# IJssel River. Flood Risk Management Report

## Model-Based Analysis Report

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# Summary

This report explores a model-based driven solution for a multi-actor problem scenario in order to offer a solid planification for meeting the security and safety challenges presented by the flood risks along the IJssel River without making other aspects of inhabitants' lifes a tradeoff (e.g., economic activity from transport or agriculture, biodiversity, cultural and historical areas, etc.). Thus, from the perspective of the central actor, Rijkswaterstaat, policies that integrate all actors in this *Flood Risk Management Plan for the Upper Branch of the IJssel River* were explored. The key performance indicators used were the Expected annual damage, Expected number of deaths, Room for the River (RfR) costs, Dike heightening costs and Evacuation costs. These costs were aggregated as Total costs and along with the Expected deaths, disaggregated by location to have a clear view of the spatial distribution of the impacts.

The research is deeply embedded within the multi-actor arena of the decision-making process, which proves to be a significant challenge for modeling purposes. This is presented as a multi-level governance challenge to bring all stakeholders into a common understanding and agreement (Rijke et al., 2012).

Therefore, the approach is based on a combination of explorative and optimization of the model. First, the exploratory approach obtains extreme results of *not doing nothing* (BAU), *all RfR*, *all Dike Heightening* and the *proposed policy from the actor debates*, so a path could be outlined. Then, during the optimization phase, the best combination of possible interventions (levers) is checked according to the desirable key performance indicators.

From the open exploration it became clear that both dike heightening and Room for the River measures are very effective in decreasing the expected number of deaths and the amount of damage. Within the optimization no clear policy direction was found. After re-evaluation 24 possible policies were formed. These policies are very widely spread over the uncertainty and policy lever space, making it difficult to select a clear set of best policies.

It is recommended to investigate these 24 polices more in depth with the wishes and demands of the involved actors taken into account. Furthermore is it recommended to further investigate the optimization with more constraints to further reduce the possible policies and ensure a more clear policy direction.

In general Rijkswaterstaat is recommended to apply a diverse policy which incorporates a mix of dike heightening and room for the river measures to ensure the safety of the IJssel river area and incorporate the wishes and demands of the actors involved.

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# 1. Problem Framing

Flood Risk Management awareness is a real concern in The Netherlands since the last century, but especially arose by the floods of 1993 and 1995 (Baan & Klijn, 2004; Rijkswaterstaat Room for the River [RfR], 2013; De Bruijn et al., 2015). As Kwakkel et al. (2016) pointed out, water resources planning is considered a wicked problem, where modeling, simulation and optimisation cannot be straightforwardly applied. Thus, a different way of functioning is being used, considering all the stakeholders as well as new technical solutions like room-for-the-river (RfR) to tackle flood management.

RfR is used not as a substitute but to complement the strategy of dike heightening and reinforcement, which is thought to be limited and/or not enough (Baan & Klijn, 2004). These concerns and actions are mainly due to the fact that "extreme weather events are expected to occur more frequently, rising flood risks", especially in low-lying countries (Caloia & Jansen, 2021). Accordingly, the aim of this report is to provide a robust solution accepted by all stakeholders and actors along the IJssel River, representing the role of the main actor, Rijkswaterstaat (see Fig. 1).

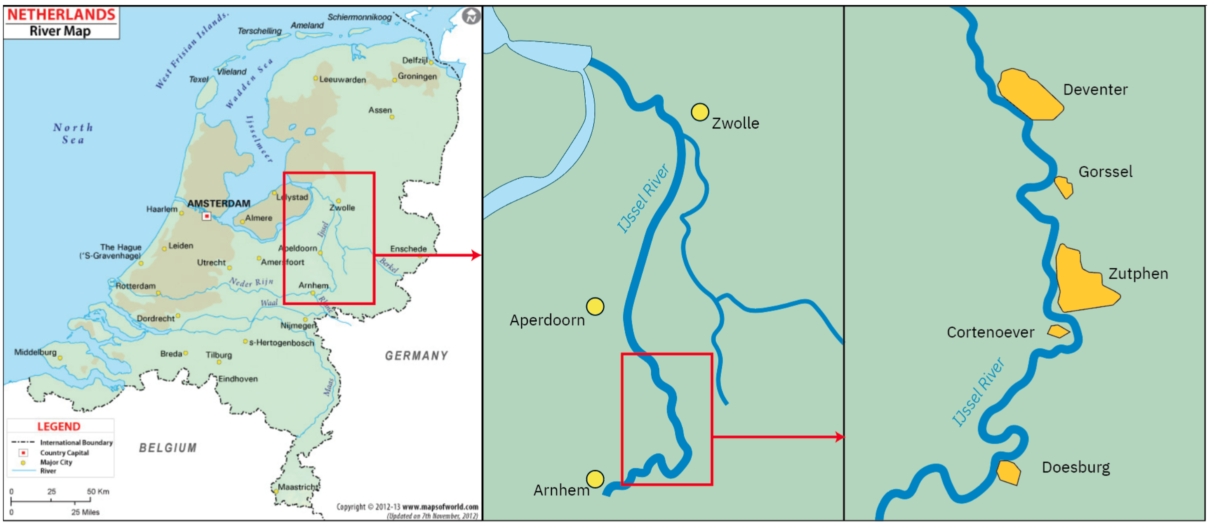


**Fig. 1.1.** IJssel River Map and Area of action of the project ("Netherlands River Map," 2021).

As Rijkswaterstaat, the following mandates have to be complied:

1. Propose a robust policy, in line with the political vision of the Delta Commission, and with enough support to be adopted, aiming for unanimity.
2. The policy presented has to deliver actual and specific policies, rather than an agreement of future deliberation.
3. The goal is to present 'the best possible' policy. This translates into fewer casualties and costs as possible.

The project's problem framing relies on the consideration of the different actors and their interests in the development of a policy through a multi-actor decision-making process. This problem is reinforced by the implied uncertainty of forecasting future events (Walker et al., 2013) and by the necessity of achieving a broad or unanimous consensus. Furthermore, apart from the aims of each actor and their dependency on external factors — e.g., land use, urban planning, etc — the project would hold the policy by model-driven approaches, so uncertainty and lack of consensus can be cleared by evidence-sustained proposals (Kwakkel et al., 2015). Therefore, as Rijkswaterstaat, the research was driven by a key objective: to provide a robust and specific policy that is widely accepted by — ideally — all actors. Thus, a model overview is made below to explain how it operates and what are the possibilities and outcomes it provides.

## 1.1 Model Overview

Under the broad objective, we seek a comprehensive solution across the entire river basin, using a model that simulates the propagation of the flood hydrograph throughout the river channel was employed using the Exploratory Modeling Workbench, a tool that can be used to support decision-making under deep uncertainty (Kwakkel, 2017a). This model is based on the response of the infrastructure (dike system) to the multiple possible scenarios at the scoped locations, and uses different problem formulations (see Table 1) that follow the XLRM Framework (Lempert et al., 2003), outlined in Fig. 2.

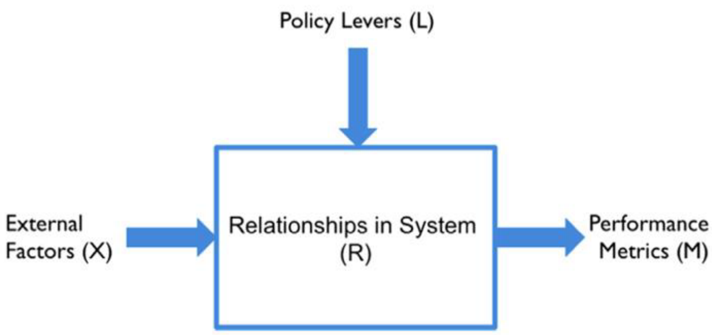


**Fig. 1.2.** XLRM Framework. Where External factors (X) represent uncertainties that affect the performance of the system which policymakers have little or no control on; Levers (L) are the set of policies studied or decision variables; Performance metrics (M) are indicators assessing how the levers perform; Relationships (R) are a set of rules or mathematical expressions linking X, L and M.

Following the possible problem formulations (Table 1) and having in mind the goals of Rijkswaterstaat (consensus and efficacy on the policy) the chosen formulation is the third. It was considered important to know the origin of the different results for the argumentation with the different stakeholders, where a balance between the placement of the measures was stated from the beginning. The possible levers to do so are stated in Annex C, where all the factors for the model from within the XLRM framework are detailed.

**Table 1.1.** Overview of the different problem formulations and its outcomes.

| Outcomes | PF 0 | PF 1 | PF2 | PF 3 | PF 4 | PF 5 |
|---|---|---|---|---|---|---|
| Expected Annual Damage | ✖ | ✖ | ✖ | | ✖ | |
| Total Investment Costs | | ✖ | | | | |
| Dike Investment Costs | | | ✖ | | ✖ | |
| RfR Investment Costs | | | ✖ | ✖ | ✖ | |
| Evacuation Costs | | | ✖ | ✖ | ✖ | ✖ |
| Total Costs | | | | ✖ | | ✖ |
| Expected Number of Deaths | ✖ | ✖ | ✖ | ✖ | ✖ | |

In order to discover the best levers combination (see Appendix C), first there is an exploratory phase using PF2, followed by an optimization phase using PF3 to account for some effects in terms of costs and safety, and how it is distributed by locations. This approach continues, as is being explained in detail in Section 2. According to our mandate and key objectives, there are no fixed thresholds apart from the preferences of the provinces and other actors (see Appendix A). However, safety and security, in the long run, are treated as a big concern. Therefore, a threshold will be set for the number of deaths. An additional target of Rijkswaterstaat is minimizing costs.

Therefore, the project is structured from a deep understanding of both model and actors' interests to the advice model-based policy. Thus, this report is structured explaining the approach used and the methodology followed, then, the results obtained from the models are shown and explained. Finally, a discussion around those results and a conclusion with the policy advice is formulated.

# 2. Methodology

For this analysis, exploratory modeling approaches are used, which are extremely valuable when critical information is unavailable, and such is the case in policy analysis due to significant uncertainties (Bankes, 1993). The analysis is performed using the Exploratory Modeling Workbench implemented in Python, which allows to easily perform exploratory modeling with existing models under deep uncertainty (Kwakkel, 2017). In this report, first open exploration is used to generate, among three other policies, a base scenario with no policies affecting the outcomes. This was followed by optimization and robustness methods to determine the most robust strategies.

## 2.1 Open exploration

To get an initial understanding of the model and the options for the policy development an open exploration was performed. This exploration consisted of four policies of which three represent extreme situations and the fourth represents the policy developed within the two debates with the six voting actors. The first policy included a Business-As-Usual (BAU) scenario, which sets all levers to zero for every time step. The second policy calculated the outcomes for a scenario where only dike heightening takes place. Within this scenario the dikes are increased with 5 dm at every location at every time step. The third scenario entails an only Room for the River (RfR) policy, which employs room for the river at every possible location at every timestep. The fourth scenario describes the accepted policy by the actors, which employs RfR at locations 0, 1 and 2 for every timestep, dike heightening at locations 3 and 5 with 3 dm every timestep and the policy includes an early warning system of 3 days. The results were obtained by running the ema-workbench with 200 scenarios and for Problem Formulation 2 (PF2). This aggregated formulation was chosen to get a clear overview of the results for the whole IJssel area.

## 2.2 Multi-Objective Robust Decision Making (MORDM)

Although MORO (Multi-Objective Robust Optimization) was the first approach considered to get to the most robust policies, as this is one of the main goals of Rijkswaterstaat, it was not possible to perform this high quality methodology due to the lack of computational power within the group (see Section 2.3). Therefore, it was decided to perform the MORDM approach which also proves to have advantages, offering a balance between optimality in various reference scenarios and robustness over a larger ensemble, while requiring only a relatively modest increase in computation costs as compared to MORO (Bartholomew & Kwakkel, 2020). It enables the generation of planning alternatives that show key tradeoffs on set objectives by performing optimization search prior to scenario discovery (Watson & Kasprzyk, 2017).

Figure 2.1 shows the steps of the MORDM approach. The first step, the problem specification, is done to determine the outcomes of interests and get a better understanding of the problem. A more detailed description of the problem specification can be found in chapter 1.

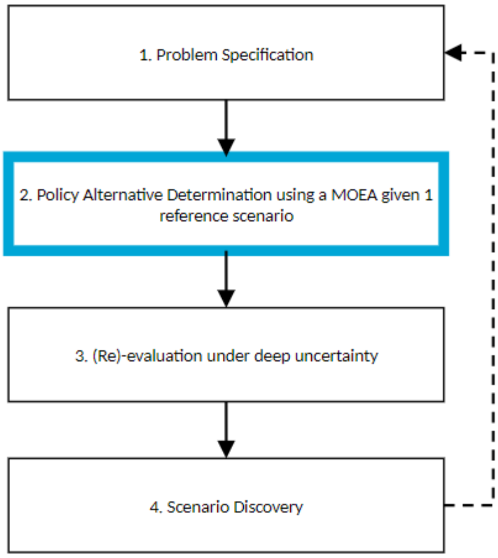


**Figure 2.1.** MORDM approach flowchart.

After the problem specification step, a pool of candidate strategies is generated using Multi-Objective Evolutionary Algorithms (MOEAs). This pool of candidate strategies defines the best possible trade-offs. The algorithms select the Pareto optimal solutions that optimize the different outcomes. For this research, optimizing the outcomes means that all outcomes need to be minimized. The optimization is done over a single reference scenario, which includes the averages of all uncertainty values. The exact values used for the reference scenario are shown in Table 2.

**Table 2.1**. Values used in the reference scenario

| **Uncertainty** | **Value** |
|---|---|
| Discount rate | 2.5 |
| Flood wave shape | 75 |
| Final breach width | 190 m |
| Breach width model | 1.5 /day |
| Dike failure probability | 0.5 |

The optimization is run for an epsilon-value of 0.25 and 10 000 function evaluations. The number of function evaluations resulted from a tradeoff between convergence and computational intensity. After 10 000 function evaluations, the model converged. An epsilon of 0.25 was chosen to get a desired amount of candidate strategies. After the optimization, a hard constraint was set for the average number of deaths, which should not be more than 0.005 for the whole IJssel river area. The policies that do not meet this threshold will not be considered within the rest of the analysis. The remaining pool of candidate strategies is then evaluated under deep uncertainty by re-evaluating every policy over 1000 scenarios. The number of scenarios used is again a tradeoff between a good evaluation and computational power.

After the selection of candidate solutions is obtained, Scenario Discovery (SD) is applied. SD is an approach to participatory computer-assisted scenario development which assists policy-makers and analysts in identifying policy-relevant scenarios by interactively applying statistical and data-mining algorithms to large databases of simulation-model results (Bryant & Lempert, 2010). In this research, after the evaluation under deep uncertainty, scenario discovery is used to determine the parameter ranges that cause the outcomes of interests and thus discover the vulnerabilities of the candidate strategies. The scenario discovery will consider the expected number of deaths. While a constraint was already set to keep the average number of deaths below 0.005, it is also important that the number of deaths are distributed equally. Therefore the scenario discovery will find the range of values for the uncertainties that result in the expected number of deaths being below 0.001 for all five locations.

To test the robustness of the candidate solutions, the signal-to-noise ratio (or mean-variance metric) and the maximum regret robustness metrics are used. The mean-variance metric is a descriptive analysis tool, which attempts to balance the mean and variability of the performance of a decision alternative over different scenarios (McPhail et al., 2018). Since all outcomes need to be minimized, the signal-to-noise ratio is calculated by multiplying the mean by the standard deviation. The maximum regret robustness metric is the difference between the performance of a candidate solution in a specific scenario and the best possible performance of a candidate solution in that scenario (Savage, 1951, as cited in McPhail et al., 2018). The maximum regret is the maximum regret value of a policy across all scenarios. Candidate solutions with a low maximum regret are favored.

## 2.3 Multi-Objective Robust Optimization (MORO)

In the following section the steps followed for the MORO methodology are described, however due to technical issues no results were obtained.

Analyzing the robustness of solutions is critical to determine the effectiveness of policies. While the MORO approach has high computational costs compared to MORDM and multi-scenario MORDM, it has the strongest guarantee of robustness even after re-evaluation as well as smaller ensembles of scenarios requirements (Bartholomew & Kwakkel, 2020). These advantages, paired with a clear focus on model robustness lead to the choice of MORO as the preferred method for candidate solutions.

After the problem specification step, the MORO approach is similar to the MORDM approach. For this research, a domain criterion was intended as a robustness metric for the expected number of deaths. This metric calculates the fraction of scenarios below our threshold. Optimization is used to maximize this fraction. For the total costs, RfR costs, and the expected evacuation costs, the raw costs were minimized. The optimization was performed for all outcomes over 50 scenarios and 5000 function evaluations.

The generated pool of candidate strategies was then evaluated under deep uncertainty by increasing the number of scenarios to 100. The results of this evaluation were then used in scenario discovery, to determine the parameter ranges that cause the outcomes of interests.

After the evaluation under deep uncertainty, scenario discovery was used to determine the parameter ranges that cause the outcomes of interests and thus discover the vulnerabilities of the candidate strategies.

After running the optimization, the Jupyter notebook crashed before the results could be saved properly. Since the MORO approach has high computational costs, it was chosen to not run the MORO script again, but to focus on the MORDM approach.

# 3. Results

## 3.1 Open exploration

Based on the parameters described in Section 2.1, results for the open exploration were obtained (Figure 3.1.)

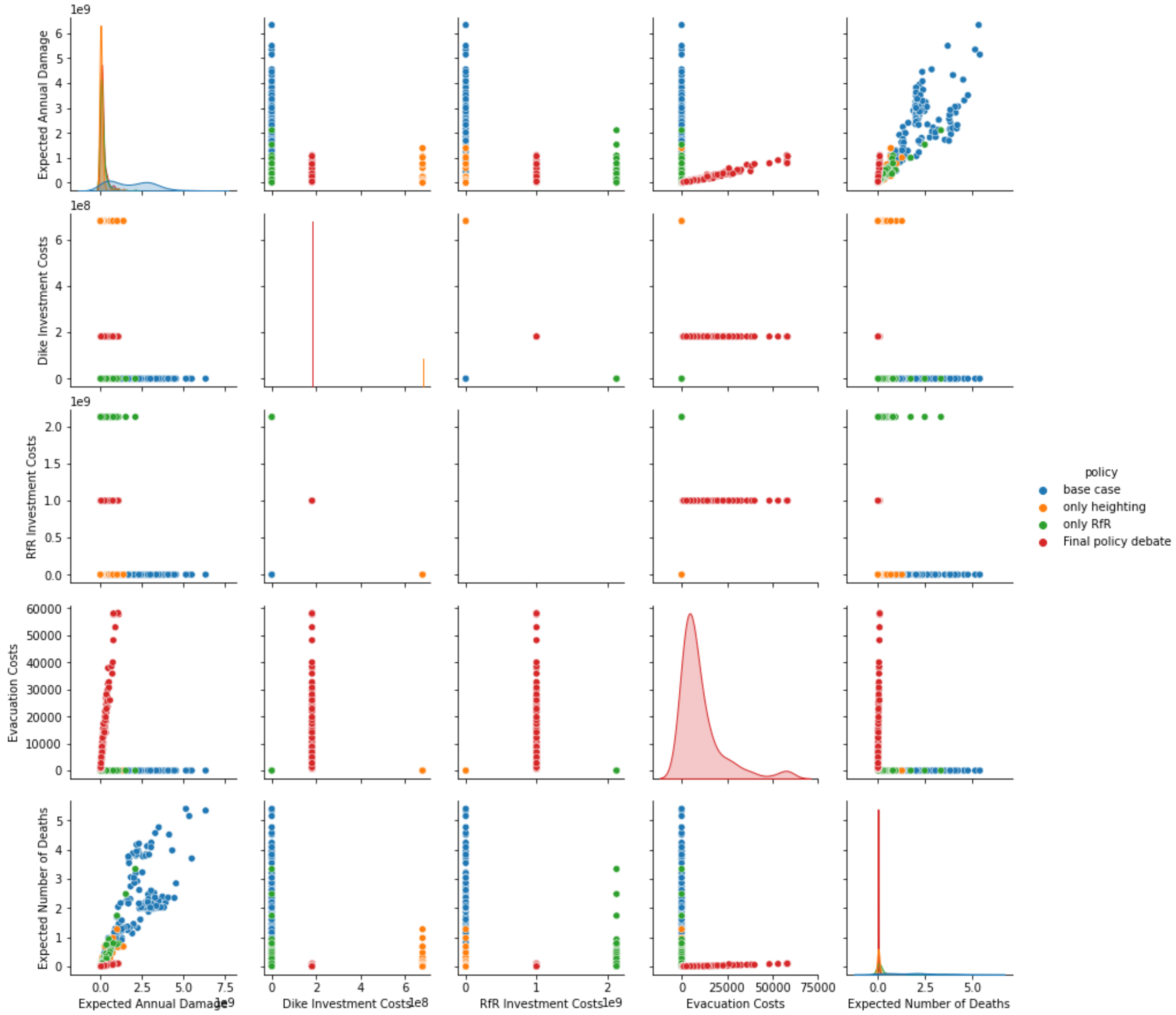


**Figure 3.1.** Results of open exploration.

From figure 3.1 it can be seen that for the base scenario the number of deaths and the expected amount of damage are highest, supporting the need for adaptations in the region to reduce the flood risk and risk for damages. Furthermore, it is also visible that both dike heightening and the Room for the River project significantly decrease the amount of deaths and damages. When looking at the graphs which display the investment costs for the dike heightening and RfR versus the expected amount of damage, it is visible that both policies have a similar effect on the costs of damages, despite having significantly different investments. This also highlights the need for mixed solutions, since both solutions have advantages and disadvantages. A mixed solutions approach is represented by the policy that was agreed upon in the final debate. Figure 3.1 shows that this policy reduces the number of deaths as well as the damage even more. However, there is a tradeoff between casualties and damage, and costs since this policy increases the evacuation costs and also results in investment costs for dike heightening and RfR.

## 3.2 MORDM

The MORDM optimization was run with problem formulation 3, 10 000 nfe's and an epsilon of 0.25. From this the model found 395 possible solutions. Within figure 3.2 the convergence of the model is shown. As is visible, the model converges around the 10 000 evaluations, however for security it would be better to run the model with a lot more evaluations to be sure of the convergence.

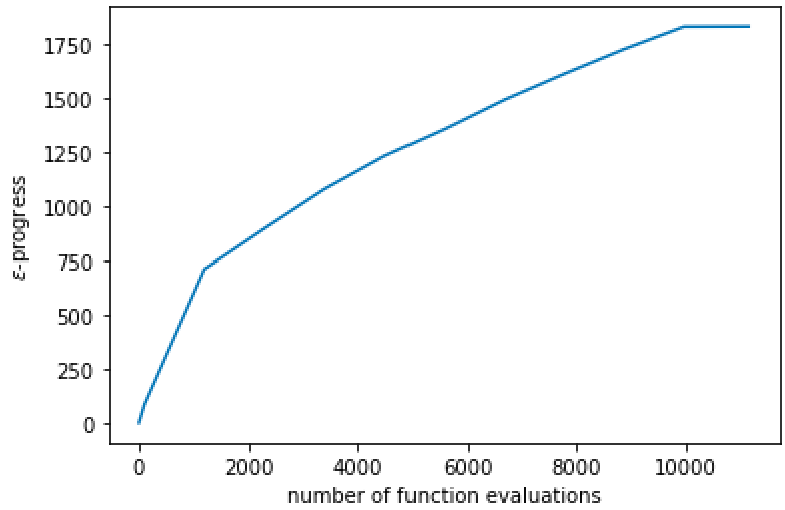


**Figure 3.2.** Convergence of the MORDM

In figure 3.3 the trade-offs between the different policy solutions are shown. However this figure is very unclear due to the large amounts of found solutions. So no conclusions can be extracted from it for a policy direction.

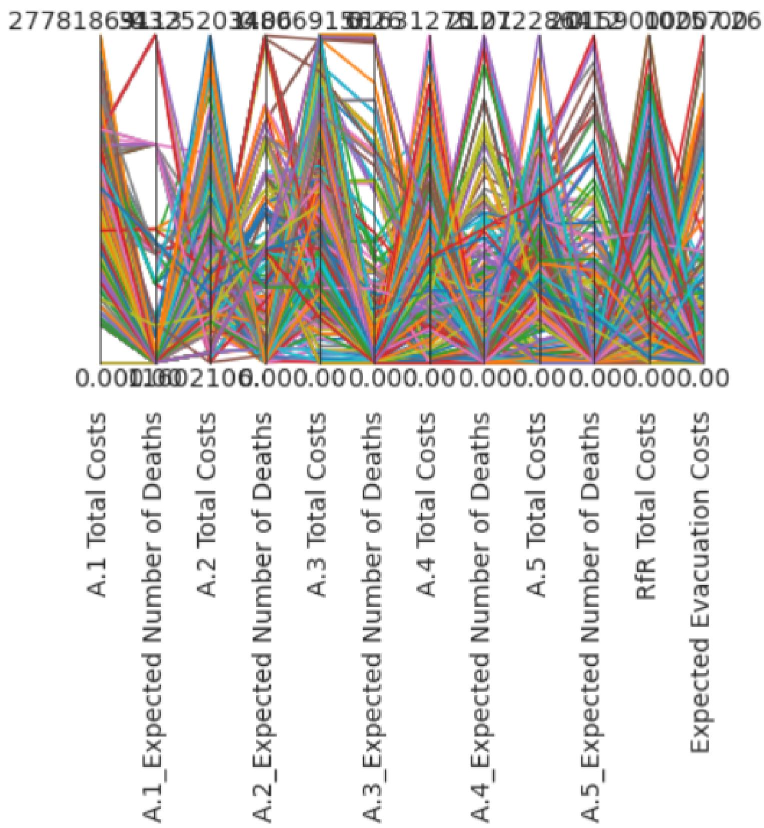


**Figure 3.3.** Parcoords plot

### 3.2.1 Scenario discovery

Due to the large number of possible solutions a re-evaluation was done for scenario discovery. This re-evaluation was done with 1000 scenarios per possible policy. Additionally an extra constraint was set, where scenarios with an average expected deaths higher than 0.001 were discarded. This reduced the number of possible scenarios to 24.

In figure 3.4 the trade off between the coverage and the density of the solutions that were found by the PRIM algorithm. The coverage shows the ratio between the number of cases of interest in a box versus the total number of cases of interest, meaning a high coverage is preferred as this box will then contain a large amount of cases of interest (Bryant & Lempert, 2010). The density value can be interpreted as a precision value, the value represents the ratio of the total number of cases of interest in a scenario versus the total number of cases in a scenario (Bryant & Lempert, 2010). For the density value, a high value is also preferred.

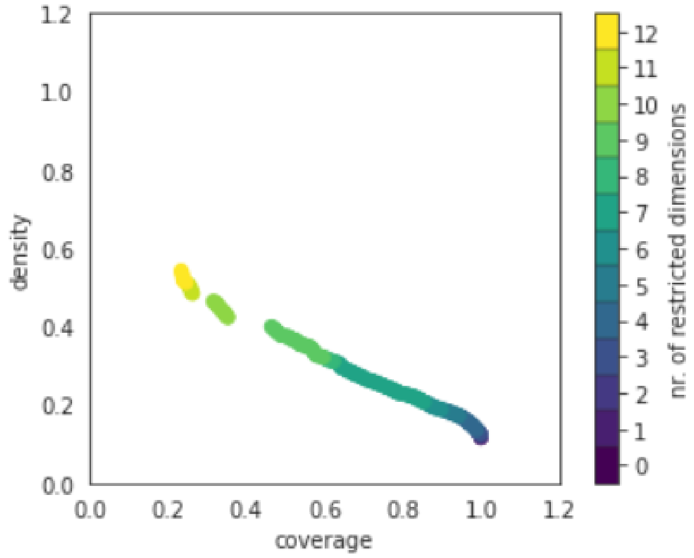


**Figure 3.4.** Density of the found boxes plotted against the coverage of the boxes.

Figure 3.4 does not have the shape you would prefer from a PRIM algorithm optimization. It is visible that there is no optimal box that has a high value for both the coverage and the density. For a high coverage of around 0.8 a low density of approximately 0.2 is shown and similarly for a high density. These non-optimal values are likely caused by the non-linearity of the model and the cases of interest not being nicely fitted into one box.

Despite the non optimal shape of figure 3.4 a preferred box of solutions was chosen, this box was then further inspected producing figure 3.5. This figure shows the amount of restricted uncertainties, and the values of these uncertainties. figure 3.5 also shows the values for the coverage and density which are strictly speaking too low.

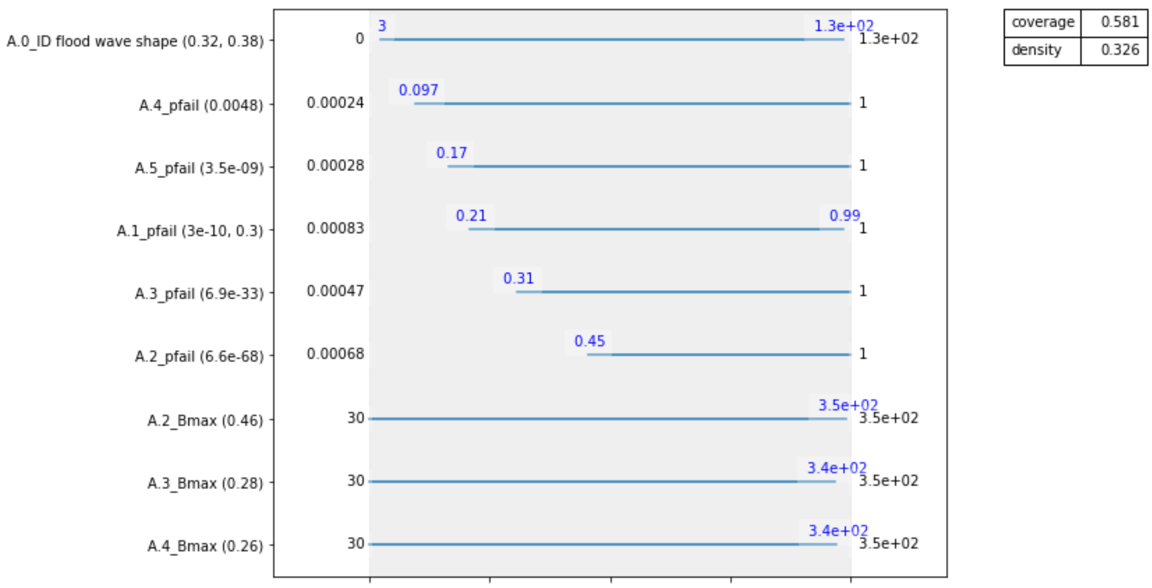


**Figure 3.5.** Restricted uncertainties for chosen box, box 140.

From figure 3.5 it can be deducted that the chosen box has quite a lot of restricted uncertainties. What stands out is that the dike failure probability is included for all five locations, where the chance that the dike fails in dike ring 2 is more likely than a failure in dike ring 4. This would suggest that dike ring 2 should have a higher priority for adaptations within the policy as this area is more vulnerable than for example dike ring 4.

In figure 3.6 the values seen in figure 3.5 are shown graphically within a pair plot. Where the orange dots and lines represent the true values, and blue the false values. A true value is here a case where the expected deaths of everyone of the five locations is below 0.001. As is visible in figure 3.6, these cases are very widely spread out and there are a lot of possible scenarios that satisfy the constraints. Which makes it very hard to deduct clear policy implications from this graph.


**Figure 3.6.** Visualization of coverage of chosen box.

### 3.2.2 Robustness evaluation

For the robustness evaluation the found solutions were evaluated on signal-to-noise ratio and on maximum regret.

The signal to noise ratio shows the mean of a dataset divided by its standard deviation, when an outcome is set to maximize, or multiplied by its standard deviation when an outcome is to be minimized. Because all outcomes need to be minimized both the average value and the standard deviation need to be small. In figure 3.7 a parcoords plot is again shown. This figure shows the signal-to-noise ratio for the different outcomes, ideally all ratios are very small. Due to the number of policies, the plot is hard to interpret. However, it can be concluded that no policy has a low signal-to-noise ratio for all outcomes of interest. Therefore, there is again a tradeoff between the different outcomes of interest.

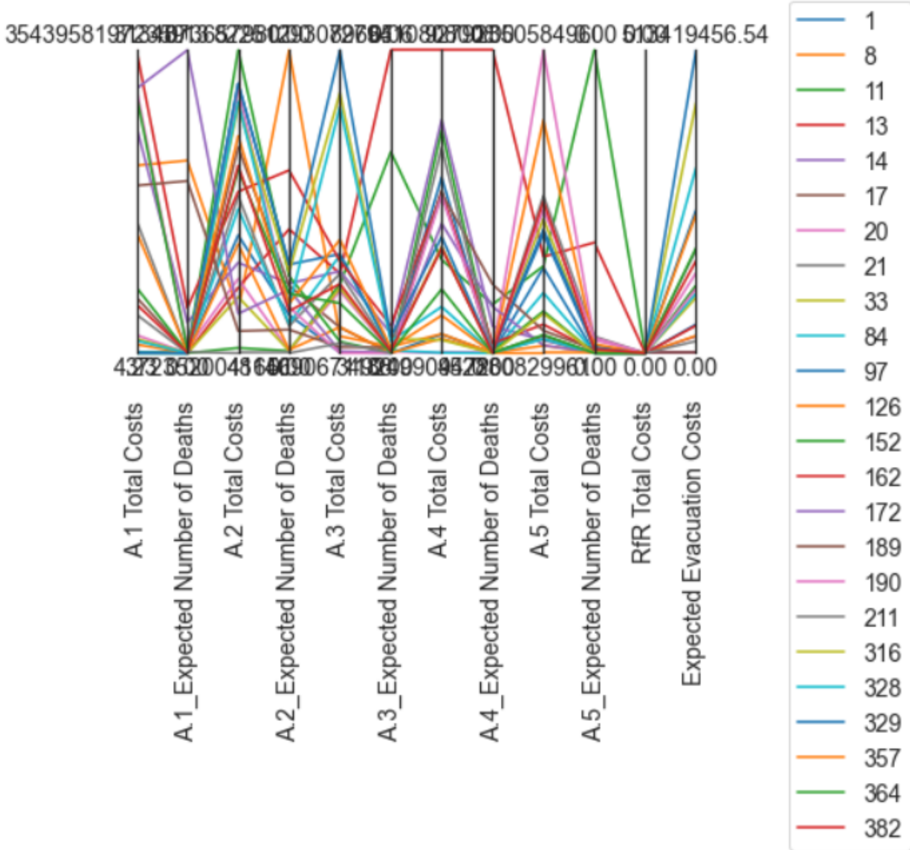


**Figure 3.7.** Parcoords plot of the signal to noise ratio for multiple outcomes

The maximum regret shows the difference between the performance of a specific policy in a scenario and best possible performance in that scenario. The maximum regret is then the maximum value of regret of a policy over all scenarios. Intuitively, a low maximum regret value is favored. Figure 3.8 shows the parcoords plot summarizing the maximum regret values of the policies. Again, no policy has a low maximum regret value for all outcomes of interest. What is interesting, is that policy 13 results in a low maximum regret for the number of deaths in dike ring 3 and dike ring 4, as can also be seen in the heatmap in figure 3.9.

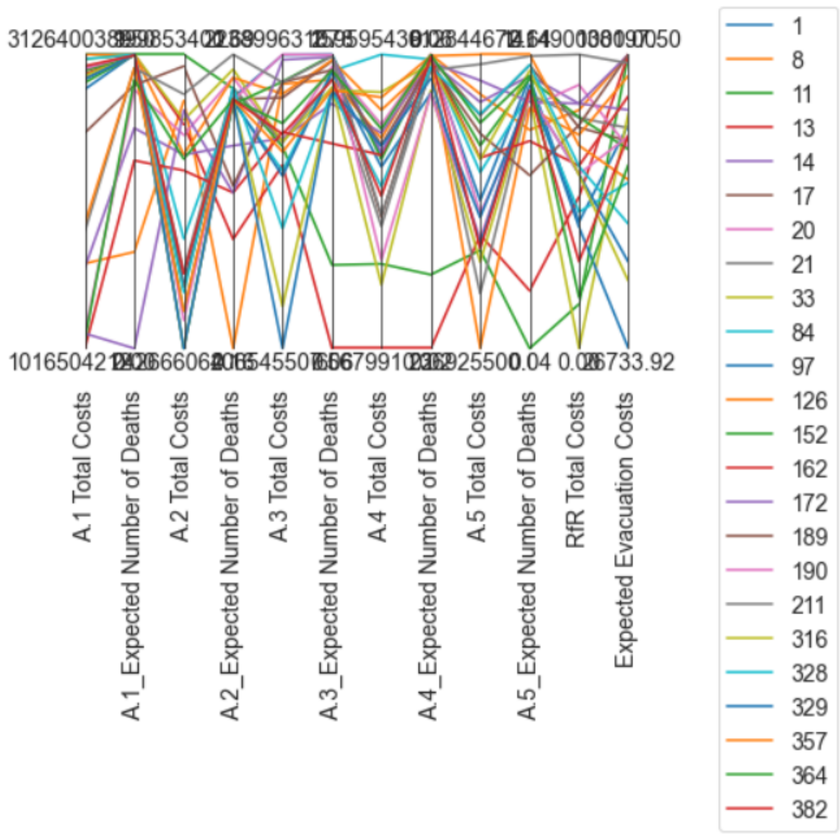


**Figure 3.8.** Parcoords plot regret evaluation

Figure 3.9 shows the heatmap of the maximum regret metric. It shows the exact values of the maximum regret for all policies and all outcomes of interest. This heatmap helps to track the policy lines in the parcoord plot (figure 3.8). The values are color coded, which helps interpret the heatmap itself as well as the parcoord plot.

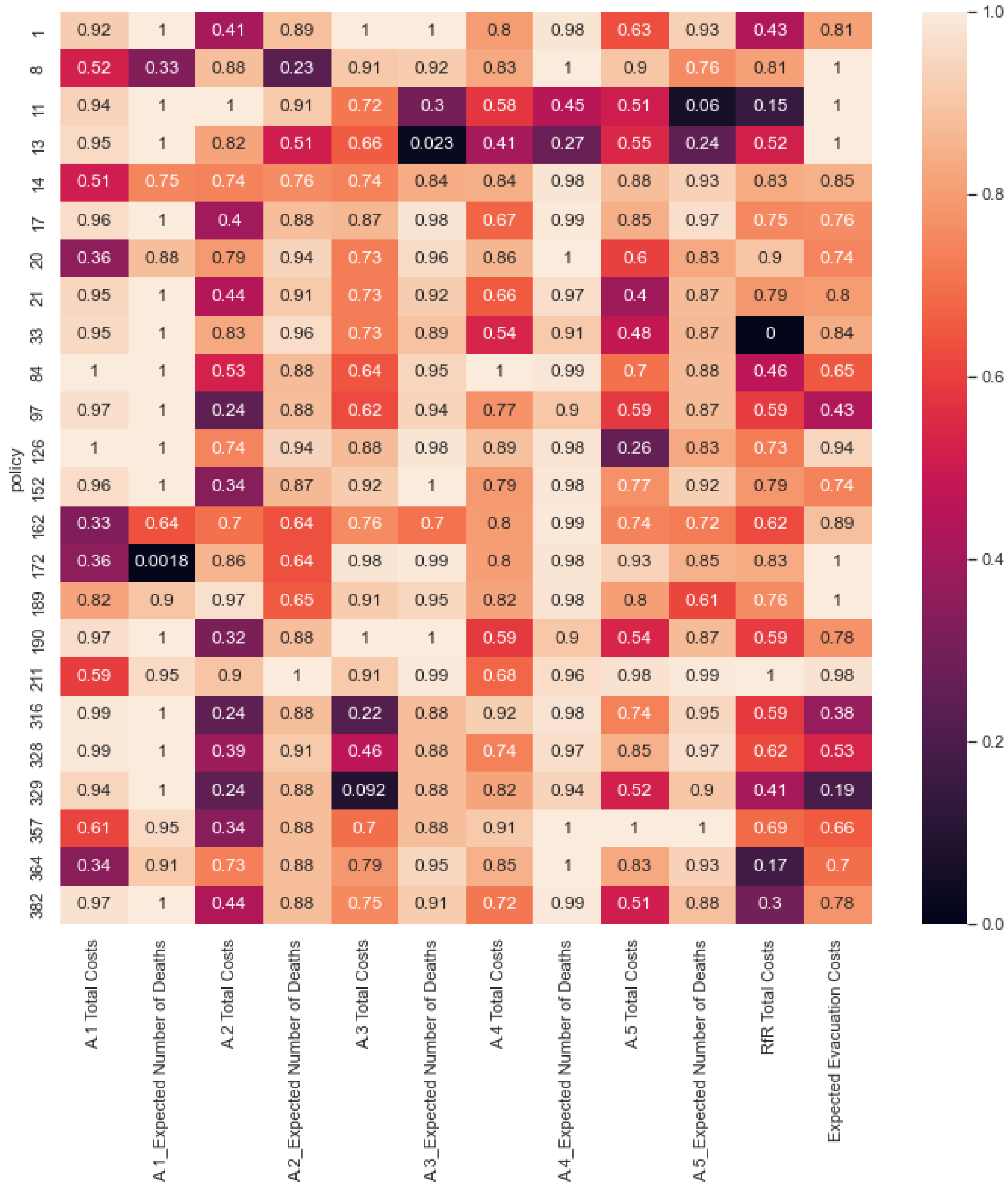

**Figure 3.9.** Heat map maximum regret

# 4. Discussion

Results from the open exploration showcase the complexity of the researched problem. Following a BAU approach would lead to a significant expected number of deaths and costs that vastly surpass the investments that would be required to partially avoid these. Alternatively, following only one type of solution can have its disadvantages, as well as being possibly rejected by different actors due to diverse interests. Thus, pursuing the acceptance of all actors can provide a pathway towards a comprehensive and combined solution. The proposed policy proves to have some clear advantages all-round, as well as having the support of all actors, however it does not include an adaptive approach or robustness.

While the optimization model achieved convergence at 10,000 evaluations, increasing the amount would guarantee the model convergence. This is especially important since, to achieve a high quality of approximations to the Pareto frontier, MOEAs must converge a diverse group of solutions that cover the full extent of an application's tradeoffs (Kasprzyk et al., 2013).

The amount of possible solutions obtained, 395, proves to be a challenge for visualization and interpretation purposes. A smaller pool of 24 solutions was later achieved by setting a hard constraint on the average number of deaths, which poses a significant improvement to the latter. These results could have potentially been further improved with the MORO approach, but computational limitations for this method proved to be a significant restriction. However, the key issue identified was the lack of clear constraints that could have reduced the amount of possible solutions. Despite these shortcomings, the results obtained are relatively in line with the open exploration, since there is no single "preferred" solution. As Rijkswaterstaat, the key goal is safety and consensus, which leaves a lot of space for different policies and therefore many potential candidates. Having clear constraints could significantly reduce potential solutions obtained and therefore significantly improve interpretation and selection.

Based on the heatmap of the maximum regret metric, it seems that policy 11 and 13 seem to be good options since they have a low maximum regret score for four outcomes of interest or more. Only policy 329 also has low maximum regret scores for four outcomes of interest, but these outcomes are all related to costs. The maximum regret scores for policy 329 are quite high for the expected number of deaths. Since safety is very important for Rijkswaterstaat, this policy will not be favorable. Policy 11 and policy 13 might not be the most optimal policies since the analysis of the heatmap could have been performed in another way. Additionally, the analysis was focused on the maximum regret metric since the results from the signal-to-noise analysis were hard to interpret.

Additionally, the model itself does not include the actor landscape, but mainly focuses on economic outcomes. However, as Rijkswaterstaat, it is important to consider the interest of other stakeholders and reach a consensus. Therefore, the interests of the other actors had to be implemented as constraints. However, some interests were in conflict with the interests of other stakeholders or the interests of Rijkswaterstaat itself and were thus hard to implement into the model. Additionally, not all concerns could be modeled. For example, the model does not include a metric to measure biodiversity, which was the main concern of the environmental interest group. This highlights the need for flexible frameworks to bring all actors in collaboration and agreement, so a space of consensus can be established with Rijkswaterstaat coordinating the stakeholders' petitions within a multi-level governance approach (Rijke et al., 2012).

Finally, considering the policy arena and its corresponding tensions, as well as the uncertainties regarding climate change and flood risk, an adaptive policy strategy is favored. An adaptive strategy would result in a long term strategy, since the path taken can be evaluated at given points in time. During these evaluations, another strategy can be chosen if necessary. However, it is hard to correctly include adaptivity in the model used for this research. There are planning steps included in the model, but it remains hard to decide on the right levers for those planning steps since the future is uncertain and it is not known what the situation will be in, for example, 50 years. Additionally, potential policy lock-ins are not considered within the model. This means that restricted pathways resulting from a policy decision cannot easily be specified (e.g., applying only dike heightening, could potentially rule out RfR in the future, due to higher costs or reduced feasibility due to urban development or other phenomena) resulting in a clear model limitation for the support in decision-making.

# 5. Conclusions

Within this report an attempt to develop a policy to mitigate the flood risk in the IJssel river area was made. This was done from the perspective of Rijkswaterstaat. To develop this policy a model-based approach was used.

As Rijkswaterstaat is a governmental actor, there was a clear focus on the safety of the area for the development of the policy, meaning that the constraints for the model were made in regard to the expected number of deaths.

From the open exploration it can be concluded that there is indeed a clear need for adaptations. Without any adaptations, the number of expected deaths and the amount of damage is significant. From the open exploration it can also be concluded that by employing extreme policies like only increasing the dike heights or only implementing room for the river has a significant mitigation effect on the expected amount of damages and the expected number of deaths. Where both dike heightening and RfR have similar effects, so neither is clearly better than the other. So it can be concluded that a diverse policy where both dike heightening and RfR will be implemented, based on the preferences of all involved actors is best. This conclusion was confirmed by the results from the open exploration for the proposed policy within the debates. With this policy the number of expected deaths decreased even further alongside with the amount of damage.

Next to the open exploration a MORDM optimization was performed, with the goal to find a set of optimal solutions for the constraints provided. These constraints focussed on the number of deaths, as the main focus of Rijkswaterstaat is the safety of the areas. Unfortunately the optimization did not provide a clear set of policies that satisfy the constraints provided. After the first round of evaluation 395 possible policies were found, after re-evaluation this number decreased to 24 policies. These policies are very widely spread over the uncertainty and policy lever area, making it hard for the optimization to find a clear direction in which the policy should be developed. To develop a more clear policy direction, the 24 found policies should be investigated more in depth separately. Currently it is not possible to make a clear recommendation out of these 24 policies as no clear distinctions can be seen in the figures produced. For the selection of a policy harder constraints could also help, this will reduce the amount of possible policies even further.

From the robustness metrics a soft policy recommendation can be made, these policies are policies 11 and 13. However it is not reliable to recommend a policy purely based on these metrics. So it is recommended that these policies are further investigated.

Furthermore is it recommended to include adaptivity in the consideration of the policies, possible within the model when the computational power allows.

In general Rijkswaterstaat is recommended to apply a diverse policy which incorporates a mix of dike heightening and room for the river measures to ensure the safety of the IJssel river area and incorporate the wishes and demands of the actors involved.

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# **Appendix A.** Actors Analysis

In order to achieve a correct approach to the policy development there has been a track of all the actors involved through different interviews and meetings along the project's frametime. Thus, we set a collaborative strategy with all actors, involving them and their individual demands. Consequently, this allows us to acknowledge their preferences, interests and position about the management plan of the river.

## A.1 Actors Analysis

The actors involved in decision-making are: (i)the Transport Company, who uses the river to transport goods via ship, (ii)the Environmental Interest Group; (iii)the province of Gelderland (representing the dike rings (DR) of Doesburg, Cortenoever and Zutphen); (iv)the province of Overijssel (representing the DRs of Gorssel and Deventer); the (v)Delta Commision and us, (vi)Rijkswaterstaat. All these actors have their own interests, values, agendas and knowledge of the area (see Table A.1).

**Table A.1.** Stakeholders' interests and power overview. *Room for the River (RfR); Dike Highthening (DH); Dike Ring (DR).*

| Actor | Interests | Power |
|---|---|---|
| Delta Commission | → Long-term solution to the problem (100+ years).<br>→ Take into account environmental impact on water, economic consequences and liveability of the area. | Vote & Veto |
| Transport Company | Maintain their business along the river:<br>→ Protection from floods.<br>→ Do not affect their BAU work procedure. | Vote |
| Environmental Interest Group | → Preference on RfR instead of DH.<br>→ Increase biodiversity along the river. | Vote |
| Overijssel Province Government | → Safety for their areas avoiding DH in the upstream of the river (this would move the flood risks to their province).<br>→ Share impacts with Gelderland Province.<br>→ Protect their farmlands and accomplish their DR' goals. | Vote |
| Gorssel - DR4 | → Protect farmlands (economic source).<br>→ Avoid land use from farmers to RfR or compensate for displacements. | None |
| Deventer - DR5 | → Safety of their citizens (reduce expected number of deaths to the minimum).<br>→ Relocating people is possible if they are well compensated. | None |
| Gelderland Province Government | → Safety for their areas and protection of the economic gains from the river activity.<br>→ Involve the private sector (represented by the Transport Company).<br>→ Comply with their DR's goals.<br>→ Share impacts with Overijssel Province. | Vote |
| Doesburg - DR1 & Cortenoever - DR2 | → Safety for the farmland<br>→ Security of income for the farmers and stable employability | None |
| Zutphen - DR3 | → Low risk of floods 1/10.000 years is acceptable risk for them | None |

| | | |
|---|---|---|
| | → Prefer NOT to move, otherwise, well compensated (they need the surrounding areas to build more houses) | |

## A.2 Actors Position

**Table A.2.** Thresholds and position with the levers of each Actor. RfR = Room for the River; DH = Dike Hightening; EWS = Early Warning System.

| Actor | Threshold (Qualitative) | Position |
|---|---|---|
| Delta Commission | → Long-term perspective<br>→ Minimize the costs<br>→ Minimize deaths estimations | Avoid DH and impulse RfR |
| Transport Company | → Avoid RfR in dike ring 1 | Avoid RfR<br>Maximize DH |
| Environmental Interest Group | → Preference on RfR instead of DH.<br>→ Increase biodiversity along the river. | Maximize RfR |
| Overijssel Province Government | → Reduce EWS for reducing evacuation costs (only if it doesn't add any considerable risk)<br>→ Minimize the DH in Gelderland, so the problem is not moved to them<br>→ Land use compensation | RfR in Gelderland |
| Gelderland Province Government | → Avoid RfR in areas 1 and 3, especially in 3 (Zutphen) as the port construction would be negatively impacted<br>→ Minimize the impacts in Zutphen (the most populated city). | Avoid RfR in the Gelderland as much as possible. |

According to this, there are several conflict points, not only in where to put RfR, but also directly in if it is put or not. Thus, there was a collaborative exploration of alternatives with the Environmental Interest Group and the Delta Commision to achieve different ways and techniques that can be applied, so RfR is made without DH and there is no loss of navigability. These solutions were presented to the Transport Company, so they were informed of the alternatives and accepted them, as well as with the provinces, so an agreement in terms of compensation was made.

# **Appendix B.** Python code

The used jupyter notebooks can be found in the following github repository: espreeuw/epa1361_group8_2022.

And through the following link: https://github.com/espreeuw/epa1361_group8_2022

# **Annex C.** XLRM Factors

| X | | | |
|---|---|---|---|
| **Factor** | **Description** | **Range/set** | **Unit** |
| Flood wave shape | A normalized curve describing the way discharges at the most upstream location change over time. There are 140 possible wave shapes. | 0-140 | |
| Dike failure probability[1] | Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dike. | 0-1 | |
| Final breach width[1] | The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain. | 30-350 | m |
| Breach width model | The way the breach width develops over time, with the uncertainty being the growth rate. The final breach width can be reached within 1,3 or 5 days. | (1, 1.5, 10) for 5,3,1 day respectively | 1/day |
| Discount rate[2] | It determines the present value of the future expected damage. The lower the value, the more damage to future generations is valued. | (1.5, 2.5, 3.5, 4.5) | |

Fig. C1. X Factors for the simulation model

| L | | | |
|---|---|---|---|
| **Factor** | **Description** | **Range** | **Unit** |
| Dike heightening[1,2] | Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand. | 0-10 | dm |
| Early warning | Early warning systems anticipate a threat and help limiting damage and/or avoiding deaths. The earlier the alert, the more effective the response, but also the more uncertain it is that the event will actually happen. False alerts can be costly and undermine people's trust into the authority. Waiting too long is also problematic as the efficacy of late alerts is poor. In the model you can choose how much time in advance to give the alert. | 0-4 | days |
| Room for the River[2] | RfR projects widen the river bed thus lowering the water levels associated to a given water volume. There are five RfR projects which can be either implemented or not (1 or 0). Each project corresponds to a profile of water level reductions across locations. | 0-1 | |

Fig. C1. L Factors for the simulation model

| M | | | |
|---|---|---|---|
| **Factor** | **Description** | **Range** | **Unit** |
| Expected annual damage[1,2] | Expected annual value of flood damage over the planning period. Clearly, for each location, the lower this value, the better. | | € |
| Expected number of casualties[1,2] | Same as above but related to amount of casualties and not economic damage. | | |
| Dike investment costs[1,2] | Investment costs of raising dikes. | | € |
| Evacuation costs | Function of the number people evacuated and the number of days they need to be out from home. The estimation is based on the 1995 evacuation in the Netherlands. | | € |
| Room for the river costs | Investment costs of the implemented Room for the river project. | | € |

Fig. C1. M Factors for the simulation model