 in time steps 0 (early stage) and 2 (later stage), and to slightly raise dikes in Dike Ring 3 in time step 0 (early stage). It also recommends moderate raising of dikes in Dike Ring 5 in time steps 0 (early) and 2 (later).

<u>Policy 2 - All in on RfR (orange line)</u>:
This policy involves no investment in dikes in our region, only in RfR, and still results in the lowest possible expected annual damage. It recommends implementing RfR in Dike Ring 2 in time steps 1 (moderate) and 2 (late) and in Dike Ring 3 in all time steps (0, 1 and 2). It proposes to raise the dikes in dike ring 2 in time steps 0 (early stage) and 1 (moderate stage) and to slightly raise the dikes in dike ring 5 in time step 1 (moderate stage).

<u>Policy 3 - Short term RfR and dike increase balanced (green line):</u>
This policy achieves very low expected annual damages with low to medium dike investment costs and very low to medium RfR investment costs. It provides flexibility in RfR expenditure while keeping overall costs low. It recommends implementing RfR in Dike Ring 2 in time step 2 (late stage) and raising the dikes in Dike Ring 2 in time steps 0 (early stage) and 4 (as soon as possible) and in Dike Ring 5 in time steps 1 (moderate stage) and 2 (later stage).

<u>Policy 4 - Minimal expenditure (red line):</u>
This policy involves 15 million in damage but includes a decent RfR budget and no investments in our dike rings 3 and 4. It is probably not desirable, but it is reasonable. It advises immediate implementation of RfR at dike ring 2 in time step 1 (moderate) and at dike ring 3 in time step 0 (as soon as possible). It suggests raising the dikes at dike ring 2 in time steps 0, 1 and 2, and raising the dikes at dike ring 5 in time steps 1 and 2.

<u>Policy 5 - No room for RfR (purple line):</u>

This policy has low expected annual damage with heavy investment in dikes and some investment in RfR. It proposes not to implement RfR at all, but to raise the dikes at dike rings 3 and 5 in time steps 0 (early stage) and 2 (later stage).

Table 1: The effect on dike rings when implementing policies

	RfR					Dike increase				
	Dike Ring 1	**Dike Ring 2**	**Dike Ring 3**	**Dike Ring 4**	**Dike Ring 5**	**Dike Ring 1**	**Dike Ring 2**	**Dike Ring 3**	**Dike Ring 4**	**Dike Ring 5**
Policy 1:										
Policy 2:										
Policy 3:										
Policy 4:										
Policy 5:										

High investment | Moderate to high investment | Low to moderate investment | No investment

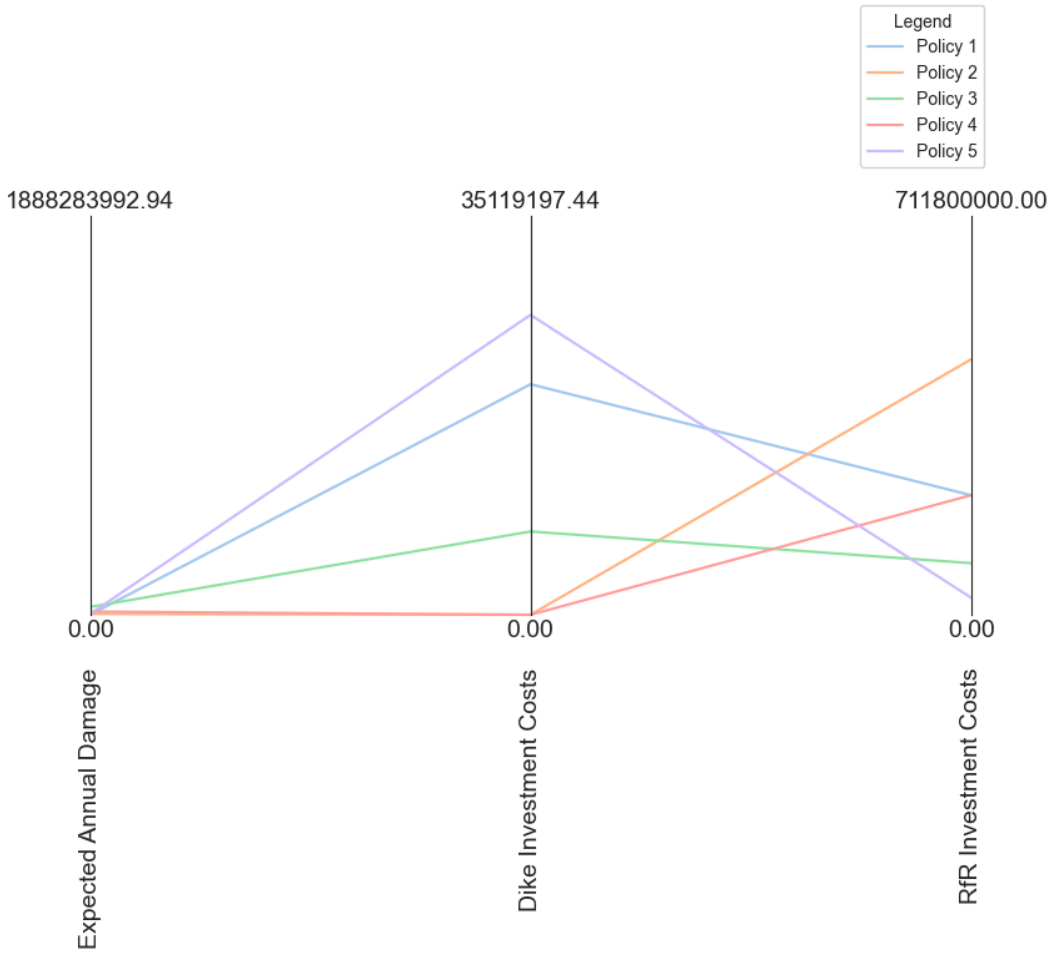

Figure 6: Final policies

3.2.2 Robust search

To assess the robustness of the 5 selected policies, we simulated the 5 policies over 20.000 randomly sampled scenarios. This process is technically a repeat of scenario discovery, but instead of using the zero policy, we used the 5 selected optimised policies. The idea is to see if the PRIM algorithm would find different boxes with fewer 'bad' scenarios to ensure that the policies work against new randomly selected scenarios. The constraint is set to the top 25% instead of the top 15% and 10% for damage and fatalities respectively, as we did in open exploration, because when using these higher constraints no boxes with sufficient density were found. In other words, implementing the policies instead of a zero policy led to a significant reduction in the number of scenarios exceeding our constraints for expected annual damages and expected annual damages, which already indicates the added value of implementing the policies. Furthermore, the fact that the box with constraints set to the top 25% contains far fewer experiments than the initial box with higher constraints and zero policy, indicates that the policies are effective in reducing damage and fatalities in dike rings 3 and 4 and are therefore robust.

Next to the just explained robustness check, we also decided to calculate the maximum regret for each policy. The results of this analysis are presented in Appendix D8. The maximum regret analysis showed significant potential costs associated with different policies, as Figure 6 also already indicated. Policies that invest less in room for the river and dike investment costs could lead to relatively high damage costs in worst-case scenarios. Similarly, policies that invest heavily in dikes and room for the river could face high expenditure that may prove unnecessary if major floods do not occur. In summary, the analysis shows that there are potential regrets associated with any policy and that no single policy is universally optimal. Ultimately, the policy choices made by water board Rijn & IJssel will also depend on the political context and priorities.

4. Conclusion

The analyses resulted in five possible policies for protecting our dike rings 3 and 4. The policies vary in terms of outcomes; only one policy is optimised in such a way that there is no expected damage, while keeping RfR and dike investments low. The other four policies have expected annual damages between a range of 3.6 and 37 million euros. In a way, after optimization you might suspect that more than just 20% of the policies provide zero expected damages. We cannot forget we have searched a uncertainty space of very bad outcomes and carefully selected these scenarios to start the optimization process. Reading through the policies therefore becomes a matter of perspective. 37 million in expected damages may seem significant at first glance. However, when you consider that this figure represents the worst-case scenario within the top 15% of worst possible outcomes, it highlights a significant but uncertain risk. Even in this scenario, it is an expected value, not a guaranteed outcome. In the simulated dataset, there are no expected casualties with the values of expected annual damage going with the policies, this can be considered a win.

The difference between the policies is really revealed when looking into how the investments are divided. In this conclusion, we look at each policy option in more detail in the context of the political environment. We aim to provide advice on which policy should be implemented based on factors such as low/high cooperation, different levels of available funding and the degree of cooperation from residents.

Based on the following considerations we advise the following policies per political situation.

- Collaboration with other water boards, particularly in implementing Room for the River (RfR) on various dike rings, is crucial. RfR is more expensive and significantly alters the landscape than simply raising existing dikes, so dikes require less cooperation.
- The availability of funding plays a key role; with more funding, more RfR can be implemented. This determination is based on the average investment required for the policies, as shown in figure E1 in Appendix E, policies below the red line indicate low funding needs, while those above the red line indicate high funding needs.
- Resistance from local residents, particularly farmers, affects the feasibility of RfR. High resistance means that residents are less likely to cooperate and sell their land, necessitating policies that minimise RfR implementation. In addition, policies where RfR is implemented at a later stage will be more effective if there is relatively less cooperation from residents. This is the case for policies 1, 2 and 3.

Table 2: Policy options per political situation

Cooperation waterboards and other organisations	**Funding availability**	**Cooperation residents**	**Advised policy**
low	low	low	X
low	low	high	X
low	high	low	X

low	high	high	Policy 4
high	low	low	Policy 5
high	low	high	Policy 3 and 4
high	high	low	Policy 5 and 3
high	high	high	Policy 1, 2

The Rijn & IJssel water board wants to implement as much Room for the River (RfR) as possible, because it is a long-term solution that is effective in both droughts and floods and is environmentally friendly. For this reason, we prefer to implement policies 1 and 2, as these involve the most RfR investments. In addition, these policies delay the implementation of RfR to a moderate and late stage, which reduces resistance and allows time for farmers to be bought out and relocated. Still, it is important to note that policies 1 and 2 require a high level of cooperation with other water boards and organisations, significant funding and the cooperation of local residents.

5. Discussion

In this chapter, we will critically examine the key threats to the validity of our conclusions and explore potential directions for further refining or improving our analysis.

Throughout the modelling process, various assumptions have emerged. These include both inherent constraints within the model itself and challenges associated with comprehending complex socio-technical systems.

- *Constrained in scope*
  As a regional governing body, the water board is responsible not only for protecting against droughts and floods, but also for water quality. Nitrogen is a particular concern in this regard, although it is not included in the model. Climate change is also a major issue of concern for the water board, influencing structural uncertainties in water management that are not explicitly addressed in the model. Therefore, this research actually covers only a part of the water board's goals and responsibilities.

- *Potentially overlooked uncertainties*
  The uncertainties considered in the analysis were directly adopted from the case description and the provided simulation model. Because of limited time, no extra uncertainties were added to the model. If there were any significant uncertainties overlooked however, this could have led to poor policy decisions. A potential enhancement would be to first investigate if any important uncertainties were missing and should have been added to the model.

- *Impact epsilon value*
  When choosing the epsilon value, no consideration was given to the significance of the outcomes. A larger or smaller epsilon value could result in differences of thousands or millions of euros in the final outcome. This significantly reduces the accuracy of the results. Testing more diverse values could have allowed for a more informed decision.

- *Limitations on optimising just for dikering 3 and 4*
  Probably the most pressing limitation on the quality of our analysis is the decision to solely optimise for dike rings 3 and 4. Although the global sensitivity analysis pointed out that A.1_pfail (probability that the dike will withstand the hydraulic load) has the biggest impact on the expected annual damage, we decided against optimising for all the dike rings. This decision was based on the missing information on what the relative influence per dike was on this sensitivity. We used the summation over all dikes and therefore it was difficult to dissect the individual influences. By just optimising for the dike rings that are under the responsibility of water board 3, we basically ended up with policies that are mainly good for water board 3, across the chosen objectives. Even though we have presented some of our policies as more collaboration friendly, this is not what the algorithm has optimised for. You can clearly see this in policy 2 and 4, where dike investment costs are 0 for us, but some of the levers for dike increase in other areas are not zero, meaning water board 3 is highly dependent on other actors to make a decision that is also in their best interest. In

other words, it would be highly beneficial for some of our policies if some of the other actors decided to optimise their policies in a more collaborative friendly manner. When taking this even a step further, looking at potential flooding scenarios, our approach could work conflicting towards our objectives. If other actors decide to increase their dikes and are therefore protecting their own areas of interest, this might leave the area of water board 3 extra vulnerable. Water wants to escape through the path of least resistance, and if everyone decides to raise their dikes as a result of optimising cooperation policies, then it could be really unfortunate for us. We have learned that for future analysis it is fine to look only at potential damage in the area we are responsible for, but when looking at the cost of solutions it is beneficial to look further than just ourselves. Instead of optimising the costs for our own dike rings, we could also optimise our policy for the costs of other dike rings, to be more informed about possible cooperation between involved parties.

References

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

Dutta, S., & Gandomi. (2020). Design of experiments for uncertainty quantification based on polynomial chaos expansion metamodels. In *Handbook of Probabilistic Models* (Chapter 15). https://www.sciencedirect.com/science/article/pii/B9780128165140000151

Eikelboom, W. (2022, September 27). *Waarom de IJssel een probleemrivier kan worden*. Rivierverhalen. https://www.rivierverhalen.nl/waarom-de-ijssel-een-probleemrivier-kan-worden/

Glas, P. (2023). Nationaal Deltaprogramma 2024 Hoofdlijnen. In *Deltaprogramma*. Rijksoverheid.https://www.deltaprogramma.nl/binaries/deltacommissaris/documenten/publicaties/2023/09/19/dp2024-hoofdlijnen/DP2024_Hoofdlijnen.pdf

Het werkgebied van Waterschap Rijn en IJssel. (z.d.). Waterschap Rijn en IJssel. https://www.wrij.nl/over-ons

Ikotun, A. M., Ezugwu, A. E., Abualigah, L., Abuhaija, B., & Heming, J. (2023). K-means clustering algorithms: A comprehensive review, variants analysis, and advances in the era of big data. *Information Sciences*, *622*, 178–210. https://doi.org/10.1016/j.ins.2022.11.139

Informatiepunt Leefomgeving. (z.d.). *Organisatie van het waterbeheer*. Accessed on June 18 2024, https://iplo.nl/thema/water/beleid-regelgeving-water/organisatie-van-waterbeheer/#h3cc89ece-618f-41ae-b7fe-e7f2434e7232

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. https://doi.org/10.1002/2017ef000649

Ministry of Infrastructure and Water Management. Ruimte voor de rivieren, 04 2022. https://www.rijkswaterstaat.nl/water/waterbeheer/bescherming-tegen-het-water/maatregelen-om-overstromingen-te-voorkomen/ruimte-voor-de-rivieren.

van Alphen J, Haasnoot M, Diermanse F. Uncertain Accelerated Sea-Level Rise, Potential Consequences, and Adaptive Strategies in The Netherlands. Water. 2022; 14(10):1527. https://doi.org/10.3390/w14101527

Razavi, S., Jakeman, A., Saltelli, A., Prieur, C., Iooss, B., Borgonovo, E., ... & Maier, H. R. (2021). The future of sensitivity analysis: An essential discipline for systems modeling and policy support. Environmental Modelling & Software, 137, 104954

Rijksoverheid. (z.d.). *Waterbeheer in Nederland*. Accessed on June 18 2024, https://www.rijksoverheid.nl/onderwerpen/water/waterbeheer-in-nederland#:~:text=Rijkswaterstaat%20en%20de%20waterschappen%20zijn,gemeenten%20betrokken%20bij%20het%20waterbeheer

Unie van Waterschappen. (2022, February 18). *Droogte - Unie van Waterschappen*. Unie Van Waterschappen. https://unievanwaterschappen.nl/waterkwantiteit/droogte-in-nederland/

Waterschap Rijn en IJssel. (n.d.). *Wat wij doen*. Waterschap Rijn En IJssel. https://www.wrij.nl/wat-wij-doen

Appendices

Appendix A - Overview Stakeholders

Table A1: An overview of the political arena, with the interest and objective of each stakeholder.

Stakeholder	**Interest**	**Objective**
Delta Commission	Long-term water safety and freshwater supply.	Promote the development and implementation of the Delta Programme, which includes measures and provisions for water safety and freshwater management. (Informatiepunt Leefomgeving, z.d.)
Environmental interest group	Biodiversity and nature conservation.	Protect natural habitats and promote sustainable water management practices.
Transport company	Efficient and reliable inland shipping	Facilitate the transportation of goods along the IJssel, considering water levels and infrastructure.
Rijkswaterstaat	Focuses on managing large bodies of water, including the sea and rivers.	Propose and implement national water policy and manage infrastructure for national waterways. (Rijksoverheid, z.d.)
Water Boards	Effective and sustainable water management within their respective regions. (Rijksoverheid, z.d.)	To manage water levels, ensure water quality, and protect against flooding in their designated areas.
- Drents Overijsselse Delta (first called Groot Salland Waterboard)	Regional water management in Overijssel.	Manage water levels, water quality, and flood protection in the Deventer region.
- Vallei & Veluwe Waterboard	Regional water management in Gelderland.	Manage water levels, water quality, and flood protection in the Zutphen region.
- Rijn & IJssel Waterboard	Cross-border water management between	Manage water levels and water quality, including cities like

	Gelderland and Overijssel.	Zutphen and Gorsel. (Rijksoverheid, z.d.)
Provinces Gelderland & Overijssel	Regional water safety, environmental protection, and economic development. (Rijksoverheid, z.d.)	Translate national water policies into regional measures, manage certain operational water management tasks (like groundwater removal), and oversee groundwater quality. (Rijksoverheid, z.d.)
Dike rings Rural areas Urban areas	Advocate for the interests of the inhabitants of their area.	Protecting citizens from flooding .. .. while ensuring year-round agricultural activities. .. while ensuring urban recreation
Analysts	Providing in-depth analysis and strategic insights for regional water management.	To provide strategic insights and recommendations to enhance water management practices, ensure water quality, and improve flood protection.

Appendix B - XLRM framework

B1. Uncertainties (X)

Table B1: The uncertainties of the simulation model.

Name	Description	Type [Dimension]	Values
Discount rate *{timestep}*	The discount rate used to calculate the present value of damages.	Categorical [dmnl]	1.5,2.5, 3.5, 4.5
Shape flood wave *A.0_ID flood wave shape*	A standardised curve representing the shape of an incoming flood wave over time, with 132 predefined curves.	Integer [dmnl]	0-132
Breach width dike ring *A.{dike_ring}_Bmax*	The ultimate width of the breach, where a wider breach allows a larger volume of water to flow into the floodplain per unit of time	Real [meters]	30-350
Probability failing of dike ring *A.{dike.ring}_pfail*	The likelihood that the dike will endure the hydraulic load.	Real [dmnl]	0-1
Breach growth *A.{dike_ring}_Brate*	The rate at which the breach expands over time	Categorical [1/day]	0,1.5, 10

B2. Levers (L)

Table B2: The levers of the simulation model.

Name	Description	Type [Dimension]	Values
Room for the River	Decision to activate the RfR project at the specified location. Once activated, the project remains in effect.	Integer [dmnl]	0-1
Early Warning System	The number of days before a threat to issue a warning. False warnings can erode trust in the system. An earlier warning provides more time for evacuation but also increases the risk of a false warning.	Integer [days]	0-4

Dike increasement	The amount of dike elevation.	Integer [decimeter]	0-10

For Room for the River and Dike increasement there are several time steps in which the action can be implemented. The time steps are divided into an early stage (step 0), a moderate stage (step 1) and a late stage (step 2).

B3. Outcomes (M)

Table B3: The outcomes calculated by the simulation model. The green marked outcomes are selected for the optimization step.

Name	**Description**	**Type [Dimension]**
Expected Annual Damage	Discounted expected annual flood damage.	Array [euro]
Dike Investment Costs	Investment costs for raising dikes.	Array [euro]
Expected Number of Deaths	Expected annual number of flood-related casualties.	Array [person]
Room for River Costs	Investment costs for Room for the River projects.	Array [euro]
Expected Evacuation Costs	Evaluation costs based on the number of people and the duration they must leave their homes.	Array [euro]

Appendix C - Scatter plot for determining objectives

This scatter plot shows the relation between expected annual damage and expected annual deaths. A somewhat linear relation can be spotted where higher damages lead to more casualties. Both objectives are of importance but when looking closer we can distinguish that optimising for only damage will be sufficient. We set one casualty as the threshold since we are aiming to have no casualties. What becomes visible is that if we would optimise for as little casualties as possible we could still end up with damages of nearly 2 billion euros. If we reverse the point of view however, we can see that once we can optimise for expected damages under 300 million euros, there is no single datapoint with expected annual deaths above one. Therefore, minimising the expected annual damage is sufficient as long as we keep it under 300 million euro in expected damages. It is important to note, that this only applies for this dataset and other relations could exist in other datasets.

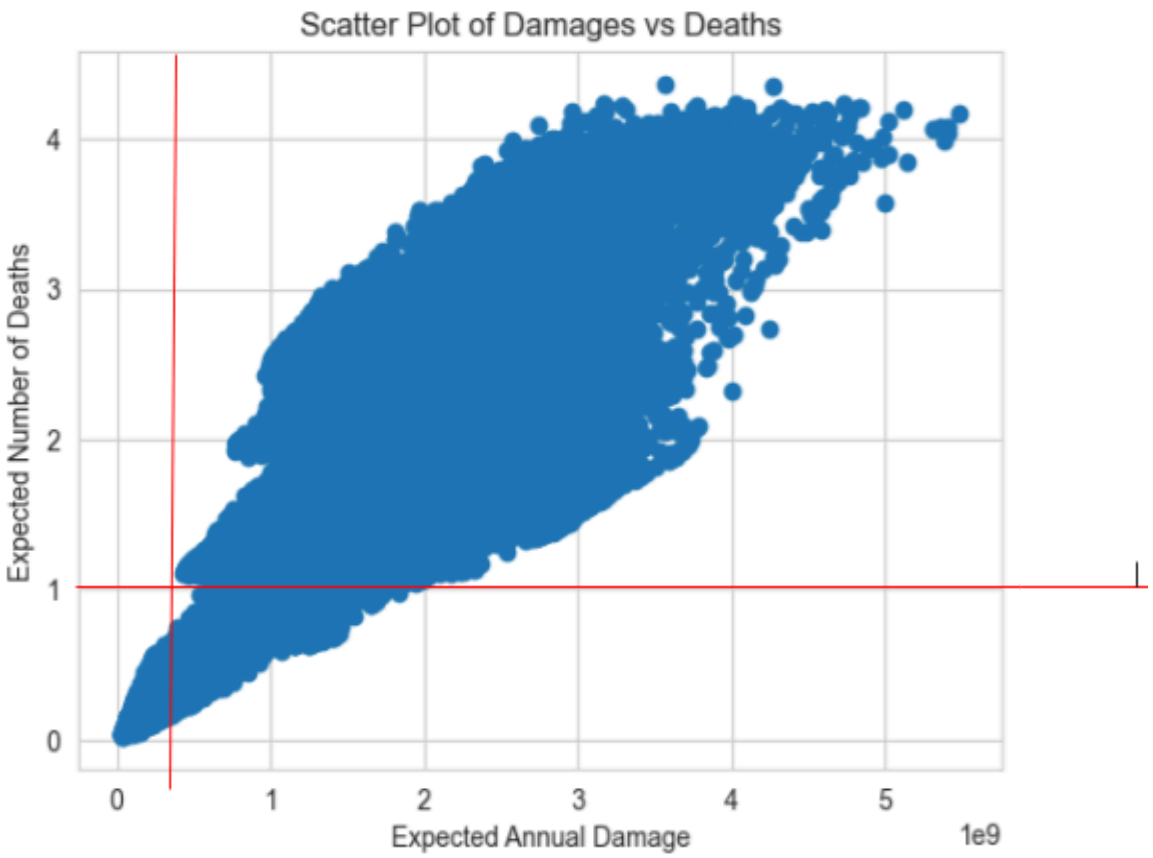

Figure C1: Scatter plot of damages vs deaths.

Appendix D - Additions to the results

D1. PRIM Analysis

Figure D1 shows the outcome of the PRIM analysis executed during the open exploration step. All different boxes are shown in the figure, of which parts of the experiments within a box contain values for the target variables that exceed the constraints of 85% for expected annual damage and 90% for expected number of deaths. Every box differs in their density and coverage combination. For further research we have chosen box 54 (one of the upper green boxes) with a density of 0.725 and a coverage of 0.610.

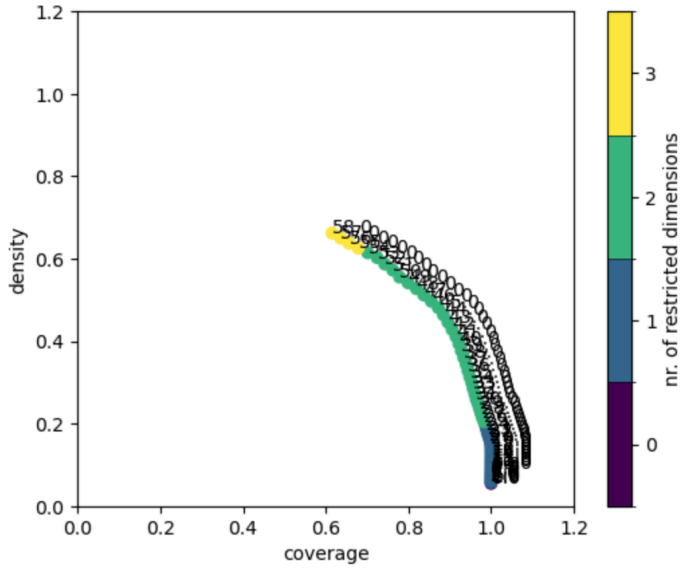

Figure D1: Results of the PRIM Analysis

D2. Scenarios

Figure D2 shows the five scenarios resulting from the scenario discovery in combination with the k-means clustering performed during the open exploration. The x-axes show the uncertainties of the model. The combination of the values of the uncertainties results in the scenarios.

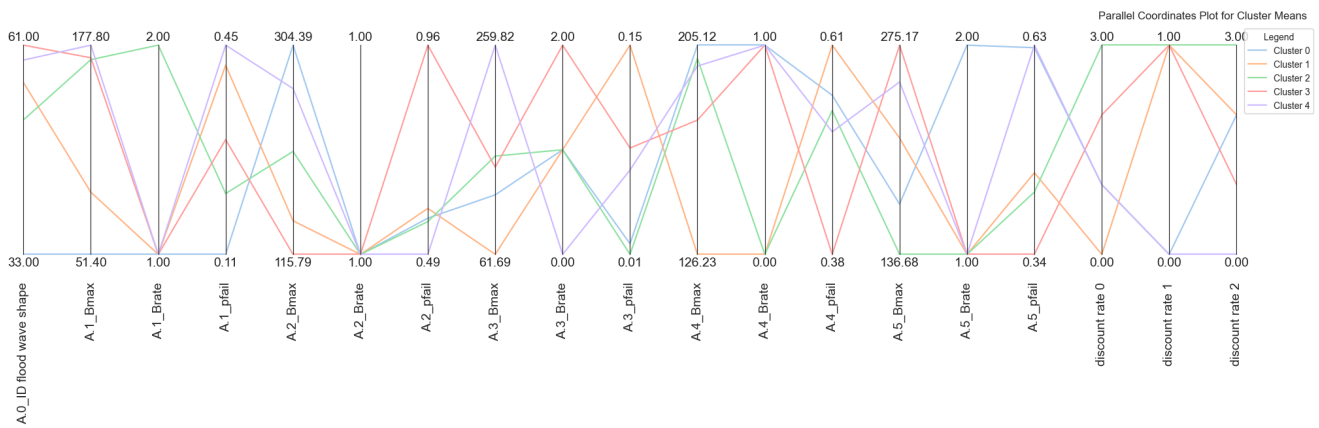

Figure D2: scenario clusters

D3. Uncertainties Worst Case Scenarios

Figure D3 shows that for box 54, with a density of 0.725 and a coverage of 0.610, the experiments within the box have a value of A1_pfail between 0.022 and 0.45 and A3_pfail between 2.6e-06 and 0.15.

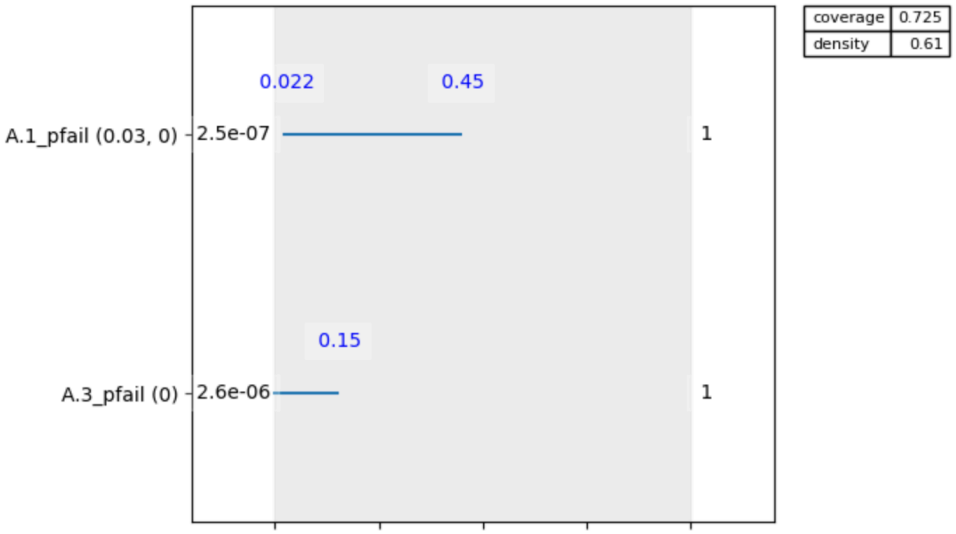

Figure D3: Uncertainties contributing to worst case scenarios

D4. Directed Search - Reduction process

We started with 857 policies, as can be seen in figure D4. After applying the Pareto optimum algorithm, 34 policies were left, which is shown in figure D5.

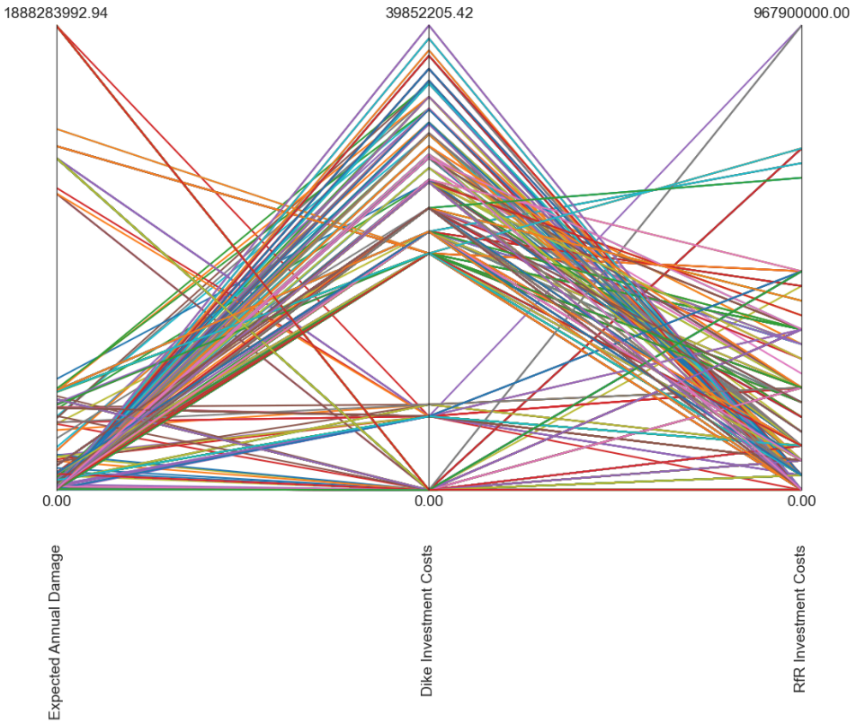

Figure D4: Policies at the start of directed search.

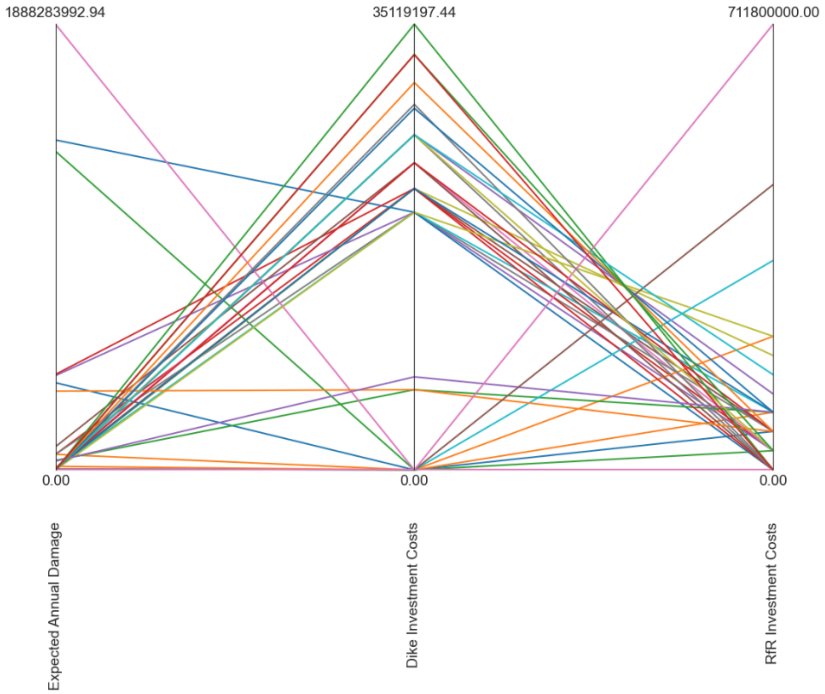

Figure D5: Policies after Pareto optimum.

After this, we began narrowing down to a set of preferred policies based on self-chosen constraints:

1. The seven policies with the highest expected annual damages were deemed unacceptable and dropped.
2. Policies with no RfR (Room for the River) investment were excluded as they do not align with the goals of Water Board 3.
3. The policy with the highest RfR cost was considered infeasible due to its high investment cost and was also dropped.
4. The five policies with the highest dike investment costs were excluded because they did not align with the goals of Water Board 3.

This process left us with 16 Pareto optimal solutions, as can be seen in figure D6.

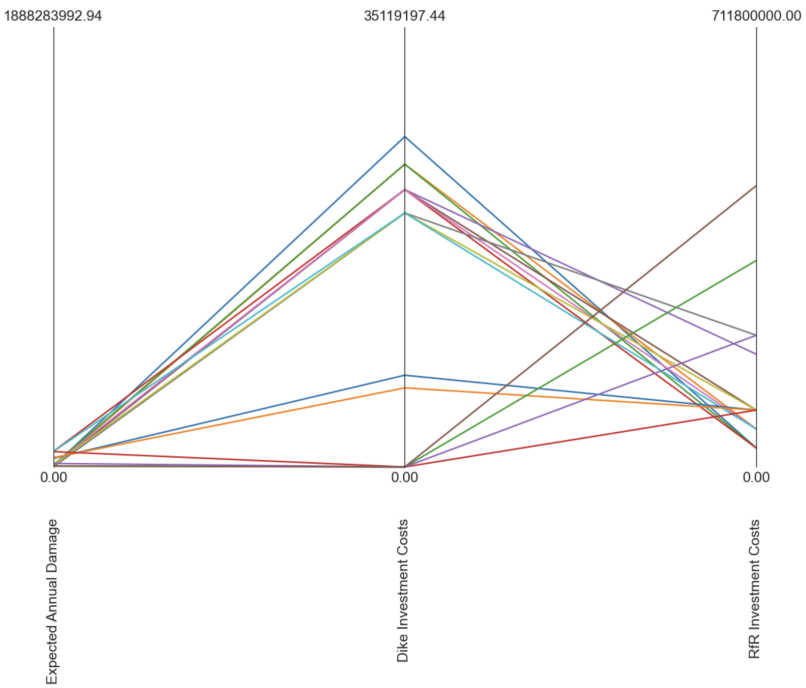

Figure D6: Policies after constraints.

From these, we selected five distinct policies that either align with the goals of Water Board Rijn & IJssel or could work in alliances with multiple parties:

1. This policy has the lowest possible values for all outcomes and the smallest absolute difference between investing in dikes and RfR.
2. This policy involves no investment in dikes, only in RfR, and still results in the lowest possible expected annual damage.
3. This policy has the third lowest expected annual damage.
4. This policy involves 15 million in damage but includes a decent RfR budget. It is probably not desirable, but it is reasonable.
5. This policy has low expected annual damage with heavy investment in dikes and some investment in RfR. This scenario could involve collaboration with other parties for budget allocation.

D5. Convergence Metrics

Figure D7 shows the convergence for different convergence metrics. All convergence metrics seem to be stabilising at around 10.000 NFE, the convergence metrics spacing however at around 19.000. It could be argued that it also stabilises at around 10.000 but that the lines are just not as flat as the other graphs. However, overall, most convergence metrics show stabilisation for the amount of NFE used.

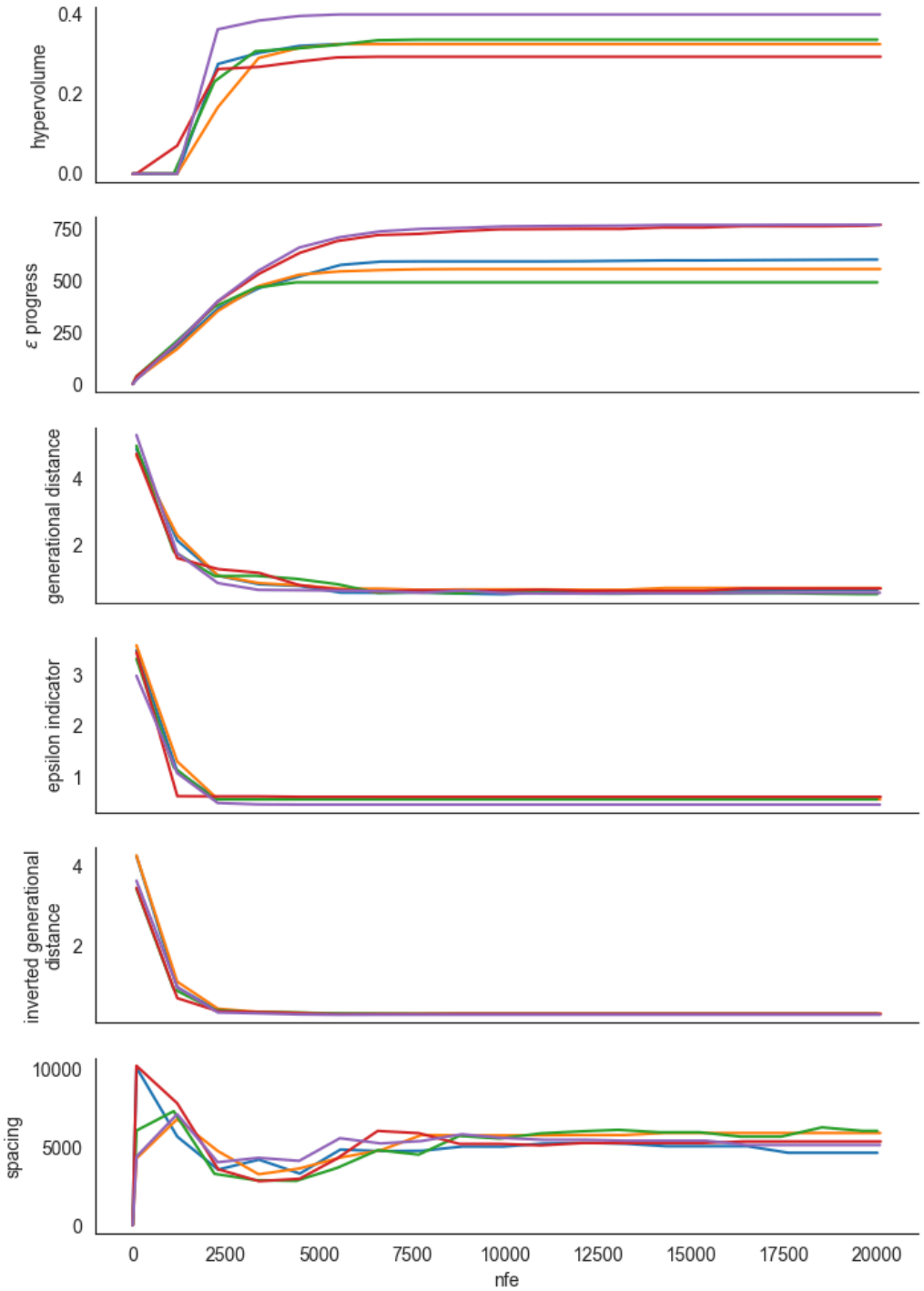

Figure D7: Convergence metrics that clearly show the convergence with 20.000 NFE.

D6. Lever Values for the 5 Policies

Figure D8 shows the lever values for all five policies, detailing the specific measures implemented at each time step (0, 1 or 2). The time steps are mentioned at the end of the lever name. Here's what the values mean:

- Value of 0: indicates that the policy does not implement this lever.
- RfR (Room for the River) with a value of 1: indicates that the policy implements RfR for this dike ring.
- Dike Raise (0 to 10): Indicates the amount of dike increase for this dike ring, with higher values indicating more significant increases.
- Days to Threat (0-4): Indicates the number of days before a warning is issued.

More detailed information on the levers can be found in Table B2.

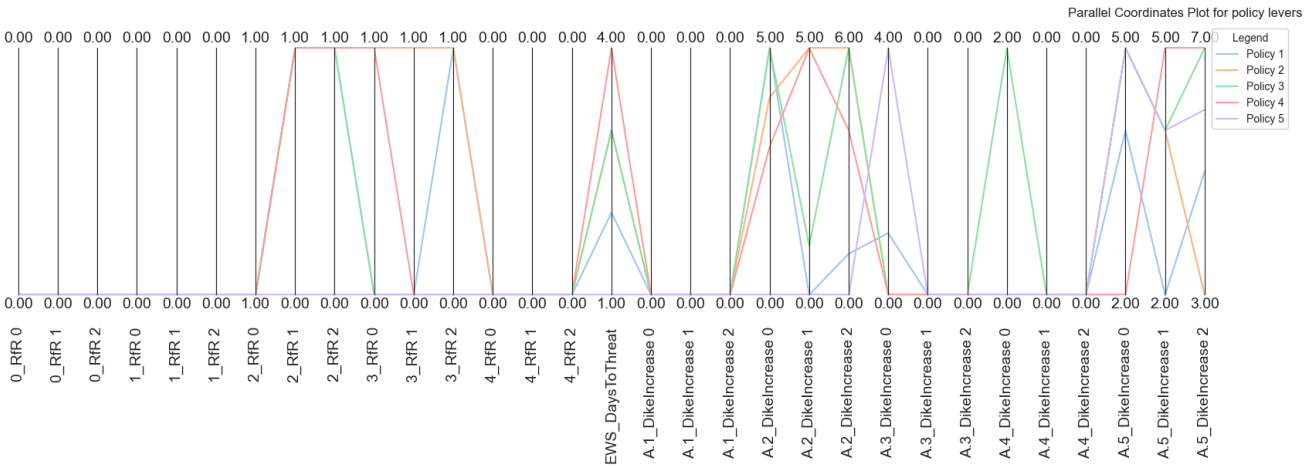

Figure D8: Lever values for the 5 policies

D7. Feature Scoring

Next to the SOBOL analysis performed during the Global Sensitivity Analysis, Feature Scoring has also been executed. The results of Feature Scoring are presented in Figure D9.

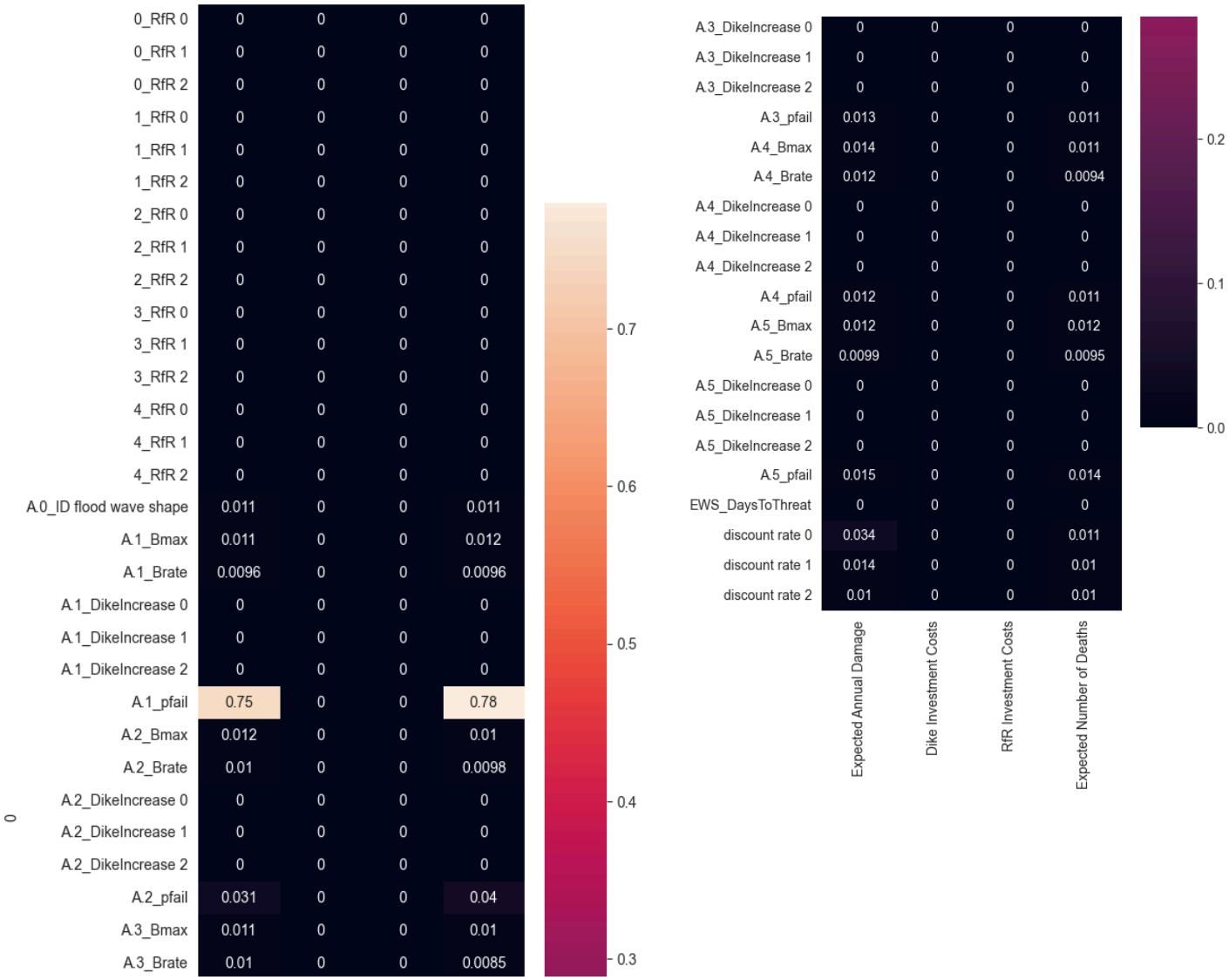

Figure D9: Results Feature Scoring

D8. Maximum Regret

Figure D10 shows the maximum regret for the three outcomes. The best possible outcome for all three outcomes is a regret of zero. The worst outcomes are 37 million euros of damage, 26 million euros of dike investment costs and 425 million euros of Room for River costs.

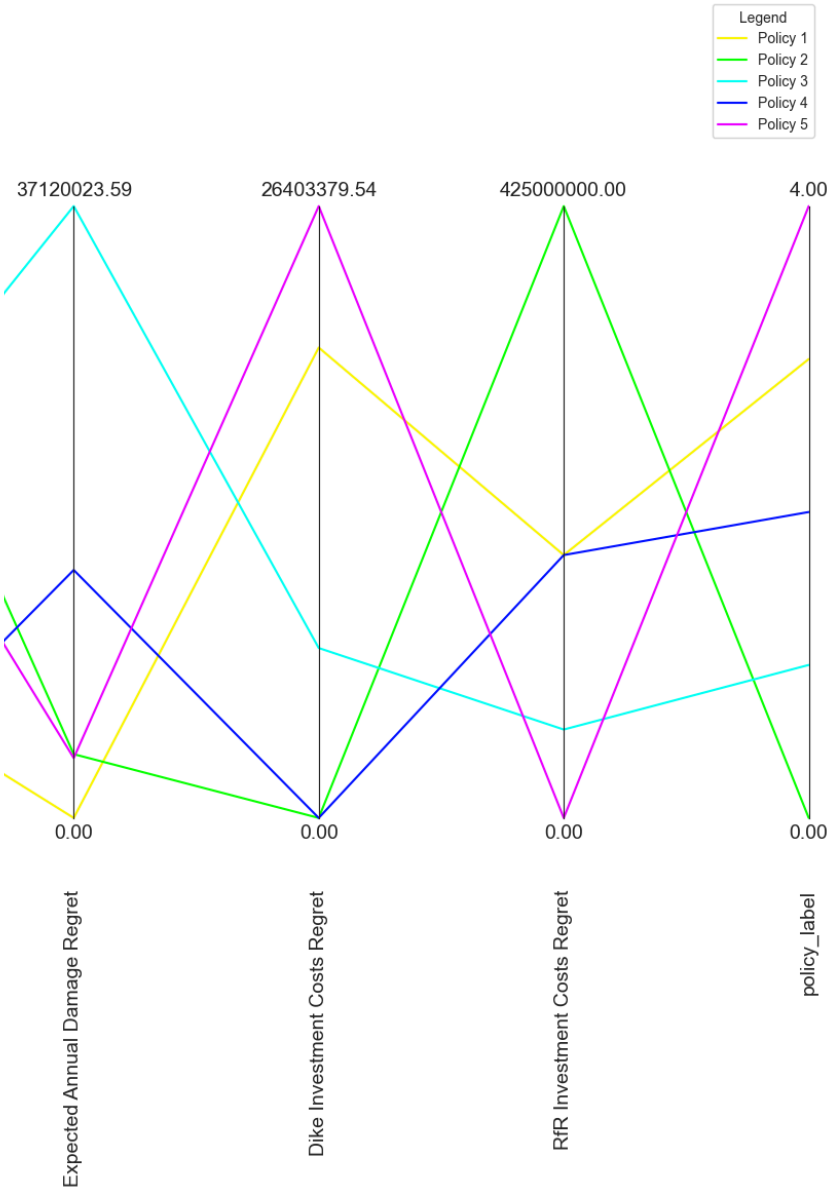

Figure D10: Maximum Regret results

Appendix E - Addition to the conclusion

The total cost is calculated by summing up the dike investment cost, the RfR investment cost and the expected annual damages in euros. The red line represents the mean of the total cost over the 5 policies.

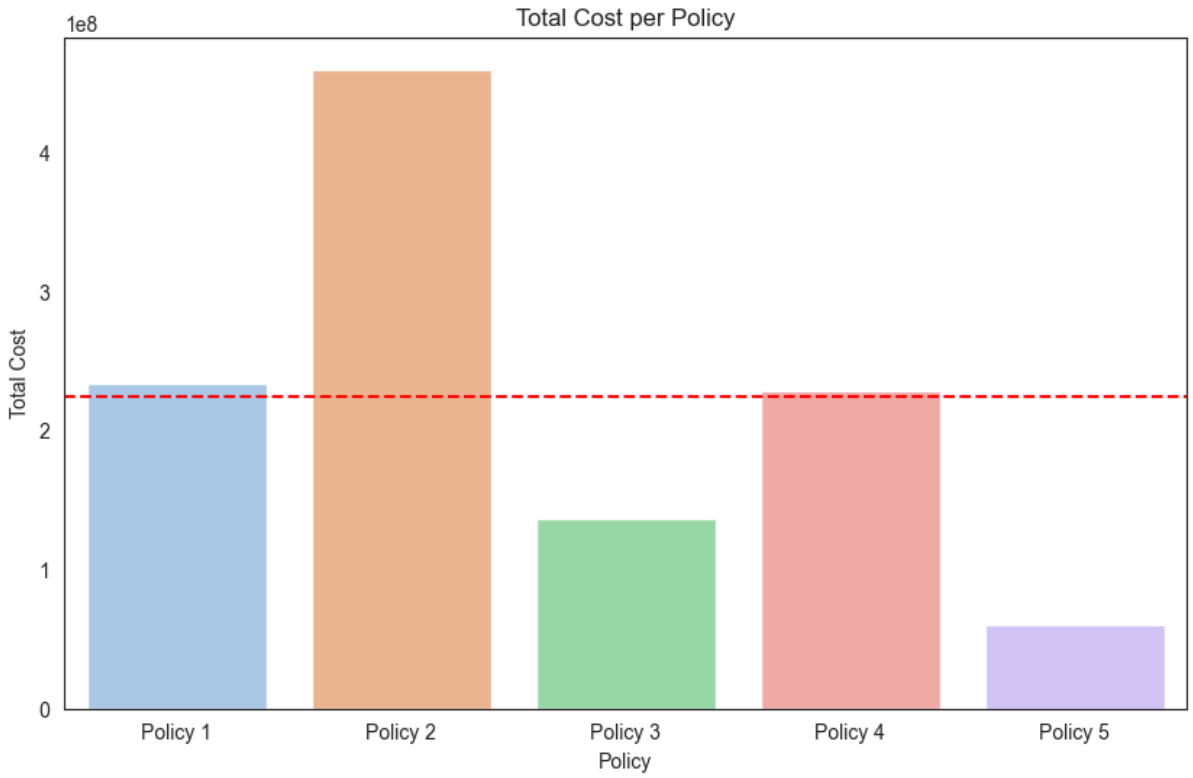

Figure E1: Total cost per policy, including average investment per policy