IJssel River Flood Risk Management Report - Part 1 Analysis

Model-based decision-making

Group 5: Transport Analyst Team

Hubert	Florian	3677710	Industrial Ecology
Bermudez	Federico	5889138	Industrial Ecology
Trescoli	Javier	5889162	Industrial Ecology
Torscht	Lukas	5891957	Industrial Ecology
Bout	Kiki	4612272	Engineering and Policy Analysis
Croué	Gaël	5898226	Industrial Ecology
Zenhäusern	David	5898218	Industrial Ecology

Summary

This technical report was requested by Ijssel's Transport Company (TC). The purpose was to provide guidance on the risk flood management policies for the upper trench of the Ijssel River that the TC should be sponsoring to the Rijkwerstraat and the Delta Commission. The TC aims to maximize trade volume as well as reduce the risk of damages at any point.

As with most long-term policy problems, advising on such measures requires an approach that accepts the inherent uncertainties as well as different perceptions of the desirable and undesirable outcomes of these long-term policy problems. Exploratory Modeling Approach (EMA) is the modeling approach that supports modelers, researchers, and policymakers in running, testing, and experimenting with policies under conditions of deep uncertainty and reflecting multiple, even opposing, values of desired outcomes. If done correctly and transparently, EMA introduces a degree of adaptivity and dynamism that allows long-term planning to deal with uncertainty and different desirable outcomes.

As Analysts for the Transport Company, we used EMA to produce policies that aimed to meet the TC's goals as well as be acceptable for other stakeholders, especially the Rijkwerstraat and the Delta Commission. Once we formulated the problem within the boundaries of the model, we focused mainly on two measures: Expected Annual Damage (EAD) and Minimum Water Level (MWL). The latter indicator was not within the model, which was created to make sure that the policies do not impact the TC's ability to trade.

Firstly, an Exploratory Policy Analysis (EAP) ran 30 policies through 50 scenarios, which provided many insights. The outcomes of EAP were subjected to Scenario Discovery, where we used Subspace partitioning to identify policies that minimize EAD and maximize MWL. Scenario discovery was done to identify the seed required for worst-case scenarios, the undesired outcomes according to our problem formulation, as well as best-case scenarios.

PRIM was used to identify patterns in the data sets obtained through subspace partitioning. Whilst there was enough data within the worst-case scenario, PRIM could not run on enough data for the best-case scenario, which meant iteratively revisiting the Subspace partitioning until we obtained enough data.

Once we obtained the Reference Scenarios, Many Objective Robust Decision-Making (MORDM) was used twice to test the robustness and the performance under the uncertainty of the candidate policies. In the second iteration of MORDM we included budgetary measures in light of the debates with other stakeholders Once we had an analysis of the regret values, one policy was chosen that reasonably met the TC's requirements.

The policy was finally subjected to a Global Sensitivity Analysis (GSA), identifying how two dike rings were sensitive to failure, increasing EAD and END. The final policy suggested was adapted to reduce the probability of high EAD and END.

1. Introduction **4**
1.1. Structuring the policy problem 4
1.2. Exploratory Modeling Approach explanation 5
1.3 Problem formulation 6
2. Methodology **8**
2.1 Exploratory Policy Analysis 8
2.2. Scenario Discovery and PRIM 9
2.3. Many Objective Robust Decision-making (MORDM) 10
2.4. Sensitivity Analysis 10
3. Results **11**
3.1 Model exploration 11
3.2 Scenario Discovery and PRIM 12
3.3 Many Objective Robust Decision-making (MORDM) 15
4. Discussion and Conclusion **21**
4.1 Discussion 21
4.2 Conclusion 22
References **23**
Appendix **24**
Appendix A. Figures and tables of modeling process 24
Appendix A.1. Policy lever values 24
Appendix A.2. Results 24
Appendix A.3. Results Scenario Discovery 27
Appendix A.4. Results MORDM - First Iteration 29
Appendix A.4. Results Global Sensitivity Analysis 32
Appendix B. Code 34
Appendix C. External Factors, Levers and Measures 35

1. Introduction

1.1. Structuring the policy problem

As climate change worsens, sea level rise and changes in the water cycle increase dangerously the risk of flood. The Netherlands is vulnerable to this increasing uncertainty in scale and intensity of the water cycle. From the flood of 1953 (Kaufmann et al, 2016) to the most recent in July 2021 (Koks et al. 2022) in Limburg. Flood Risk Management (FRM) practice is dealing with higher stakes, becoming more relevant and scrutinized by many more stakeholders, as the Netherlands is intensely developing its capabilities to mitigate flood risk (De Bruijn et al., 2015).

FRM refers to the set of strategies, measures, and actions implemented to minimize the potential impacts of floods on human lives, infrastructures, and the environment. It involves a combination of preventive, protective, and preparedness measures to reduce the likelihood of flooding, mitigate its consequences, and enhance the resilience of the communities.

Flood is increasingly a "wicked problem" as the consequences of floods and measures taken are more impactful and affect more stakeholders. Wicked problems are " *characterized by the involvement of a variety of stakeholders and decision-makers with conflicting values and diverging ideas for solutions…what makes wicked problems especially pernicious is that even the problem formulation itself is contested"* (Kwakkel, Walker, & Haasnoot, 2016, p. 1). Within modeling, these problems can also be defined as *unstructured,* as there is no common way to measure the same problem. This means that FRM policies within the Netherlands are influenced not only by a few isolated decision-makers behind closed doors, but by a complex web of interests, priorities, and actors, reflected in this case study. Consensus on what is *really* the problem with floods and *how* to face this problem optimally is not a given, complicating an agreement on the long-term planning of FRM.

In our specific case, we are exploring the FRM of the upper trench of the Ijssel River, as analysts of Ijssel's Transport Boat Company (TC). The main decision-makers are the Delta Commission and Rijkwaterstraat and aside from TC, the other stakeholders who care about the policies surrounding FRM, are: Gelderland Province, Overijssel Province, and an environmentalist group advocating for local biodiversity.

This report is written for the TC and aims to frame a robust and accurate policy proposition that meets the following conditions:

(1) River Ijssel must be navigable at all times

(a) Maximize the trade volume
(b) Minimize the risk of flood risk in the entire river, as the TC cannot transport goods if any river is broken

(2) Strong preference for dikes heightening over “room for the river” policies as it increases water height
(3) No policy implemented is better than a policy that harms the TC’s economic interests

The transport company's goal is to make sure that as much trade volume happens within the Ijssel river, as the higher the volume, the more profit. However, they cannot support policies that reduce the level of the water as that would reduce the amount of mass their boats can transport and therefore, less trade. In addition, they have to support protection policies that reduce the risk of flood as if a dike fails at any point, the water level of the river will decrease, reducing the transport company’s trading volume.

Before explaining further the TC’s problem formulation, it is pertinent to explain how the Exploratory Modelling Approach and the specific model we will be using in the following section.

1.2. Exploratory Modeling Approach explanation

Exploratory Modeling Approach (EMA) is a modeling approach suitable to aid decision-making under deep uncertainty - when the stakeholders involved in decision making, cannot agree on how the system works, what are the desirable and undesirable outcomes and what are the mos probable futures affecting them (Kwakket & Haasnoot, 2019., p. 356). EMA provides a variety of tools that allow modelers to run and test experiments under conditions of deep uncertainty.

EMA is an appropriate conceptual and methodological approach which allows us to test policies and choose the most suited TC, considering how other stakeholders understand the problem, without taking risks in reality.

The EMA Workbench we will use,simulates the propagation of a flood through the upper branch of the Ijssel River, assessing how the protective infrastructure and policies perform under different scenarios of flood. The model is conceptually built upon XLRM framework, which consists:

- ***X*** represents the *external factors*: uncertainties affecting the system's performance over which the policymaker has no control.
- ***L*** represents the *levers*: a set of policies under study (i.e., decision variables).
- ***R*** represents the *relationships* within the model: a set of rules and/or mathematical expressions linking X to L for computing M.
- ***M*** are the *measures*: indicators assessing the performance of the levers (i.e., decision objectives).

What is relevant for the modeler is how to use *levers (L)* to maximize or minimize the desired measures (*M)* and perform desirably under as many uncertain external factors as possible (*X)*.

- The levers within this model are Dike Heightening (DH), Room for River (RfR) and Evacuation Alarm. In addition, DH and RfR can be defined further by a time step, which defines when the policy will be implemented, as well as by their location along the Ijssel River. These locations are called Dike Rings (DR) and total 5 throughout the model. DRs have different contexts. Rural dike rings like numbers 2 and 4 have a strong farmer lobby that does not mind flooding from time to time and puts emphasis on agricultural activities. On the other hand, dike rings 3 and 5 are urban, populated, and are interested in finding a safe option that will avoid damage. DH can be either medium or high.

Lastly, the following measures within the model orient how we measure the performance of a specific set of policies under the uncertain external factors. These outcomes are the following:

- Expected Annual Damage (EAD) - yearly expected damage from floods
- Expected Number of Deaths (END) - yearly expected deaths from floods
- Dike Investment Costs (DIC) - total costs of implementing the DH
- Room for River Investment Costs (RIC) - total costs of implementing the RfR
- Expected Evacuation Costs (EEC) - cost of evacuation related to the number of people and the duration they must leave home

In the following section we conclude the introduction by presenting other stakeholder's priorities and how that impacts our own problem formulation.

1.3 Problem formulation

As we described above, TC desires a FRM policy that will keep the river navegable at all times and reduce the risk of flooding along the river, as well maximize trade by increasing water levels. What do the other stakeholders want?

Firstly, the two so-to-say problem owners are Rijkwaterstraat and the Delta Commission. Rijkwaterstraat is a public agency that is responsible for large public infrastructures such as highways. They organize the policy process by taking every actor's needs into account. The Delta Commission has nearly as much power as the Rijkswaterstraat, and aims in particular at avoiding deaths and damage in the regions.

The problem framing of the provinces and dike rings is slightly different, if provinces still aim for a relatively balanced solution, Finally, the environmental group wants to protect local biodiversity and give more room to the river by creating alluvial plains, which is a very diverse ecosystem and home for a number of species.

We built a problem formulation (PF) that was based on a pre-existing problem formulation, PFII plus a measure of our own, Minimum Water Level (MWL). PFII is an aggregate function

that includes all 5 measures, extracted from the EMA Workbench. However, none of these measures clearly connected to the river's water height. River height is an extremely valuable metric to measure how policies can impact the river heigh and therefore, the navigability and the trading volume of the TC. The higher the water level (to a certain point), the more volume of trade and the more profit.

However, MWL became part of the PF from the second step, Scenario Discovery onwards, whilst the open exploration used PFII as is.

In addition, we adopted PF II for two reasons. First, as this objective is not linked to space and time it would not be too computationally demanding. Second, for negotiation purposes during the debate, PF II assesses all five outcomes and thus provides the most information among the remaining PF. This allowed flexibility in the later stage of the modeling to find specific policies to meet metric thresholds of other stakeholders that emerged during discussions and the debates, such as DH and RfR costs.

In conclusion, we chose a PF that includes all measures plus our own sixth measure, Minimum Water Level. During the exploratory phase we maximize EAD and MWL and meet comfortably our own conditions, we do use other measures as we include other stakeholder's own thresholds in order to identify robust policies that other stakeholder can support.

In the following section we go into detail about the methodology of our modeling.

2. Methodology

In the following section, we explain our methodological steps.

2.1 Exploratory Policy Analysis

The first method and step is an open exploration of the model. This way, a preliminary understanding of the model and the effects of implementing policy measures and policy measures combinations is provided. The performed open exploration contains an elaborated set of policy measures which can be divided into five categories: (1) Business-as-Usual scenario; (2) Dike heightening scenarios; (3) Room for the River scenarios; (4) Dike heightening and Room for the River in different timestamps and (5) Debate scenarios. The policies included in the open exploration phase of this model are listed and described in the table below. The results can be found in Appendix A.1 & A.2, whilst the exact definitions and values per policy lever of the policies used in the open exploration can be found in Appendix C.

Table 1: Overview policies open exploration phase

Policy nr.	**Policy names***	**Policy description**
P0	Business as Usual (BAU)	No policy levers are implemented
P1-P2	Medium**/High*** increase of every Dike Ring	Medium/High dike heightening policy levers are implemented for every Dike Rings
P3-P7	Medium increase of one Dike Ring	Medium dike heightening policy levers are implemented for one Dike Ring at the time
P8-P12	High increase of one Dike Ring	High dike heightening policy levers are implemented for one Dike Ring at the time
P13-P15	Medium/High increase combination for multiple Dike Rings	Medium and high dike heightening policy levers are implemented for a combination of Dike Rings
P16-P20	Room for the River for one Dike Ring	Room for the River policy lever is implemented for one Dike Ring at the time
P21	Room for the River for every Dike Ring	Room for the River policy lever is implemented for every Dike Ring
P22-P25	Medium/High increase of every Dike Ring in timestep 1/2	Medium/High dike heightening policy levers are implemented for every Dike Ring for timestep 1 and timestep 2
P26-P27	Room for the River for every Dike Ring in timestep 1/2	Room for the River policy lever is implemented for every Dike ring for timestep 1 and timestep 2
P28-P30	Medium/High increase and Room for the River combination for multiple Dike Rings	Medium and high dike heightening policy levers, as MINIMwell as Room for the River, are implemented for a combination of Dike Rings

** All policies levers are implemented in the first time step unless mentioned otherwise*
*** Medium dike heightening: 5 dm*
**** High dike heightening: 10 dm*

The results of the identified policies were generated by running our PF, applying 50 scenarios per policy obtaining 1500 final experiments.

2.2. Scenario Discovery and PRIM

The first step used in the modeling phase is scenario discovery. This is useful to determine the uncertainty space that leads to the worst cases. The worst-case scenario is defined according to the objectives as (1) a water level that is lower than the minimum water level for shipping boats to circulate. This value corresponds to 4 meters for the highest river shipping class (Rijkswaterstaat, 2020) and (2) an EAD which does not increase compared to the current situation. As the TC would prefer no policy rather than accept any policy that goes against their interests, this first step acts as a vulnerability analysis to identify the policies we advise the TC to not accept.

Scenario discovery aims to find a subspace in the uncertainty space that statistically significant leads to worse outcomes. These represent vulnerabilities in proposed policies and to describe these scenarios in a manner useful for decision-makers and stakeholders (Bryant & Lempert, 2010). We use the technique of subspace partitioning to divide the uncertainty space into subspaces based on similarities or differences in the observed behavior of the desired outcomes. Instead of treating the entire parameter space as a single entity, subspace partitioning enables a deeper understanding of regions where specific patterns or responses occur. Subspace partitioning will provide the seed for the reference scenario of the following multi-optimization and allow a more accurate exploration of the lever space.

First, an experiment selection policy is run with a Latin Hypercube Sample (LHS) . We then set thresholds to the objectives' value to define the worst cases:

(1) MWL: previously, the target min water level rise value (for BAU) was identified as 4.807 m. This lands in between the 95 and 99% confidence intervals, which would indicate only a 5% probability of a higher water level. To define a realistic target, an external source was consulted. The Rijkswaterstaat indicates a minimum water level of 285 cm for the IJssel River (Rijkswaterstaat, 2023). Taking a CEMT Klasse of VIa boat (Rijkwaterstaat, 2020) as the optimal solution for the Transport Company, a minimum water level of 4m can be deemed acceptable. We set the threshold at 4m and 4.8m as the space that would allow us to maximize trade volume.

(2) EAD: the exploration of the model showed that there is a negative relation between the EAD and the MWL. We deduce that whatever increases in the MWL, the EAD will decrease. The threshold is EAD at BAU.

The exploration of the parameter space is allowed by PRIM a data mining algorithm that uncovers hidden patterns and relationships between the desired outcome and the parameter space, providing insights into their ranges. PRIM constructs boxes on the dataset of experiments and optimizes them according to a measure called fitness metrics. These can be the coverage or the density of the box.

Coverage measures the proportion of instances within a sub-box that exhibit the target outcome. Density represents the concentration or distribution of instances within a sub-box. PRIM iterates this process until finding the box that exhibits the best fitness metrics' values. Finally, PRIM generates rules based on the optimized subspaces. The rules capture the patterns and behaviors observed within the box. If there is high density and coverage, that box can be further researched as candidate strategies for policy.

2.3. Many Objective Robust Decision-making (MORDM)

Using MORDM, the first group of candidate solutions is identified. These policies are analyzed using robustness metrics. After this, a second scenario discovery is applied and used for a second iteration of the MORDM process. This is done both to reduce the computational power required and to obtain more reliable data which improves the quality of the analysis. In addition, we can use measures and thresholds which are important for other stakeholders in this step. As transport company analysts, this is used to suggest policies that are robust and meet their conditions as well as potentially other stakeholder's desirable outcomes.

2.4. Sensitivity Analysis

Finally, a global sensitivity analysis will be performed on the final policy selected. The selected method for this is a variance-based sensitivity analysis (Sobol), as it is deemed to provide accurate results and it can easily be applied using the EMA workbench. The main purpose of this is to finetune the understanding of the final policies suggested and adapt the policy if the results reveal that there is a particularly strong relation between an uncertainty and an undesirable outcome. Due to computational requirements, only the final policy is analyzed with this method.

In the following section, we present the results from each step introduced in the methodology.

3. Results

3.1 Model exploration

As mentioned in section 2.1, the policies are analyzed based on several criteria. The criteria used in the model exploration are the *M, the measures,* consisting of: (1) Average Annual Damage, (2) Dike Investment Costs, (3) Room for the River investment costs and (4) Expected casualties. Evacuation Costs were excluded during discussions with the Rijkswaterstaat and Delta Commission. These correspond to the outcomes extracted from problem formulation 2. For every policy tested in the model exploration, the mean of the four criteria is calculated. These values can be found in Appendix A.2.

Furthermore, the policy results of each scenario are visualized output graphs such as the one observed in Figure 1. The figures of more scenarios can be consulted in appendix A.2..

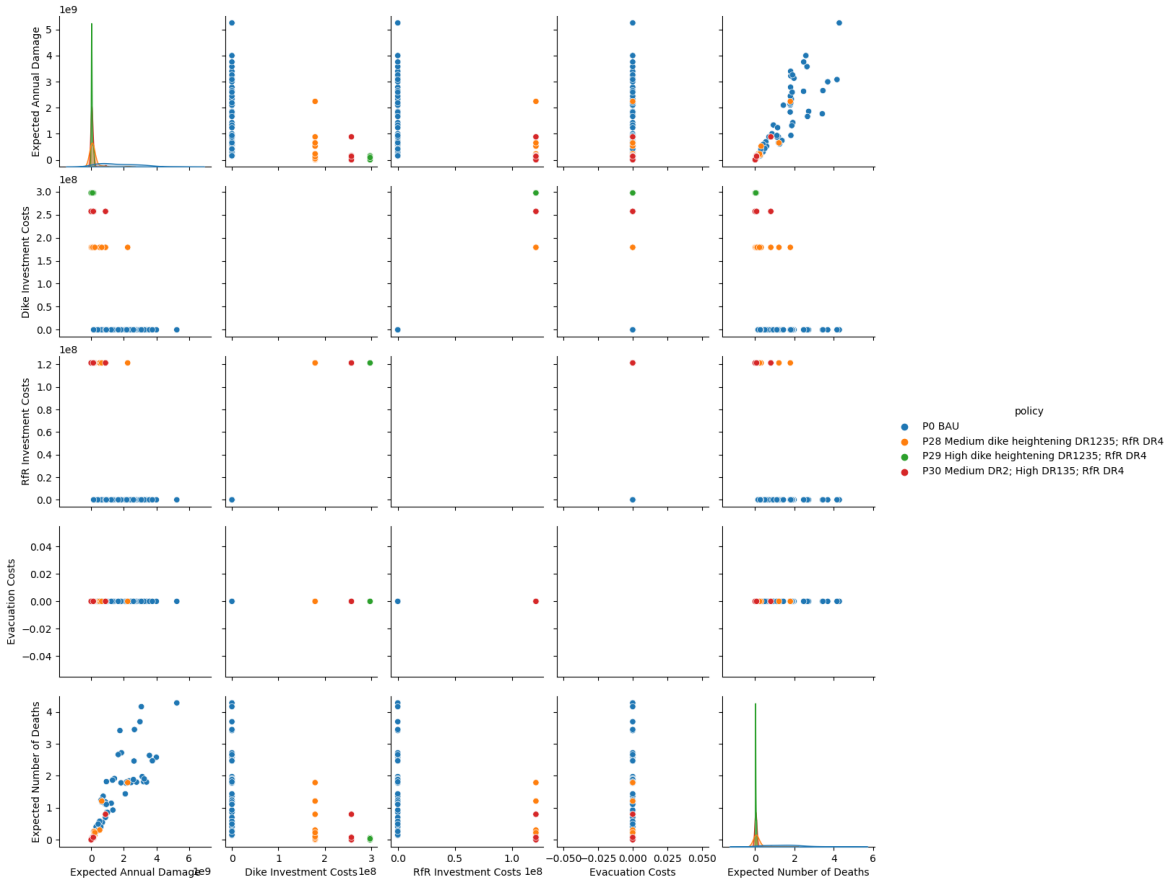

Figure 1: Pair plot showing results for simulated policies P28-P30, with different Dike heightening and RfR values

Based on the statistics and the output graphs, the following interpretations of the model can be made. First, dike heightening is a more effective policy than Room for the River based on the expected annual damages and expected number of deaths. However, applying dike heightening requires more financial sources. Moreover, combining dike heightening for multiple Dike Rings with Room for the River in multiple locations seems to be one of the most effective policies. In this case, dike heightening for Dike ring 1, 3 and 5 and applying

Room for the River in Dike ring 2 and 4 are proven to be a successful combination. Furthermore, Room for the River can be an effective policy regarding minimizing the expected annual damages and the expected number of deaths. However, it is required to apply this policy to multiple locations to reach this effective result, as in some cases applying it at only one location creates a situation that is worse than the Business-As-Usual scenario. On top of this, this requirement leads to high investment costs. Last, it can be stated that the sooner policy interventions are integrated, the lower the expected annual damage and the expected number of deaths. The costs of integrating policies is independent of the time of implementation, as these stay equal over time.

3.2 Scenario Discovery and PRIM

As stated previously, the process begins with a scenario discovery. Here a simulation is run with 1,000 scenarios and 10 policies. In Appendix A.3, Figure 13 shows the results of this simulation. From these results, it can be interpreted that the uncertainty space for several policies can be reduced, specifically for the MWL measure. For EAD, the uncertainty space can be considered small, the absolute decrease potential is instead more important for this outcome. Finally, there is no clear correlation between a high minimum water level and EAD, which suggests a dampening effect by, for example, dike heightening measures.

The next step corresponds to subspace partitioning, where policies that are better and worse than the business as usual (BAU) scenario are sought.

The model is run using 200 scenarios with a BAU policy. From this, the following values are extracted from the mean of these results:

1. EAD = 1.5 B EUR
2. Max Water Level = 4.5m
3. MaxWater Level = 8.35m

To ensure the quality of the policies and minimize potential damages, the confidence interval chosen is 95%, therefore, the desired policies should meet the following criteria:

1. EAD < 3.1843 B EUR
2. Min Water Level > 4.8070 m
3. The spread between min and max water level can be interpreted as a potential increase in profit for the Transport Company. Therefore, the preferred water level spread is > 4.3480 (preferred water spread = max water level rise - min water level rise, or 9.1551 - 4.8070)

The outcomes of this step are analyzed, and the minimum water level of 4.8070 m is not reached in most cases. The value is then adjusted to the 90% confidence interval and set as 4.7027m.

With this new minimum water level value, the subspace partitioning algorithm PRIM is initiated. Figure 3 shows the results of this.

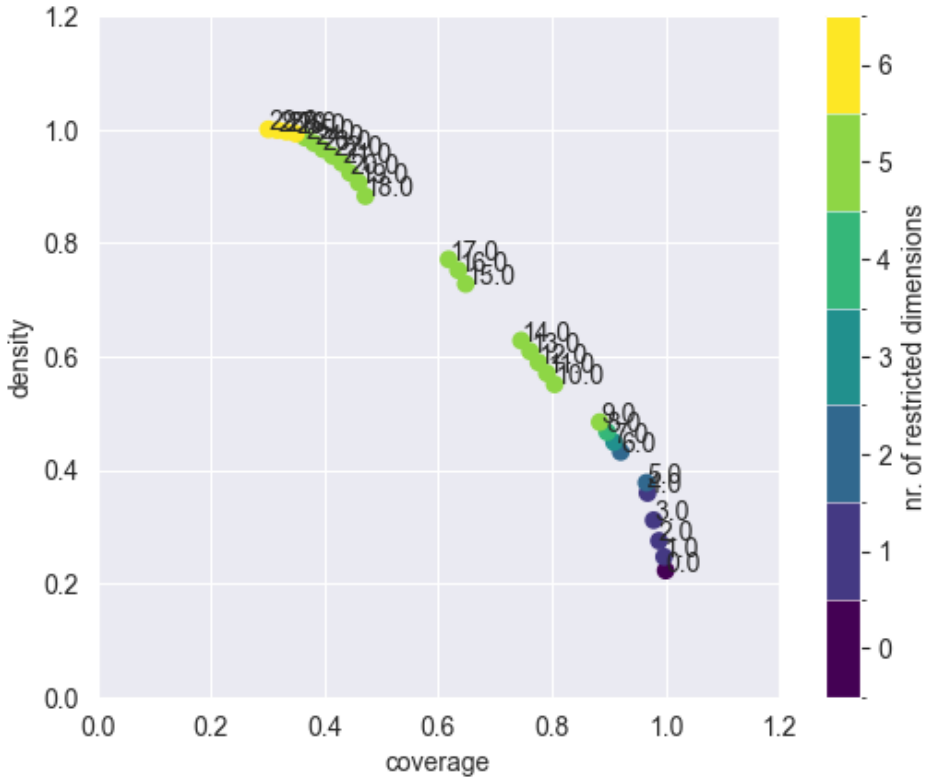

Figure 2: PRIM results: coverage vs density of simulated policies

From this figure, the tradeoff between coverage and density is clearly observed. Therefore, middle values are preferred as they contain an acceptable number of interesting and precise scenarios. To analyze this, the results with a density higher than 60% and coverage higher than 70% are chosen, which corresponds to box 14.

Further inspection of this box is visualized in Figure 4, where the uncertainties and policies are plotted. The range of RealParameters are visualized as a blue line, while Categorical Parameters are visualized with a dot.

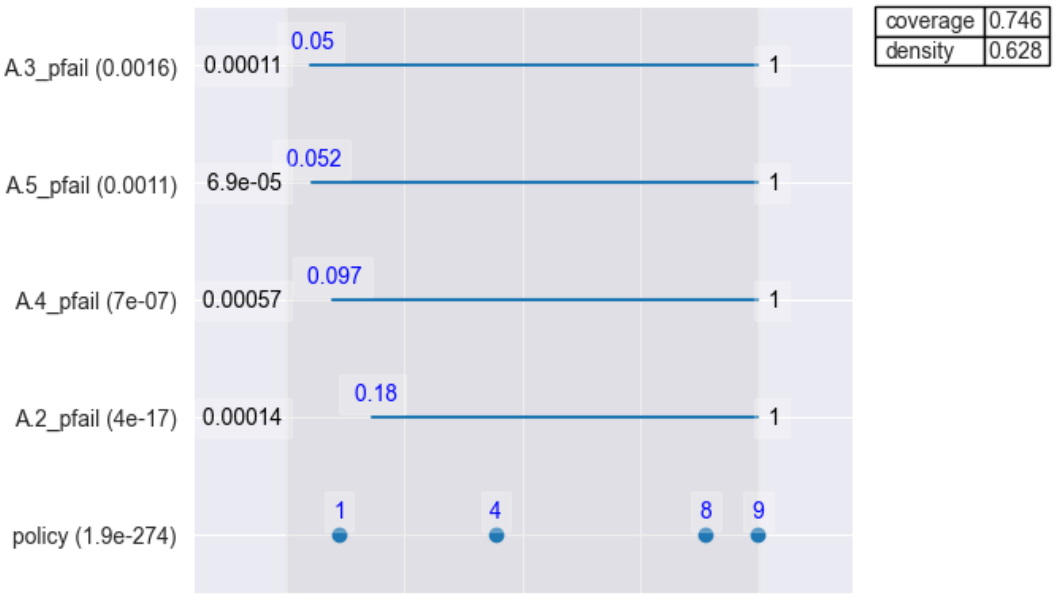

Figure 3: Box 14 uncertainty intervals

From this, it can be concluded that no uncertainties are excludable, however, policies 1, 4, 8 and 9 have a low water level. The uncertainties relating to failure probability (A{x}_pfail) lack statistical significance to accurately assess their influence on the outcomes.

Further visualization results in Figure 5, which shows the uncertainties in a pair plot. Here, orange dots represent cases where the desired minimum water level is reached (identified as “true” in the figure legend). This figure then shows that there is a relation between lower water levels (true) and higher fail probabilities.

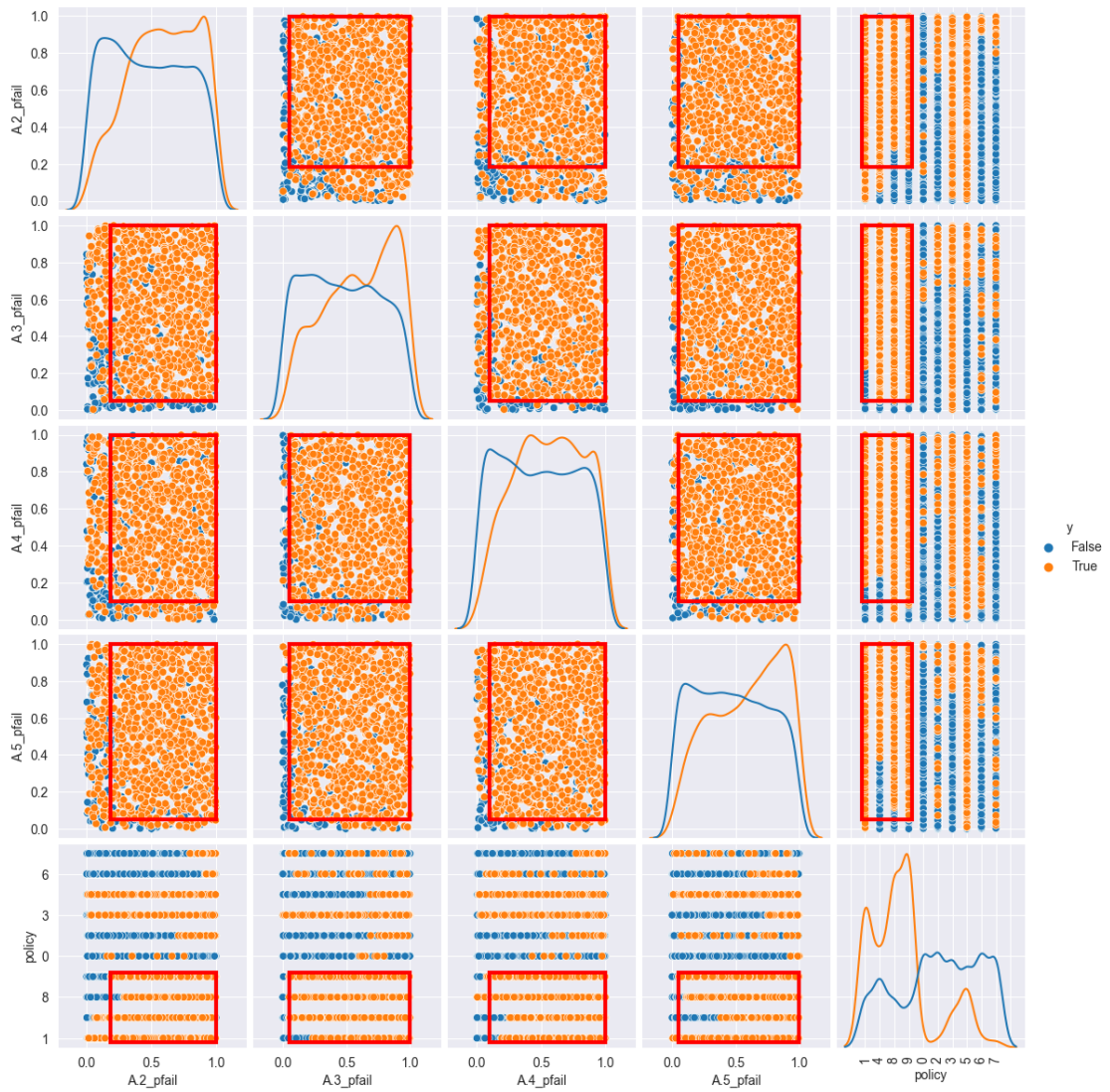

Figure 4: Pair plot showing box 14 uncertainty intervals

Further analysis done using dimensional stacking shows the need for an increase in statistical significance. This can be done by increasing sampling size.

In the next step, a second simulation is run using 4,000 scenarios and 10 policies. The objective will be to find the worst case scenario. Through this second iteration, Figure 6 is again obtained to analyze uncertainty intervals.

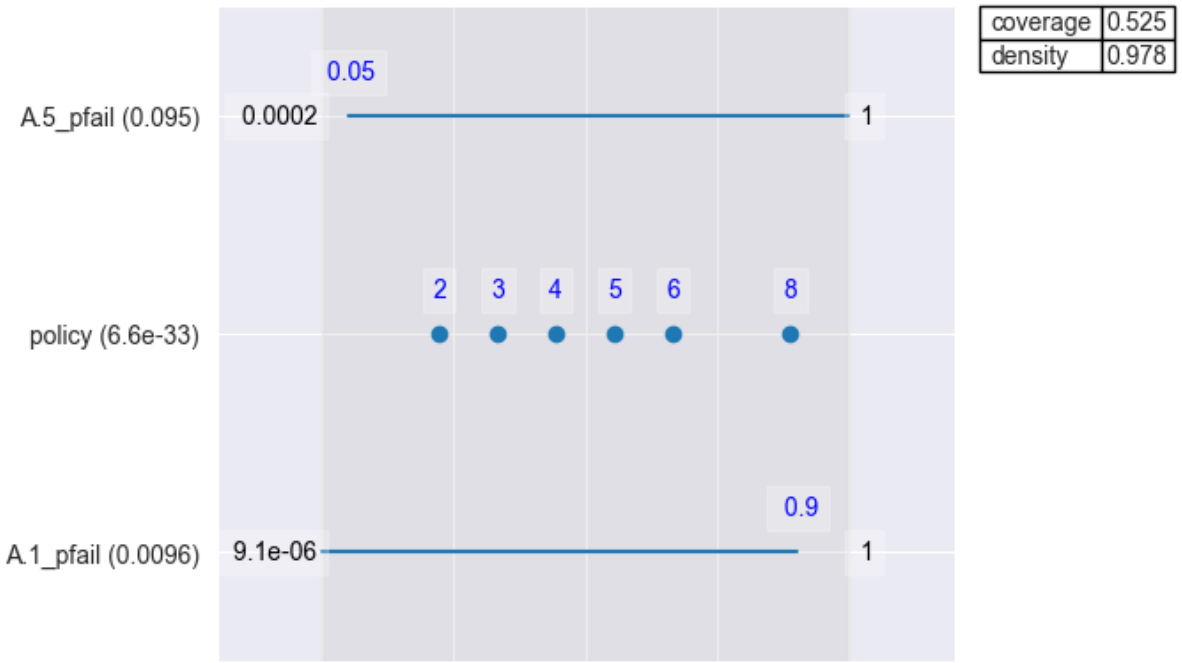

Figure 5: Box 8 uncertainty intervals for second iteration

This plot is useful to identify the worst cases. In this case, all policies except for 7 and 9 correspond to worst-case scenarios, and are therefore extracted. These policies are provided to the Transport Company and serve as material for the policy debate, as they wish to challenge policies that harm their interests. As mentioned in Section 2.2, the value from the water authority (Rijkswaterstaat) is adjusted and corresponds to 4m of water level. Exploring the output tables manually, it can be observed that this value is met in all scenarios. This point will be expanded on in the discussion section.

After the worst case is identified, an attempt is made to identify best-case policies. However, the uncertainty analysis shows a density lower than 0.5, so the best case analysis is not performed at this stage.

Finally, the results from boxes 7, 8 and 10 from the worst-case analysis are used to define the seed that will be used as the reference case for the first iteration of the MORDM. The uncertainty values for this can be seen in Table 4 in Appendix A.3.

3.3 Many Objective Robust Decision-making (MORDM)

MORDM was run twice to ensure maximum data quality. The resulting figures from the first iteration can be consulted in Appendix A.3. This first iteration is used to identify a group of favorable policies and further adjust the seed values. As mentioned earlier, the minimum water level is reached in all cases, so the main outcome of interest is changed to EAD. This information, along with the group of policies extracted in this step are provided to the Transport Company group and are used for the policy debate.

After the scenario discovery section of the first iteration of MORDM, and by applying a feature scoring analysis, the uncertainty A.1_pfail is again identified as the main parameter

of interest. For the second iteration, this value is adjusted further to 0.099 (0.2-0.0005/2). The values for the seed used in the second iteration of MORDM are observed in Table 2.

Table 2: Seed values for reference scenario for first iteration of MORDM.

Variable	**Value**
discount rate 0	2.5
discount rate 1	2.5
discount rate 2	2.5
A.0_ID flood wave shape	75
A.1_Bmax	190
A.2_Bmax	190
A.3_Bmax	190
A.4_Bmax	190
A.5_Bmax	190
A.1_pfail	0.2-0.0005/2
A.2_pfail	0.5
A.3_pfail	0.5
A.4_pfail	0.5
A.5_pfail	0.5
A.1_Brate	1.5
A.2_Brate	1.5
A.3_Brate	1.5
A.4_Brate	1.5
A.5_Brate	1.5

These values are used to set the reference scenario and initiate the second MORDM iteration. The model is executed with an epsilon value of 0.05 and NFE of 100,000. The convergence is plotted and shown in Figure 7.

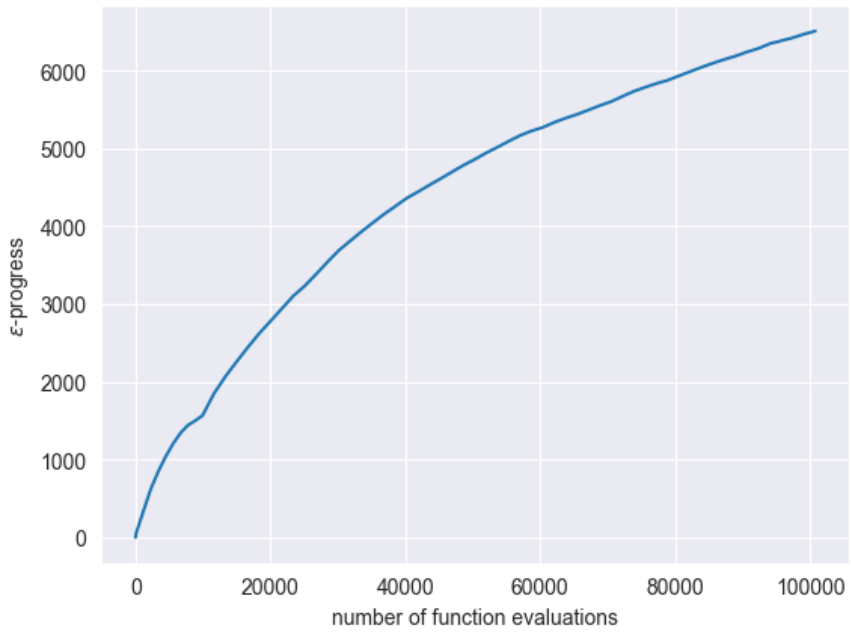

Figure 6; Convergence plot for second iteration of MORDM. Epsilon= 0.05 | nfe= 100,000

Even with an NFE value double of that used in the first iteration, and a lower epsilon value, convergence is not reached. This takes significant computational power and is considered one of the main constraints to reach optimal result quality in this study. This will be further evaluated in the discussion section.

The outcomes obtained from this model run are plotted in a parcoords graph and shown in Figure 8.

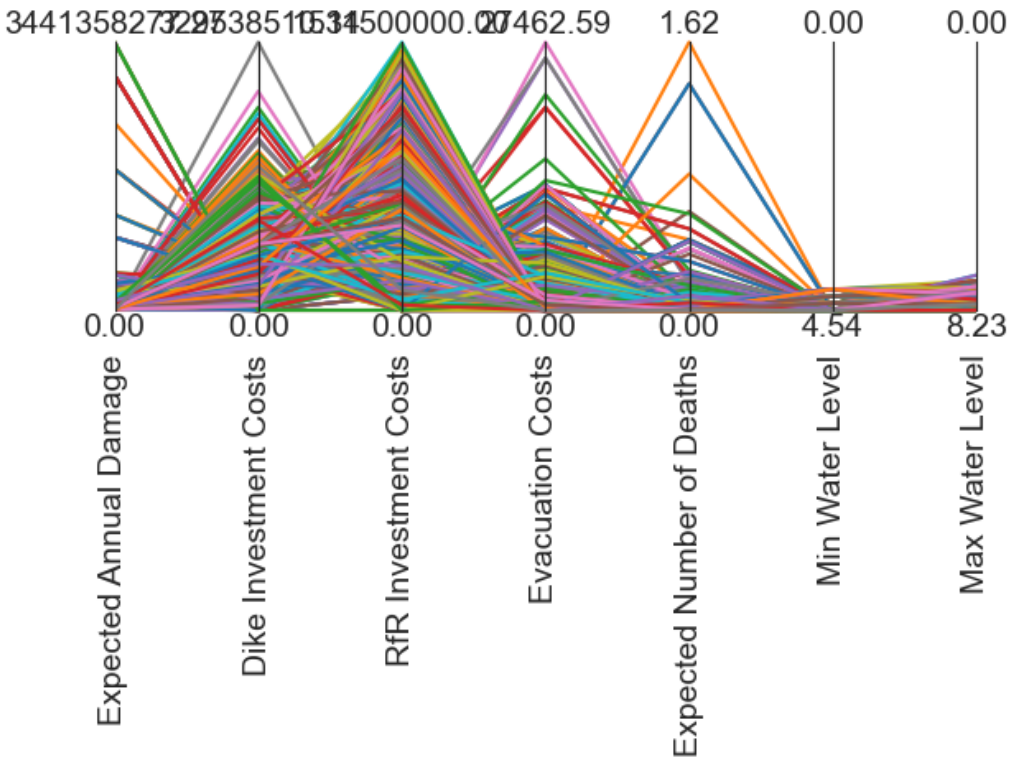

Figure 7; Parallel coordinates plot for second iteration of MORDM

From this figure, the following interpretations can be made:

1. EAD has some outliers with high values, but most scenarios are within the lower (and acceptable) range
2. All scenarios show minimum water level as acceptable
3. As with END, most values are within the lower range, but there are some outliers
4. Costs show a wide range of values

Due to the high amount of scenarios, it is hard to extract further information from the figure, therefore, further filtering is applied using the following criteria:

1. Minimum water level > 4 (this condition is always met)
2. Total investment costs < 200 M EUR (this condition is derived from policy debates
3. Minimized EAD (5%)

The policies that meet the specified conditions are then plotted again in Figure 17 in Appendix A.4. This figure shows the clear tradeoff between dike investment and RfR investment costs. Some policies can still be improved as there is still spread in values such as EAD and END.

A robustness analysis is then applied to these policies. This is done by running 1,000 scenarios within high uncertainty. The results can be observed in the robustness matrix in Figure 9.

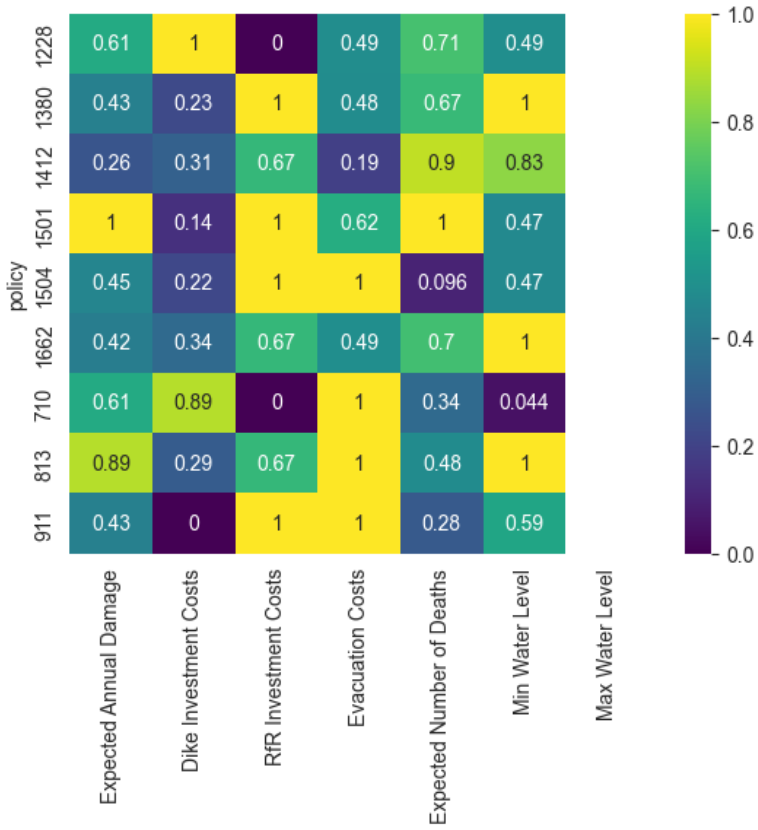

Figure 8; Robustness matrix showing regret values of selected policies in second MORDM iteration

From this figure, it can be concluded that policies 1228 and 1504 have low regret values for minimum water level, but very high costs in dike and RfR investments, respectively. Policy 710 is the best performer in terms of minimum water level, and has no RfR investment costs. The Dike investment costs are not optimal, but can be deemed acceptable. This policy has very high evacuation costs, however, this output is outside the scope of this study, as was discussed during the debates and debate preparation sessions.

To further aid in this analysis, the policies are graphed in a parallel coordinate plot using normalized regret values (Figure 10).

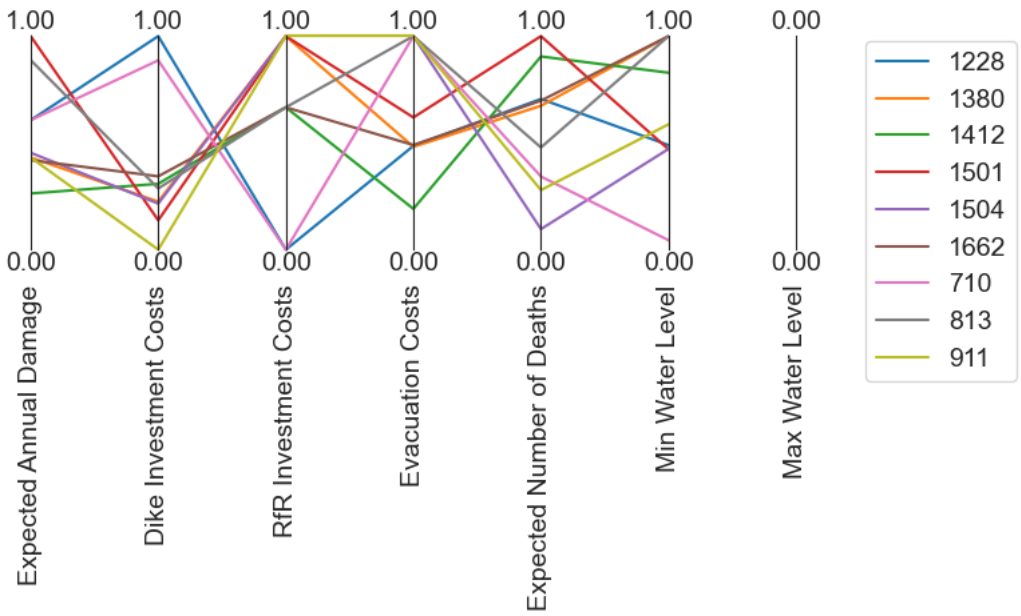

Figure 9: Parallel coordinates plot showing normalized regret values of policies from second MORDM iteration

From this graph it can be concluded that, in terms of EAD, the recommended policy is 1412, which results in the values observed in table x. Policy 710 minimizes the minimum water level completely, so it could also be considered if this value was prioritized.

Table 3: Policy 1412 lever values

Policy 1412	
2_RfR 1	1
EWS_DaystoThreat	2
A.1_DikeIncrease 0	5
A.2_DikeIncrease 0	2

A.3_DikeIncrease 0	2
A.4_DikeIncrease 0	2
A.4_DikeIncrease 2	1
A.5_DikeIncrease 0	3

3.3 Sensitivity Analysis

Finally, a global sensitivity analysis was performed to further analyze the relationship between parameters and outcomes. Due to computational power constraints, this was only applied to policy 1412. The results of this analysis for the EAD parameter can be consulted in Figure 11. Parameters corresponding to END and Min Water Level can be consulted in Appendix A.4.

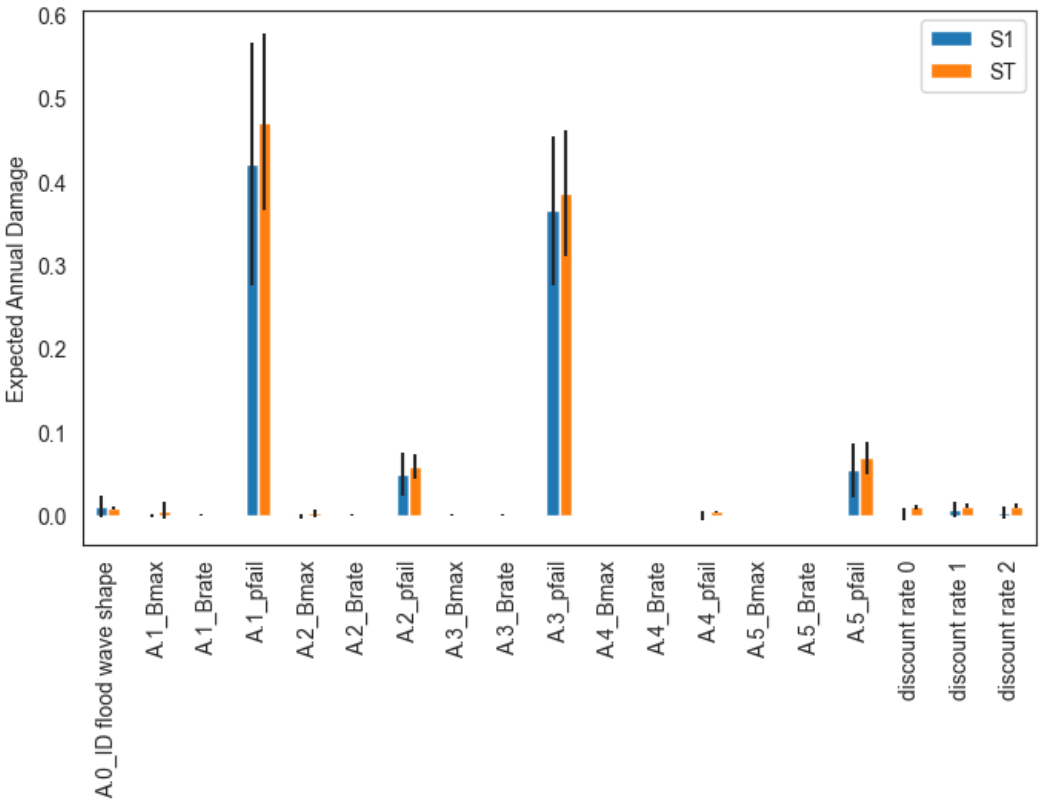

Figure 10: GSA Sobol results for EAD parameter, policy 1412

In this figure, the relationship between the parameters and the expected outcomes can be visualized. As observed previously, dike ring 1 and 3 have a stronger relationship to EAD. This information could be useful to further inform the policy debate and prioritize investments in a real-life scenario. Also the difference in ST-S1 highlights the interaction effects between the uncertainty parameters and therefore the nonlinearity of the system.

4. Discussion and Conclusion

4.1 Discussion

The main issue that was encountered was the constant compromise between what the best choice conceptually would be with the computational reality of student hardware. Computational power has been the main constraint in all phases of the exploratory and robust decision-making planning process. However, this was especially relevant during MORDM and GSA exercises.

More computational power could have allowed us to run many more experiments to explore more thoroughly the best case scenario of MWL 4.8m, but we lacked enough cases to even run PRIM on the cases that fit the threshold. This means that we had to focus on the policies within the worst case scenario that we needed to avoid.

More computational power would have also allowed us to do a GSA much earlier, which would have served to identify which uncertainties were having the most impact on the final outcomes and therefore adapt as we continued through the different phases. However we were only able to run GSA once for policy 1412 at the end. We still obtained valuable insight into which uncertainty is the most impactful on the EAD, which will be useful for policy discussions.

Aside from computational limitations, the experiments and outcomes are conditioned by how we decided to approach the mandates of the Transport Company. The fact that maximizing water level and minimizing risk of dike failure at any point in the river could not be directly extracted from any of the expected outcomes from the model, forced the team to discuss and decide how to translate the outcomes into a valid relationship with the mandates of our client.

Whilst we concluded that minimizing EAD, correlated with reduced probability of dike failure, the maximization of water level (and, therefore, trade volume) was not as clear. Therefore, a sixth outcome which produced minimum water level was engineered into the model to optimize the search process with an outcome that we believed would help us identify better policies. This was done with the help of the main lecturer of the course and creator of the EMA Workbench, Jan Kwakkel. This required us to modify the dike model function code, which surpassed our knowledge of coding and of the model. However, we successfully implemented this outcome into the model and we were able to provide a new level of data which other actors in the debate did not have.

Eventually we realized that we had been searching for a truly, best case scenario. Water levels always remained above 4 meters, which was the minimum required for boats to travel. The mandate leaves too much space for interpretation and the client provides no further guidance, leaving the modelers to decide what is the best case scenario to maximize trade volume. We set a threshold of 4.8 meters, which did not have enough cases to run a PRIM algorithm, and therefore we could not even identify policies worth further exploring. This left us with quite an ample space to explore within the MWL outcome, between 4 and 4.7.

EAD also became tricky as any policy intervention would reduce the EAD compared with BaU and all performed above 4 meters. Therefore, throughout MORDM, these two thresholds provided too many scenarios. Thankfully policy discussions introduced budgetary limits, which we used as thresholds. In addition to minimizing EAD, this allowed us to filter through the scenarios and identify policies that performed under all the thresholds.

A limitation in this approach is that the budget costs are a product of a negotiation and certain thresholds are possible under certain commitments. Therefore, that could be a gap in the policies we have recommended as the threshold for budget costs, less than 200 million, includes a budgetary commitment to pay for RfR.

Even though the MWL outcome might have complicated the process of searching for ideal policies, the development of this outcome was valuable to shift the initial inflexibility of the TC for any kind of policy which included RfR for fear of negative impact on trade. MWL allowed to openly research options where water levels still met requirements for the TC and included RfR, softening the TC's initial inflexible position within the decision arena.

In hindsight, we should have required the Transport Company to specify outcome-wise the mandate as well as factor in the problem formulation and desired outcomes of the most relevant stakeholders, such as Rijkswaterstaat and Delta Commission. The fact the Rijkswaterstaat and Delta Commission have veto powers on policies should have been a good enough reason to include their problem formulation within our own as a way to guarantee that our final recommended policies meet the requirements of the main decision-makers. However, as with the Transport Company, these actors also struggled to identify clearly their own mandates and by the time this was clearer, their input could only be added at a later stage of the modeling process. Having known this information from the beginning would have conditioned differently how to set, run, filter and test the experiments of the modeling.

4.2 Conclusion

At the conclusion of the final iteration of MORDM, we prioritized policies such as 1412, 1662, 1380 and 911 as the best performers in terms of EAD, as these would gain the most support from the decision makers. On the other hand, policies such as 710 performed the best for MWL, but these did not perform as strongly with EAD which would complicate their support from other stakeholders.

The policy that we suggested the Transport Company to sponsor is policy 1412, which has the lowest regret values for EAD and Dike investment costs as well as meeting the

requirements for MWL. In addition, another benefit within this policy is the inclusion of RfR at location 2, which could be used as leverage in negotiations with other stakeholders, such as environmentalists. A position of inflexibility around RfR if MWL is not met, can be softened with this policy.

The GSA was performed upon policy 1412, identifying that the most sensitive uncertainties were the dike failure at Dike Ring 3 and 5. Both Dike Rings were strongly related to EAD, but Dike Ring 3 also had a strong relation with END.

Therefore, if budgets allow, we would suggest a change in policy 1412, consisting in an increase increasing Dike Ring 3 by more than 2, ideally 5. This would reduce the probability of failure and therefore the potential of EAD and END at this location.

References

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

Kaufmann, M., Priest, S. J., & Leroy, P. (2016). The undebated issue of justice: silent discourses in Dutch flood risk management. Regional Environmental Change, 18(2), 325–337. https://doi.org/10.1007/s10113-016-1086-0

Koks, E., Van Ginkel, K., Van Marle, M. J. E., & Lemnitzer, A. (2022). Brief communication: Critical infrastructure impacts of the 2021 mid-July western European flood event. Natural Hazards and Earth System Sciences, 22(12), 3831–3838. https://doi.org/10.5194/nhess-22-3831-2022

Kwakkel, J. H., Haasnoot, M., & Walker, W. A. (2016). Coping with the Wickedness of Public Policy Problems: Approaches for Decision Making under Deep Uncertainty. Journal of Water Resources Planning and Management, 142(3). https://doi.org/10.1061/(asce)wr.1943-5452.0000626

Kwakkel, J.H. & Haasnoot, M. (2019) Supporting decision making under deep uncertainty: a synthesis of approaches and techniques, in Decision Making Under Deep Uncertainty – From Theory to Practice, Marchau, V.A.W.J., Walker, W.E., Bloemen, P, Popper, S.W. (eds).

Rijkswaterstaat. (2023). Minst gepeilde diepten. Vaarweeg Informatie. https://www.vaarweginformatie.nl/frp/main/#/hydro/mgd

Rijkswaterstaat (2020) Richtlijnen Vaarwegen, Rijkswaterstaat Water

Spencer, T. J., Brooks, S. V., Evans, B. J., Tempest, J. A., & Möller, I. (2015). Southern North Sea storm surge event of 5 December 2013: Water levels, waves and coastal impacts. Earth-Science Reviews, 146, 120–145. https://doi.org/10.1016/j.earscirev.2015.04.002

Appendix

Appendix A. Figures and tables of modeling process

Appendix A.1. Policy lever values

The figure below contains the included policies levers with the corresponding values. The policy lever variable names can be interpreted as follows:

- Dike heightening: A.{*Dike Ring*} {*Time step*}
- Room for the River: {*Location*}_RfR {*Time step*}

The values can be interpreted as follows:

- Dike heightening: 5 dm increase (medium) and 10 dm increase (high)
- Room for the River: 0 (no Room for the River) and 1 (Room for the River)

	P0	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P22	P23	P24	P25	P26	P27	P28	P29	P30
A.1 0	0	5	10	5	0	0	0	0	10	0	0	0	0	10	0	10	0	0	0	0	0	0	0	0	0	0	0	5	10	10
A.1 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0	0	0
A.1 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0
A.2 0	0	5	10	0	5	0	0	0	0	10	0	0	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	5	10	5
A.2 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0	0	0
A.2 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0
A.3 0	0	5	10	0	0	5	0	0	0	0	10	0	0	10	0	10	0	0	0	0	0	0	0	0	0	0	0	5	10	10
A.3 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0	0	0
A.3 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0
A.4 0	0	5	10	0	0	0	5	0	0	0	0	10	0	0	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A.4 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0	0	0
A.4 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0
A.5 0	0	5	10	0	0	0	0	5	0	0	0	0	10	10	0	10	0	0	0	0	0	0	0	0	0	0	0	5	10	10
A.5 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0	0	0
A.5 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	10	0	0	0	0	0
0_RfR 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
0_RfR 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
0_RfR 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
1_RfR 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
1_RfR 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
1_RfR 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2_RfR 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2_RfR 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
2_RfR 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
3_RfR 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1
3_RfR 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
3_RfR 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
4_RfR 0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
4_RfR 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
4_RfR 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

Figure 11: Overview policy lever values model exploration

Appendix A.2. Results

In the figure below, the mean values of the criteria per policy used during the model exploration are shown. As can be seen, a combination of several policy interventions on multiple locations is the most effective to reduce the expected annual damage and expected number of deaths. Nevertheless, this combination also requires a lot of financial sources as the investment costs rise.

These results are based on 50 scenarios of every policy. This is sufficient to gather general insights of the model. However, these average results of this model exploration can also be affected due to the limited run scenarios if many outliers are present in the data.

Policy number	Policy description	Expected annual damage*	Dike investment costs*	RfR investment costs*	Expected Number of Deaths
P0	BAU	1772,56	0,00	0,00	1,67
P1	Medium DH for every DR	175,37	189,93	0,00	0,20
P2	High DH for every DR	2,88	317,41	0,00	0,00
P3	Medium DH for DR1	971,14	53,97	0,00	1,32
P4	Medium DH for DR2	1787,35	59,41	0,00	1,74
P5	Medium DH for DR3	1470,71	28,80	0,00	1,10
P6	Medium DH for DR4	1843,13	11,07	0,00	1,78
P7	Medium DH for DR5	1784,25	36,68	0,00	1,72
P8	High DH for DR1	861,65	95,11	0,00	1,17
P9	High DH for DR2	1790,05	99,53	0,00	1,77
P10	High DH for DR3	1411,47	44,22	0,00	1,02
P11	High DH for DR4	1866,80	20,38	0,00	1,80
P12	High DH for DR5	1821,94	58,18	0,00	1,74
P13	High DH for DR1, 3 and 5	262,21	197,50	0,00	0,21
P14	Medium DH for DR2 and 4	1798,53	70,48	0,00	1,80
P15	High DH for DR1, 3, and 5; Medium DH for DR2 and 4	20,79	267,98	0,00	0,17
P16	RfR on location 1	1180,25	0,00	84,60	1,36
P17	RfR on location 2	1213,97	0,00	217,80	1,37
P18	RfR on location 3	1573,88	0,00	30,70	1,35
P19	RfR on location 4	1642,6	0,00	121,20	1,5
P20	RfR on location 5	1746,81	0,00	256,10	1,65
P21	RrF on every location	674,07	0,00	710,40	0,77
P22	Medium DH for every DR (timestep 1)	687,20	189,92	0,00	0,65
P23	High DH for every DR (timestep 1)	604,66	317,41	0,00	0,56
P24	Medium DH for every DR (timestep 2)	1243,58	189,92	0,00	1,16
P25	High DH for every DR (timestep 2)	1202,3	317,41	0,00	1,12
P26	RfR on every location (timestep 1)	543,73	0,00	710,40	0,61
P27	RfR on every location (timestep 2)	543,73	0,00	710,40	0,61
P28	Medium DH for DR1, 2, 3 and 5; RfR on location 4	140,67	178,86	121,20	0,12
P29	High DH for DR1, 2, 3 and 5; RfR on location 4	25,23	297,02	121,20	0,02
P30	High DH for DR1, 3 and 5; Medium DH for DR2 and RfR on DR4	57,80	256,91	121,20	0,04

*in millions (€)

Figure 12: Results per policy of model exploration (means)

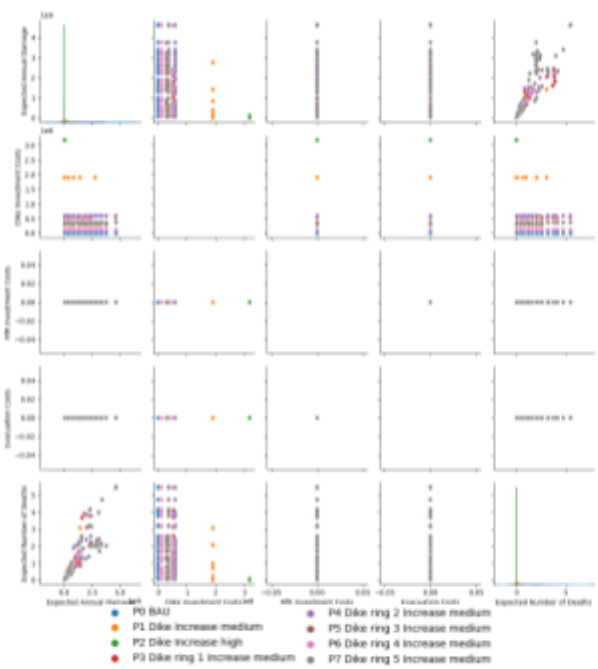

Figure 1.1: Model exploration output graph P0 - P7

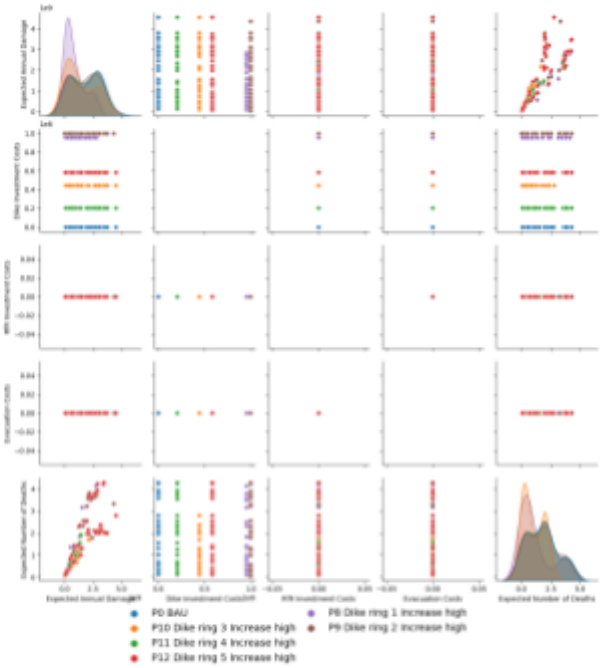

Figure 1.2: Model exploration output graph P0, P8 - P12

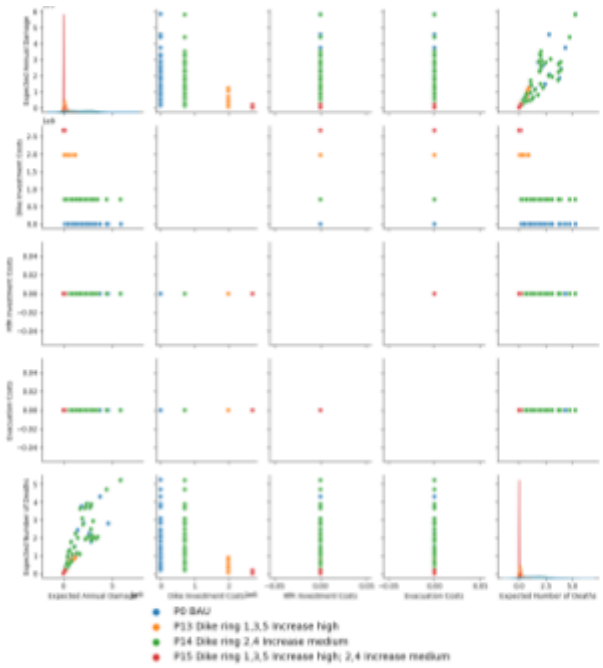

Figure 1.3: Model exploration output graph P0, P13 - P15

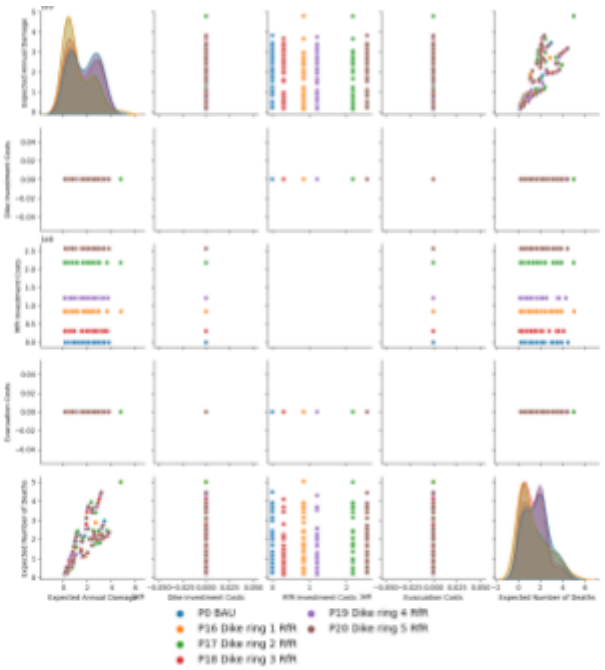

Figure 1.4: Model exploration output graph P0, P16 - P20

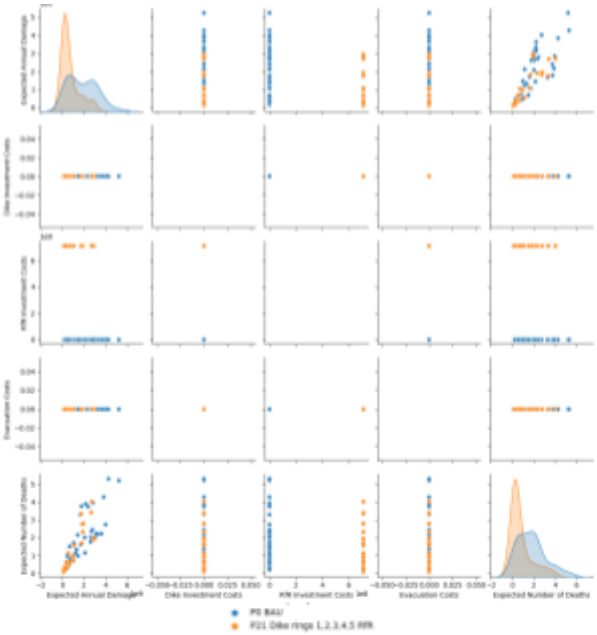

Figure 1.5: Model exploration output graph P0 & P21

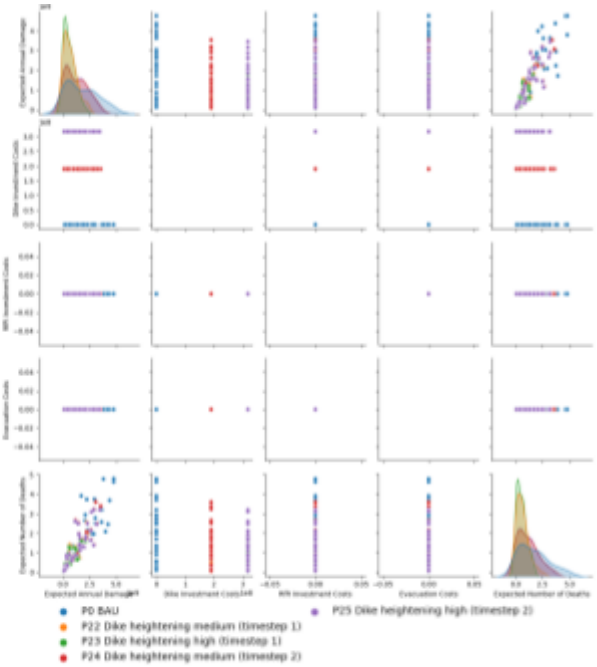

Figure 1.6: Model exploration output graph P0, P22 - P24

Appendix A.3. Results Scenario Discovery

Figure 13: First results from scenario discovery using 1,000 scenarios and 10 policies

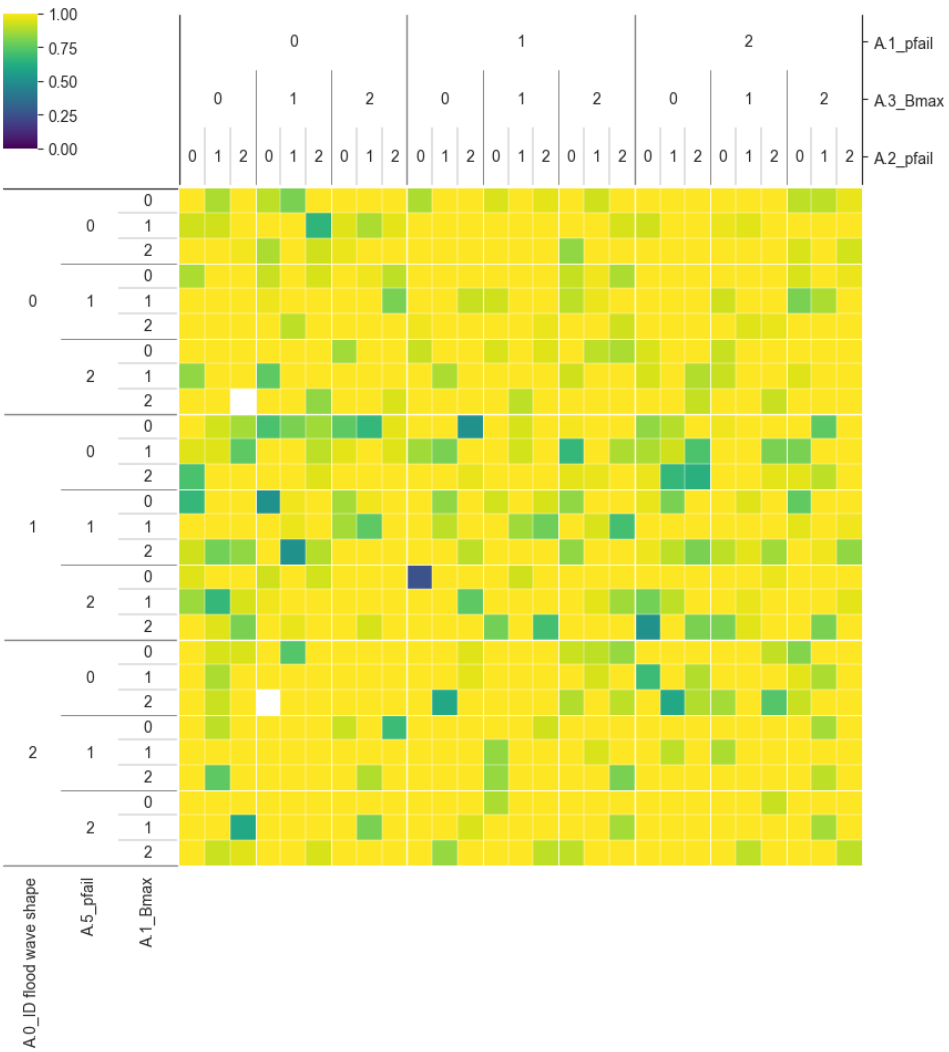

Figure 14: Results from dimensional stacking worst-case scenario analysis

Table 4: Seed values for reference scenario for first iteration of MORDM.

Variable	**Value**
discount rate 0	2.5
discount rate 1	2.5
discount rate 2	2.5
A.0_ID flood wave shape	75
A.1_Bmax	190
A.2_Bmax	190
A.3_Bmax	190
A.4_Bmax	190
A.5_Bmax	190

A.1_pfail	0.903212-0.000009/2
A.2_pfail	0.5
A.3_pfail	0.5
A.4_pfail	0.5
A.5_pfail	0.5
A.1_Brate	1.5
A.2_Brate	1.5
A.3_Brate	1.5
A.4_Brate	1.5
A.5_Brate	1.5

Appendix A.4. Results MORDM - First Iteration

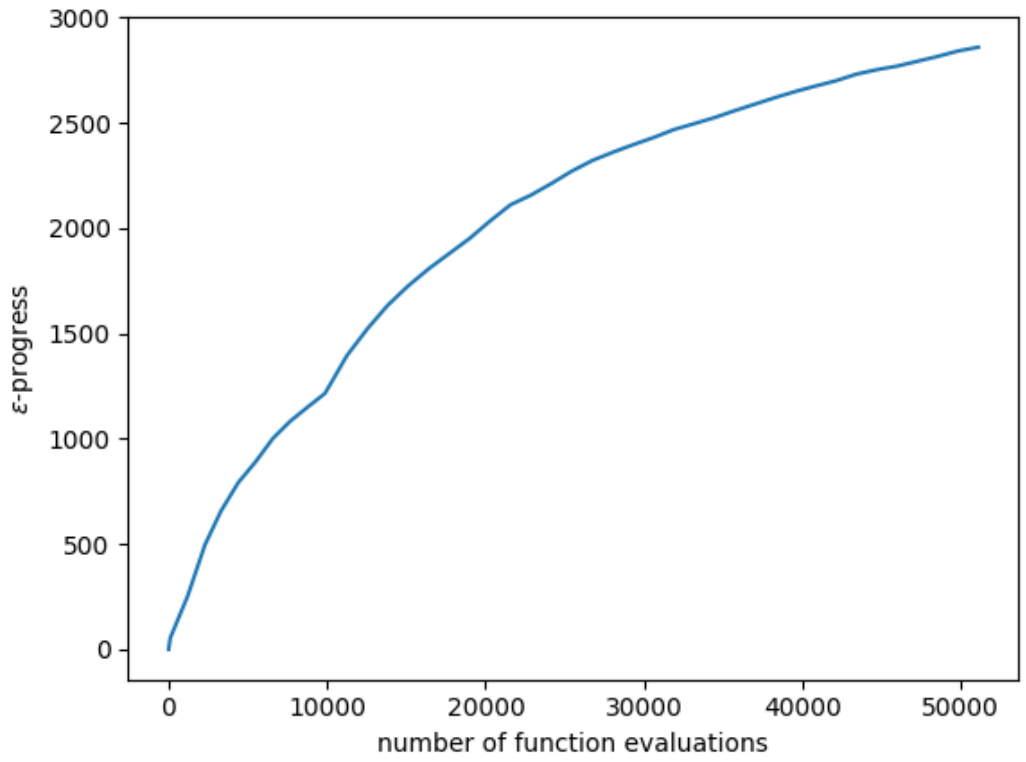

Figure 15; Convergence plot for first iteration of MORDM. Epsilon= 0.1 | nfe= 50,000

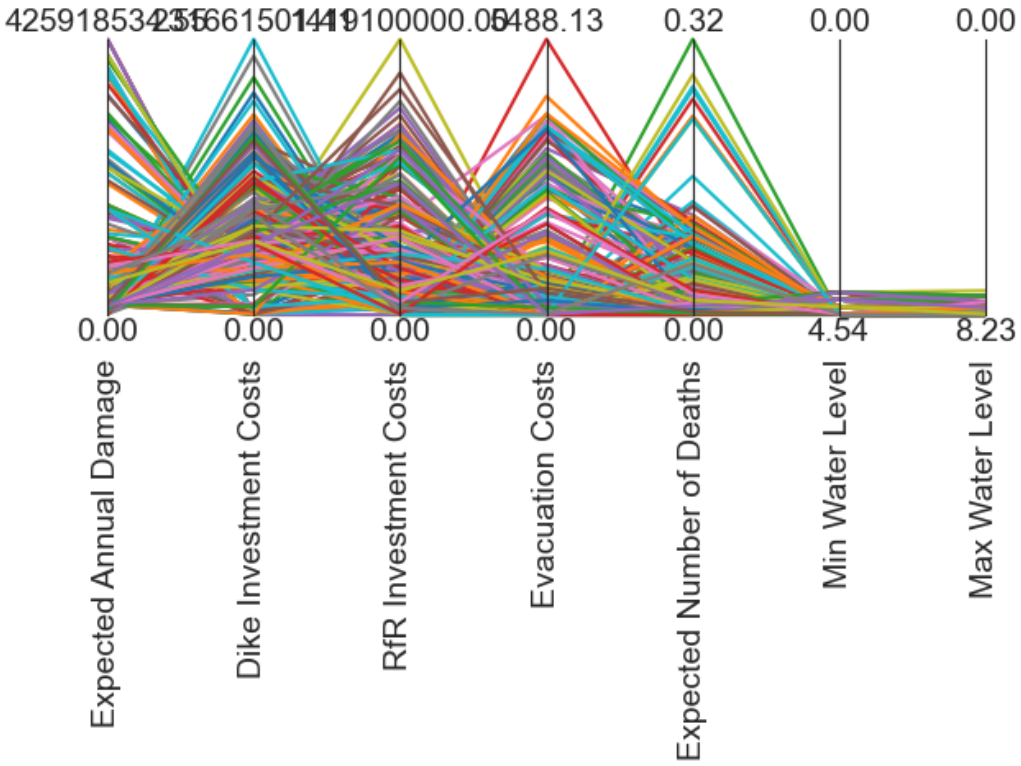

Figure 16; Parallel coordinates plot for first iteration of MORDM

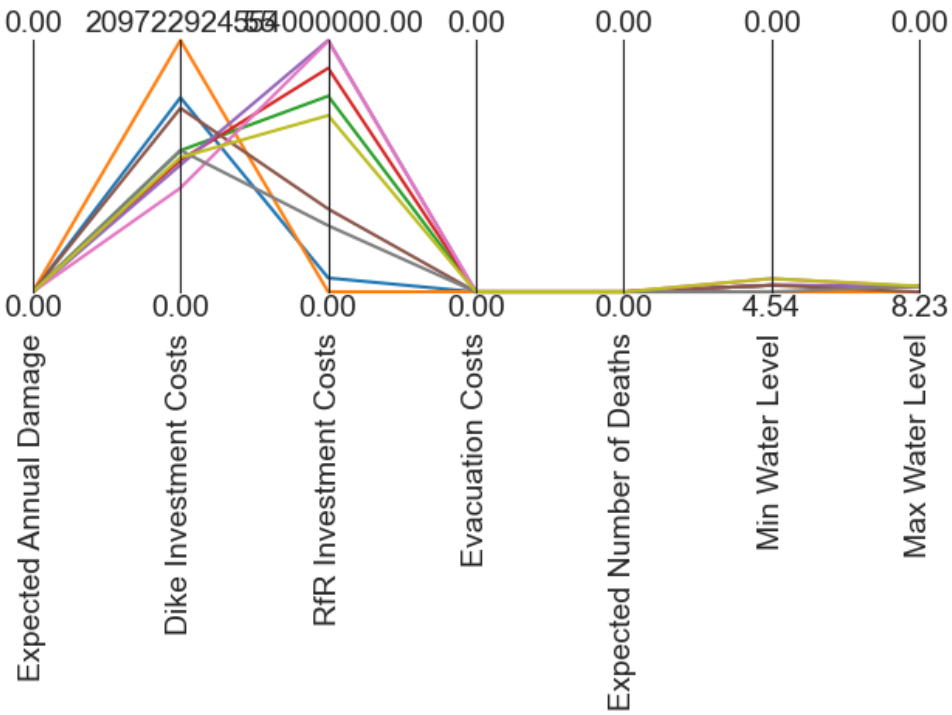

Figure 17; Parallel coordinates plot for policies where EAD=0, for first iteration of MORDM

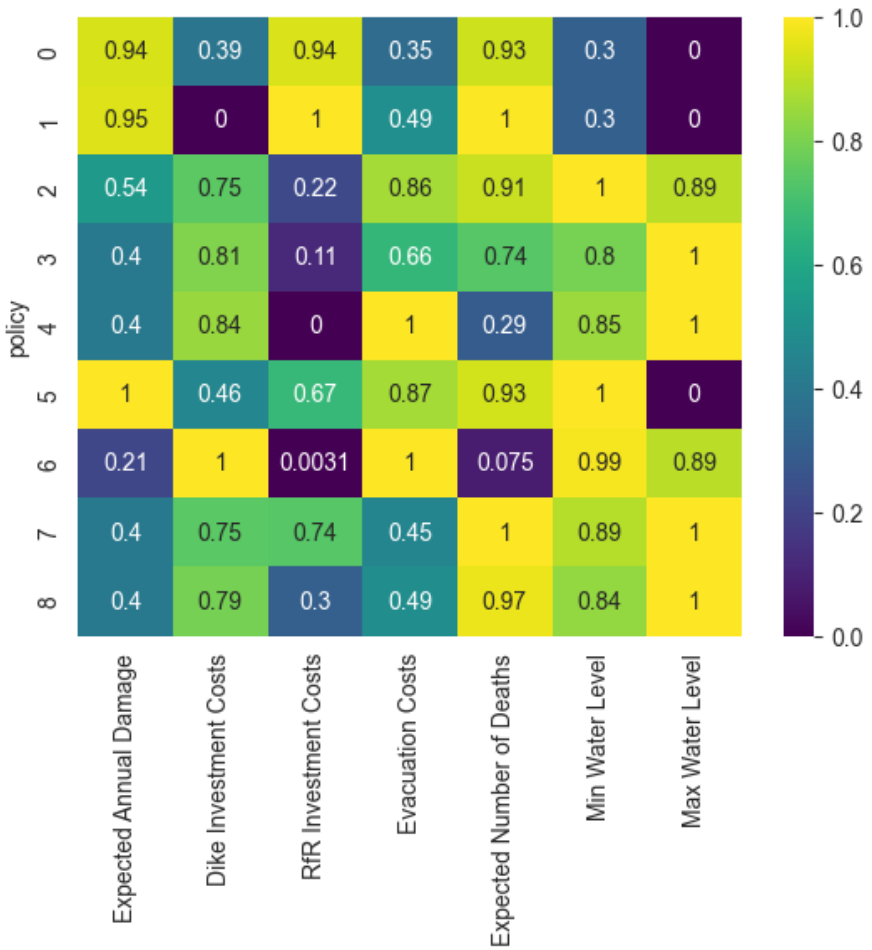

Figure 18; Regret matrix for first iteration of MORDM

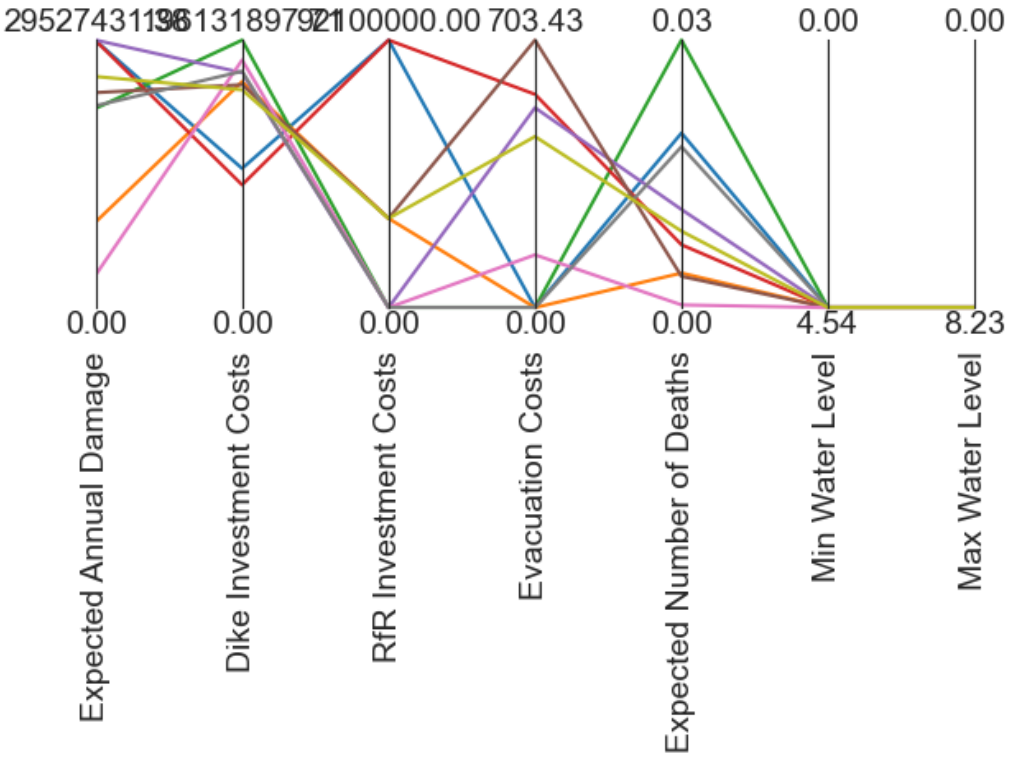

Figure 19; Parallel coordinates plot for second iteration of MORDM for policies where: min water level = 0, Investment costs < 200M, EAD < 5th percentile

Appendix A.4. Results Global Sensitivity Analysis

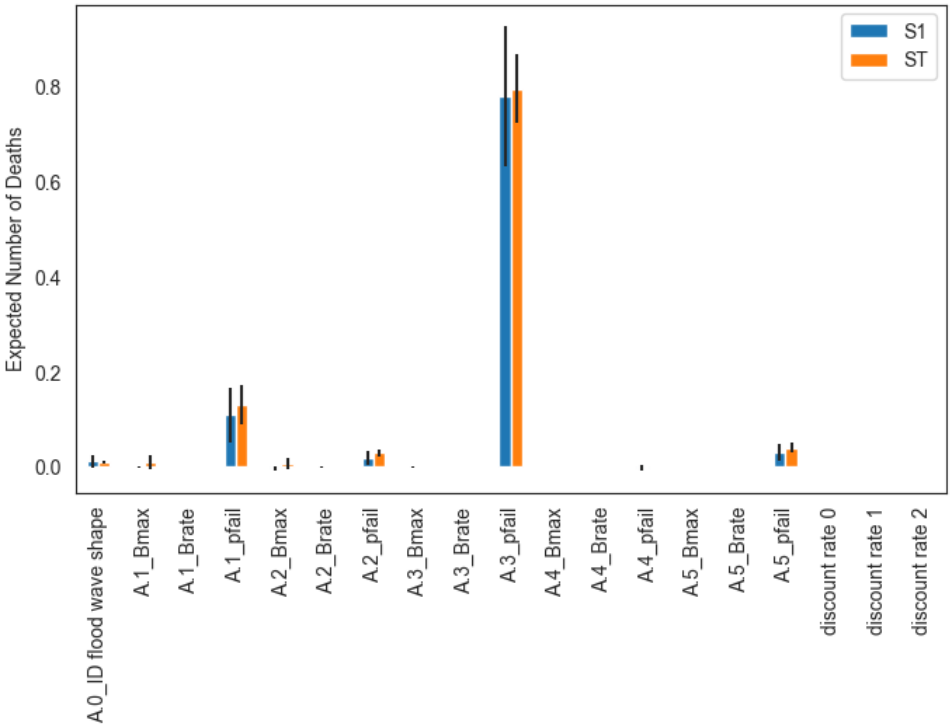

Figure 20: GSA Sobol results for END parameter, policy 1412

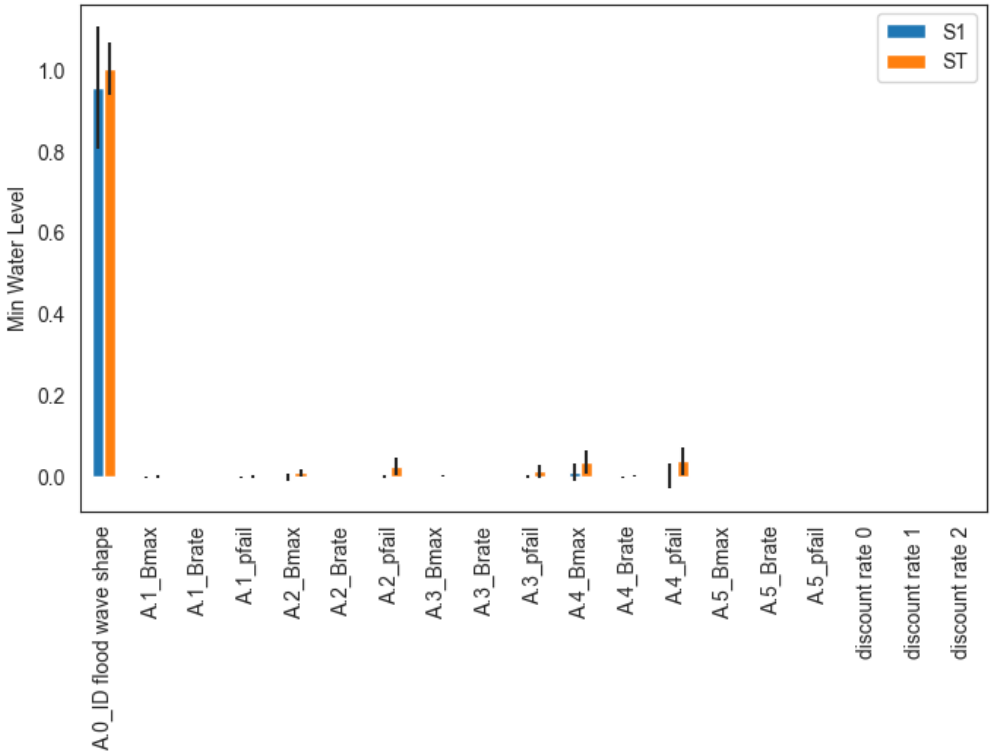

Figure 21: GSA Sobol results for Min Water Level parameter, policy 1412

Appendix B. Code

The code repository including all Jupyter notebooks used to create this study can be found in; https://github.com/florihu/MBDM_Group5/

Appendix C. External Factors, Levers and Measures

Table 5 ***X*** Uncertain external factors

type	name	values	description	dimension	notes
categorical	discount rate {timestep}	1.5, 2.5, 3.5, 4.5	discount rate for calculating present day value of damages	dmnl	
integer	A.0_ID flood wave shape	0-132	a normalized curve describing the shape of the incomming flood wave over time. There are 132 predefined curves.	dmnl	
real	A.{dike_ring}_Bmax	30-350	the final extent of the breach width. The greater the width, the larger the volume of water that enters the floodplain per unit of time	meters	Dike ring 1-5
real	A.{dike_ring}_pfail	0-1	probability that the dike will withstand the hydraulic load	dmnl	
categorical	A.{dike_ring}_Brate	0, 1.5, 10	How fast the breach grows over time.	1/day	

Table 6: ***L - Levers***

type	name	values	Description	dimension	notes
integer	{location}_RfR {timestep}	0-1	Whether to activate the RfR project at the specified location or not. Once activated, the project remains active.	dmnl	0-4 locations
integer	EWS_DaysToThreat	0-4	Number of days prior to threat to give a warning. False warnings can undermine trust in the system. The earlier the warning the more time to evacuate, but also the more chance of a false warning.	days	
integer	A.{dike_ring}_DikeIncrease {timestep}	0-10	amount of dike raising	decimeter	