EPA 1361
Model-Based Decision Making

# Flood Mitigation Policy on the IJssel River: A Model-Based Approach to Multi-Actor & Multi-Objective Decision-Making

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# Executive Summary

Climate change poses a further threat to flood management in the already at-risk country of the Netherlands. On the IJssel River, traditional flood management via dyke-heightening was sufficient enough to combat rising water levels in the past. However, with topics of environmental sustainability and resilience increasingly a national concern in the midst of rapidly increasing water levels due to changing climate, alternative flood management policies must be considered. With a multi-objective model-based approach, policy alternatives involving both dyke heightening actions and Room for the River (RfR) practices are analysed in this report for the environmental interest group that is slated to take part in the policy negotiations. It is believed that the objective of the client (The Environmental Interest Group, Free the Blue Foundation) is inclined towards sustainable measure, and RfR is a favoured policy alternative.

Two rival problem formulations, Problem Formulation 1 (PF1) and Problem Formulation 3 (PF3), exist to quantify the various problem perceptions' of all actors into two levels of abstraction. PF1 is at a national level while PF3 evaluates outcomes at the dike ring level. Different decision making under deep uncertainty (DMDU) techniques, namely Robust Decision Making (RDM) and Multi-Scenario Multi Objective Robust Decision Making (MS-MORDM) techniques have been used for both the formulations with the Exploratory Modelling and Analysis Workbench in Python (Kwakkel, 2017).

The RDM analysis shows that RfR is significantly more expensive and does not entirely change the sensitivity to dyke ring failure at particular locations. Dyke failure probability in Dyke Ring 1 and Dyke Ring 3 have been identified as uncertainties that the outcomes are more sensitive to. MS-MORDM was performed keeping in mind the client's objectives when creating hard limits.

The results show that there are a wide range of possible policy alternatives that minimise tradeoffs between costs and safety and that involve RfR in at least one time step. All of the identified policies have deaths within an acceptable range therefore removing the need for its contestation. If RfR must be implemented in an earlier time step, it cannot be disputed that the costs are significantly higher for some provinces more than others. These policies can be considered robust if a higher investment cost is sufficiently justified in the negotiation.

It can be concluded that there is room to manoeuvre in the decision making arena if a sufficiently broad, multi-issue game is created for inclusive policy making.

# 1.0 Problem Framing

## 1.1 Problem Context

As climate changes and sea levels rise, flooding poses an even greater threat to the Netherlands (Van Koningsveld et al., 2008). In addition to flood risks, biodiversity loss also threatens the low-lying nation in the wake of climate change (Dawson et al., 2011). While effective flood mitigation measures within the Netherlands are pertinent, the protection of natural environments and biodiversity are also of crucial importance. Situated amongst bustling urban centres, fertile agricultural land, and recently rejuvenated riparian ecosystems, the IJssel River, in particular, requires flood mitigation policy solutions that are robust and long-term.

Given historical reclamation of land from sea, the availability of floodplain land has already been reduced in the Netherlands (Klijn et al., 2013). Thus, due to such reduction in floodplain availability, flooding levels have already increased, independent of rising sea levels which are likely to only exacerbate the situation (Klijn et al., 2013). The combination of increased flood levels due to floodplain reduction and climate change will result in even higher flood levels and even deeper flooding depths in the IJssel River (Klijn et al., 2013). As a result, dyke deformation, slumping, sliding, or piping may occur from the higher flood levels which could overload dyke defence systems (Klijn et al., 2013). Thus, traditional flood management action involving dyke-heightening alone will no longer suffice as policy for flood mitigation, for such practice is neither sustainable or long-term oriented.

Instead, through integrated methods of ecology, civil engineering, and spatial planning, Room for the River (RfR) could serve as an environmentally sustainable, robust, and future-oriented means for water management on the IJssel River (Rijke et al., 2012). While RfR would result in better managed flooding along the IJssel river, environmental benefits relative to biodiversity, soil erosion, soil acidification, and nutrient cycling would also emerge (Böck et. al, 2018). With an integrated RfR method, a systems approach, characterised by multi-actor involvement, could also result in flood management policy that not only reduces flood risks and protects biodiversity, but also addresses the concerns of a wider variety of stakeholders via active collaboration (De Bruijn et al., 2015; Rijke et al., 2012). However, with such a multi-actor arena, Schut et al. (2010) has noted that "the environment is a site of conflict between competing perspectives, values, and interests, and the different groups and communities that represent them". Thus, the competing interests, which fuel competing claims, of the actors involved in flood risk management policy on the IJssel River require a multi-objective model-based approach for policy development involving RfR (Shut et al., 2010).

## 1.2 Actor Perspectives

Flood management on the IJssel river has the potential to have a number of economic, social, environmental, and political implications for not only riverine communities, but also for special interest groups and government. Thus, key actors and their respective objectives and interests regarding flood management on the IJssel River are identified in Table 1.

Table 1: Key actors and their respective objectives and interests regarding flood management on the IJssel River

| Stakeholder | Interests | Objectives | Preferred Policy | Possible Actions |
|---|---|---|---|---|
| **Delta Commission** | - Sustainable long term planning and water management in the Netherlands | - Consensus among actors on the issue of flood management on the IJssel River | *Not Applicable | - Vote<br>- Veto |
| **Overijssel Province** | - Protection of the interests of both rural (Dyke Ring 4) and urban (Dyke Ring 5) communities within the province | - Ensurement that organic farms are prosperous<br>- Ensurement that shipping, an activity that is vital for local economies, remains prosperous<br>- Minimisation of lost farmland to the IJssel River<br>- Maintenance of deep water along the IJssel River | RfR in Dyke Rings 1 and Dyke Ring 2 | Vote |
| **Gelderland Province** | - Protection of the interests of communities, Dyke Ring 1 and Dyke Ring 2 (rural), within the province | - Ensurement that current residents and farming communities in Dyke Ring 1 and Dyke Ring 2 are prosperous<br>- Minimisation of lost farmland to the IJssel river | Dyke Heightening in all locations or RfR in Dyke Ring 5 (i.e. anything but RfR in Dyke Ring 1 and 2) | Vote |
| **Rijkswaterstaat** | - Practical and efficient water management in the Netherlands | - Consensus among actors on the issue of flood management on the IJssel River<br>- Implementation of a flood management strategy which is practical and efficient | Not Applicable | - Veto<br>- Veto |
| **Environmental Interest Group** | - Promotion of sustainability<br>- Conservation of the environment<br>- Protection of biodiversity<br>- Mitigation of climate change | - A flood management strategy that is aligned with landscape, ecological, and cultural heritage values<br>- A flood management strategy that protects biodiversity by limiting soil erosion, soil degradation, and water pollution<br>- A flood management streategy that is resilient and has the ability to withstand and adapt to future changes | RfR in all locations | Vote |
| **Transport Company** | - Business continuity<br>- Economic profit | - Maintenance of river conditions that make it easy for large ships to sail<br>- Minimisation of incurred costs which may arise from imposed flood management strategy | Dyke Heightening in all locations | Vote |
| **Dyke Rings 1 & 2** | - Agricultural and farming continuity<br>- Prosperous living | - Minimisation of lost farmland to the IJssel river | Dyke Heightening in Dyke Ring 1 and Dyke Ring 2 (i.e. anything but RfR in Dyke Ring 1 and 2) | Express concerns to Gelderland Province |
| **Dyke Ring 4** | - Organic agricultural and farming continuity<br>- Prosperous living | - Minimisation of lost farmland to the IJssel river | RfR in Dyke Rings 1 and Dyke Ring 2 | Express concerns to OVerijssel Province |
| **Dyke Ring 5** | - Strong economic economy<br>- Prosperous living | - Ensurement that shipping, an activity that is vital for local economies, remains prosperous<br>- Maintenance of deep water along the IJssel River | RfR in Dyke Rings 1 and Dyke Ring 2 | Express concerns to Overijssel Province |

*Note, while Delta Commission serves as an unbiased body without an initial preferred policy, after engaging with other key actors and learning more about their interests and objectives, the Delta Commission proposed a Preferred Policy of RfR in Dike Ring 1 and Dike Ring 2 within the province of Gelderland in order to best meet the demands of all actors involved.

While the Delta Commission, Overijssel Province, Gelderland Province, Rijkwaterstraat, Environmental Interest Group, Transport Company, Dyke Ring 1 & 2, Dyke Ring 4, and Dyke Ring 5 all acknowledge rising flood levels as a threat to the area surrounding the IJssel River, due to their different interests and objectives, each actor has a different perception and preferred policy as to how to mitigate against such flood risks. Afterall, as noted by Sarewitz (2004), "different stakeholders in environmental problems possess different bodies of contextually validated knowledge". Operating within the political context of their respected key actors, analysts have developed scientific knowledge on the basis of simulation modelling for the IJssel River which is not independent of society (Sarewitz, 2004). With a narrow focus on the interests of each respected key actor, simplified modelling techniques employed by support analysts most likely neglect instances of ambiguity for flood management along the IJssel River (Stirling, 2010). Political pressure to ensure success of each key actors' respected mandate has likely influenced scientific outcomes which are then used to validate each actors' decision-making choices (Stirling, 2010). Thus, it should come to little surprise that the science-policy interactions resulting in strategic production and strategic misuse of knowledge have inflicted conflicting political stances amongst actors for flood management along the IJssel River (Van Enst et al., 2014).

The Overijssel Province must protect the interests of the rural organic farming communities and urban centres (Deventer) in Dyke Ring 4 and Dyke Ring 5. Thus, the Province of Overijssen perceives the implementation of RfR flood practices in Dyke Ring 1 and Dyke Ring 2 (within the Gelderland Province), as an environmentally sustainable and economically feasible flood management solution. However, the Province of Gelderland, representing rural farming communities situated in Dyke Ring 1 and Dyke Ring 2 that do not want to give up their land to the river, opposes such proposal. Instead, the Gelderland Province believes that the implementation of dyke heightening in all flood-risk zones, or alternatively, the simple implementation of RfR in Dike Ring 5 would be more suitable policy solutions. As environmental activists, the Environmental Interest Group, the client, obviously perceives RfR in all flood-risk zones as the best policy solution. Opposing such views and motivated by business continuity and economic profit, the Transportation Company strongly perceives deepened water levels resulting from dyke-heightening as the only flood mitigation solution. With the core objectives of reaching a consensus amongst key actors on a practical and efficient strategy for flood management along the IJssel River, Rijkswaterstaat and the Delta Commission are unbiased in the type of flood management plan to be implemented.

## 1.3 Rival Problem Formulations

Each actor and their respected problem perception initiates the actors' respected problem framing (Frantzeskaki & Walker, 2013). As a result, different actors pose different problem formulations, thus resulting in a variety of policy solutions which often fail to incorporate all tradeoff solutions (Quinn et al., 2017). Therefore, the outcome of a policy is unintentionally and disproportionately influenced by the framing of the problem (Quinn et al., 2017). Thus, in order to examine the multiple views of multiple actors and incorporate them into the decision-making process, a rival problem formulation approach has been used. In doing so, tensions in which arise from different actors' problem formulations can be identified (Quin et al., 2017). Each problem formulation is considered to be an "alternate quantitative abstraction" of each stakeholder (Quinn et. al, 2017). The rival problem formulations explored include Problem Formulation 1 (PF1) and Problem Formulation 3 (PF3) in the predefined model. These problem formulations have been selected for analysis, for they capture a range (from aggregated to disaggregated) of problem perceptions which are demonstrated by the actors involved.

Specifically, PF1 represents a high-level and highly aggregated perception of flood management on the IJssel River. This problem formulation represents flood risk management on the IJssel River from a more national-level perspective, which actors such as Rijkswaterstraat and Delta Commission are more likely to hold. The Transport Company, operating throughout all of the Netherlands, is also likely to hold a more national-level problem perception. PF1 considers only three outcomes; total investment costs, expected number of deaths; and expected annual damage. Given the national-level perspective of PF1, location for flooding along the IJssel River is not considered, for community and local level governance is too small in scope for national government.

Alternatively, PF3 represents a lower-level and disaggregated perception of IJssel River flood management. This problem formulation represents flood risk management on the IJssel River from a more local and community-based perspective. Actors such as Gelderland Province (in representing Dyke Rings 1 & 2), Overijssel Province (in representing Dyke Ring 4 and Dyke Ring 5), and the Environmental Interest Group are most likely to hold community-centred perspectives for flood management on the IJssel River, for the implications of policy directly affect their interests more closely. PF3 considers outcomes of total costs (for each dyke ring), total costs for RfR, expected number of deaths, and expected annual damage. In contrast to PF1, PF3 considers the outcomes at locations that are at risk of flooding along the IJssel River, for flooding damage in different locations greatly affects the interests, objectives, and overall well-being of actors which operate at the local scale.

Notably, flood mitigation policy and environmental policy can both be implemented at the national level. However, successful implementation of environmentally sustainable flood mitigation policy, such as RfR, calls for community coordination and local participation in order to ensure public support (Schut et al., 2010). Such reasoning further substantiates the selection of PF1 and PF3 as rival problem formulations for analysis.

## 1.4 Uncertainties

The differences that exist between the behaviours of best estimate models and an actual system represent uncertainty (Bankes, 2002). As described by Lempert et al. (2003), deep uncertainty, in particular, is attributed to a decision-making situation when conditions i), ii), and iii), outlined in Table Table 2, are neither known or only partially agreed upon by analysts and decision-making actors.

Table 2: Conditions i), ii), and iii) and their respective descriptions. When such conditions are neither known or only partially agreed upon by analysts and decision-making actors, deep uncertainty is present

| Condition | Description |
|---|---|
| **i** | "the appropriate conceptual models that describe the relationships among the key driving forces that will shape the long-term future" (Lempert et al., 2003) |
| **ii** | "the probability distributions used to represent uncertainty about key variables and parameters in the mathematical representations of these conceptual models" (Lempert et al., 2003) |
| **iii** | "how to value the desirability of alternative outcomes" (Lempert et al., 2003) |

Complex as a system, flooding along the IJssel River presents uncertainties which prove traditional decision-making methods for policy implementation unfit (Lempert, 2002). In order to derive estimates for model output uncertainty, elements of uncertainty can be incorporated in the parameters of the model (Maier et al., 2016).

PF1 and PF3 operate with the same five uncertainties relative to flood wave shape, dyke failure probability, final breach width, breach width growth rate, and discount rate. Uncertainties relative to dyke failure probability, final breach width, and breach width growth rate operate on all locations (i.e. all dyke rings) along the IJssel river. The uncertainty relative to discount rate operates at each of the three timesteps in the modelling process. Please see Appendix A for details pertaining to each uncertainty.

### 1.5 Levers

Levers represent different actions for flood mitigation policy. Policy action on the IJssel River can involve RfR implementation, dyke heightening, or early warning systems. Notably, both PF1 and PF3 account for all possible policy levers. Please see Appendix B for details pertaining to each lever.

### 1.6 Outcomes

Performance metrics are used to assess how well the policy levers performed (Kwakkel, 2020). These metrics represent the outcomes of interest (Kwakkel, 2017). As aforementioned, PF1 considers outcomes relevant to total investment costs, expected number of deaths, and expected annual damage. As mentioned previously, total costs (for each dyke ring), total costs for RfR, expected number of deaths, and expected annual damage are outcomes of interest for PF3. Please see Appendix C for specific information relative to outcomes of interest.

### 1.7 Constraints

Hard constraints were placed on safety costs and total number of deaths, for human safety is at the forefront of concern for flood mitigation policy. With such priority in mind, RfR has also been somewhat used as a modelling constraint, for without compromising the outcomes of safety costs and total number of deaths, RfR is preferred (by the client, the Environmental Interest Group) for implementation wherever possible.

### 1.8 Report Overview

The subsequent sections of this report are as follows: First, a model-based Approach (2.0) to flood risk mitigation policy on the IJssel River is provided, and the techniques used for analysis are explained. Second, Results (3.0) obtained from model-based analysis are put forth. Next, a Discussion (4.0) of said results is drawn. Then, Conclusions & Recommendations (5.0) as to how this analysis can aid in decision-making are proposed. Finally, a Political Reflection (6.0), for the purpose of reflecting how this report may be used in decision-making, is provided.

## 2.0 Approach

A flood risk management policy is designed while anticipating change. This anticipation, especially of climatic conditions, is becoming increasingly difficult and less reliable on past occurrences. Such a subject is a typical case of being characterised by 'Deep Uncertainty' (Marchau et al., 2019). Flood risk management policy for the IJssel River delta is one such socio-economic and multifaceted problem that requires long term planning. Decision making under deep uncertainty (DMDU) techniques could prove useful to inform policy processes in such an arena.

This section discusses the different DMDU techniques used for the analysis and expands on why and in which order such techniques were used. The analysis is performed using the Exploratory Modelling and Analysis Workbench in python (Kwakkel, 2017).

## 2.1 Modelling Workflow

It is a well researched notion that actor preferences and their evaluation of probabilities and outcomes is reliant on problem framing. Especially in the case of monetary value and loss of life, different framings of problems can create different perceptions and preferences of outcomes (Tversky & Kahneman, 1985). This line of argument runs as the spine of this approach.

Two problem formulations are considered for analysis of the model based on rival framings inferred from actor perspectives. The two formulations are analysed separately. The outcomes and more importantly, tradeoffs between outcomes are critically compared in order to provide a range of scientifically backed policy alternatives that the actor can operate with during negotiations. An overview of the approach is presented in Figure 1.

Firstly, an open exploration is used to compare the base case (do-nothing) to a case where randomly selected policies are implemented. This analysis is done to identify the need for intervention. The worst case scenario is identified from the base case run using Patient Rule Induction Method (PRIM).

Subsequently, two techniques are applied to both PF1 and PF3. An uncertainty analysis is performed to understand the vulnerabilities of four predefined policies and to evaluate their robustness across different scenarios (Robust Decision Making). Additionally, a multi-scenario multi-objective robust decision making (MS-MORDM) approach is used to perform a directed search for optimal policies and subsequently evaluate for robustness. The worst case scenario identified in the open exploration is used as a starting reference scenario in MS-MORDM. The jupyter notebooks can be run in the order of the sections outlined below

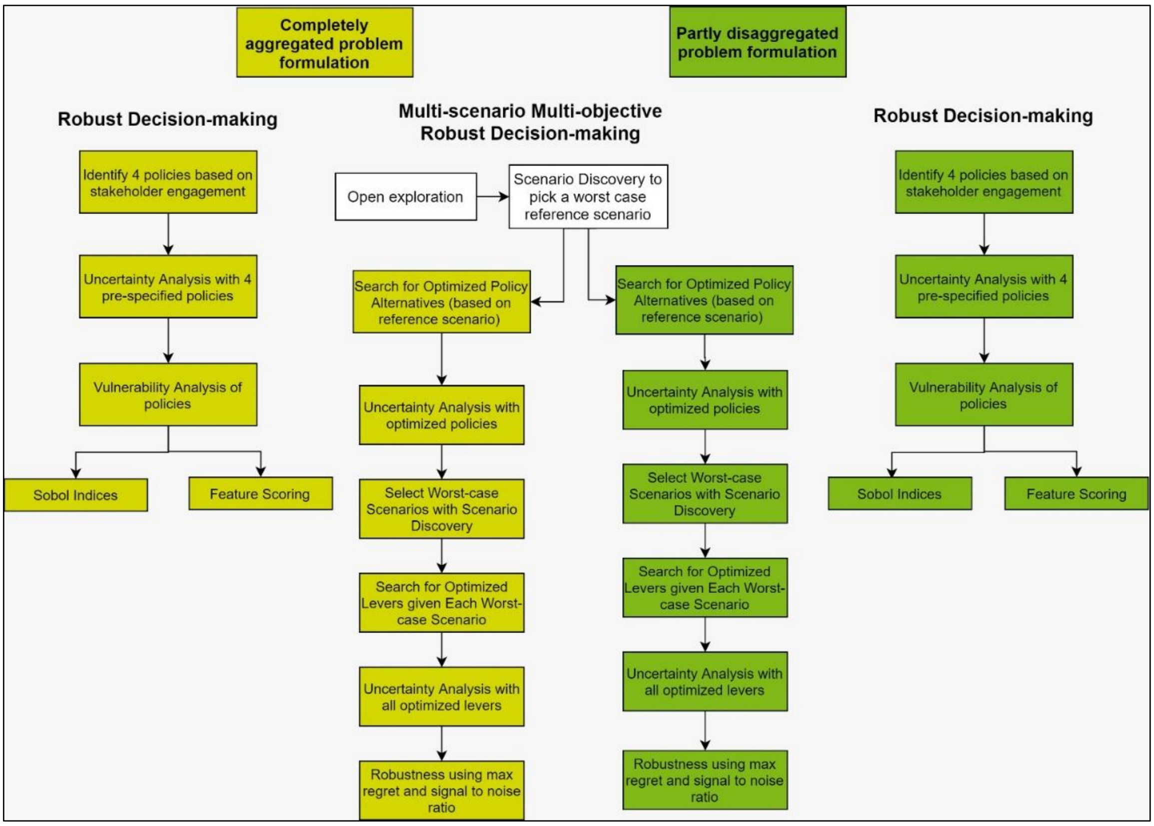

Figure 1: Method Overview

## 2.2 Open Exploration

An open exploration is performed as a preliminary analysis to explore the uncertainty space and lever space. We use it to explore the hypothesis that implementing a no-action policy (i.e., not having a policy) will result in the worst case outcomes. This approach will assist in identifying the worst-case scenario that yields the worst performance for different outcomes. A scenario, in this approach, is a set of plausible future states of the world that cause the policy to perform below expectations or cause an undesirable future outcome (Bryant & Lempert, 2010). PF3 was chosen as a starting point to find scenarios that generate the worst possible outcomes.

The open exploration is performed by randomly sampling eight policies for 3000 scenarios. The Latin Hypercube sampling method was used for this purpose. 5000 runs were performed without any policies. The outcomes were compared visually in order to understand the impact of having no policy and to draw attention to the need for intervention. Subsequently, the scenario with the highest number of deaths was identified via visual inspection to be the worst case scenario. Please see “1-Open Exploration.ipynb” for complete code documentation of the open exploration modelling workflow.

## 2.3 Robust Decision Making

The objectives of the client, the Environmental Interest Group, are aligned towards sustainability and protection of biodiversity. A multitude of the outcomes that align with the client’s objectives have not been captured in this model, such as aesthetic quality and ecological robustness (Klijn et al., 2013). Therefore, based on stakeholder objectives and the biodiversity conditions in the upstream and downstream regions of the IJssel river (Böck et al., 2018), four policies were identified. The four policies are identified in Table 3.

RDM allows for a comparison of previously identified policy alternatives and for the discovery of how various uncertainties affect the performance of each alternative. It encompasses stress testing existing policies over a large ensemble of scenarios and identifying vulnerabilities in order to improve the policies (Bartholomew & Kwakkel, 2020). This approach was used for the four identified policies.

200 scenarios were sampled using SOBOL sampling resulting in 8000 runs. The outcomes were compared for each rival formulation and each potential policy alternative.

Table 3: Policy alternatives for flood mitigation on the IJssel River

| Policy Alternative | Description |
|---|---|
| 1 | **All RFR**<br>(i.e. RFR in Dyke Rings 1, 2, 4, and 5) |
| 2 | **Upstream RFR, downstream dykes**<br>(i.e. RFR in Gelderland Province [Dyke Rings 1 & 2]; dykes in Overijssel Province [Dyke Ring 4 and Dyke Ring 5]) |
| 3 | **Upstream dykes, downstream RFR**<br>(i.e. dykes in Gelderland Province [Dyke Rings 1 & 2]; RFR in Overijssel Province [Dyke Ring 4 and Dyke Ring 5]) |
| 4 | **All dykes**<br>(i.e. Dykes in Dyke Rings 1, 2, 4, and 5) |

A global sensitivity analysis is required to account for non-linearities and parameter interactions within the model (Jaxa-Rozen & Kwakkel, 2018). Additionally, sensitivity analysis can be used to understand the relative importance of model input parameters (Saltelli et al., 2019). This can inform the negotiation process in agreeing on the relative importance of each uncertainty, as they usually tend to be exploited (de Bruijn et al., 2015). To this end, a sensitivity analysis was performed.

Sobol Global Sensitivity Analysis (GSA) provides first-order and total indices that account for the sensitivity in the outcomes due to individual parameters and higher order interactions. Variance based GSA is also argued to be most prominently used in literature (Jaxa-Rozen & Kwakkel, 2018). This was used to understand the vulnerabilities of the four identified policies.

In addition to GSA, feature scoring with the extra trees algorithm was used to assess the relative importance of individual parameters and the interaction between parameters (Jaxa-Rozen & Kwakkel, 2018). Feature scoring is a machine learning alternative to GSA that can estimate the relative importance of Sobol total effect indices with high accuracy (Jaxa-Rozen & Kwakkel, 2018).

Details on the outcomes that have not been included in the model but align with the client's objectives are specified in Appendix C. Please see "2-Robust Decision-making.ipynb" for complete code documentation of the robust decision making modelling workflow.

## 2.4 Multi-Scenario Multi-Objective Robust Decision-Making

RDM can be limiting when there are multiple objectives that are conflicting and a wide range of policy levers that can be applied (Kasprzyk et al., 2013). The policies identified in the previous step do not take into account what can be done in future time steps and multiple dyke heights that can be used to minimise losses.

Multi Scenario MORDM (MS-MORDM) can be used to search for candidate policy alternatives using many objective evolutionary algorithms (MOEAs) for several reference scenarios (Bartholomew & Kwakkel, 2020). Therefore, as a final step, MS-MORDM is applied to both the formulations.

In the first step, the worst case scenario identified in the open explanation has been used as a reference scenario to search for levers. In the second step, the levers are then subject to uncertainty analysis after using hard constraints if necessary (described in Table 4). A constraint of requiring RfR implementation was used strategically without compromising the quality of the results. If there were multiple optimal solutions, a preference was made towards those that also included RfR while minimizing deaths and safety costs. A set of reference scenarios were picked using the worst case method after using Patient Rule Induction Method to pick a set of worst case scenarios. The scenario box was selected trying to balance threshold, coverage, and interpretability (Bryant & Lempert, 2010).

In the third step, the optimisation is repeated using these reference scenarios and the policies are once again subject to uncertainty analysis. Finally, the robustness of the policies were evaluated. Robustness metrics quantify the robustness of the decision alternatives and subsequently allow for comparison and ranking. However, given that different robustness metrics are seen to produce different outcomes, the stability of the decision alternatives can be identified in similarity of robustness metrics that use different transformations (McPhail et al., 2018).

Using the robustness classification provided by McPhail et al. (2018) as illustrated in Figure 2, two robustness metrics were selected: "mean-variance" and "minimax regret".

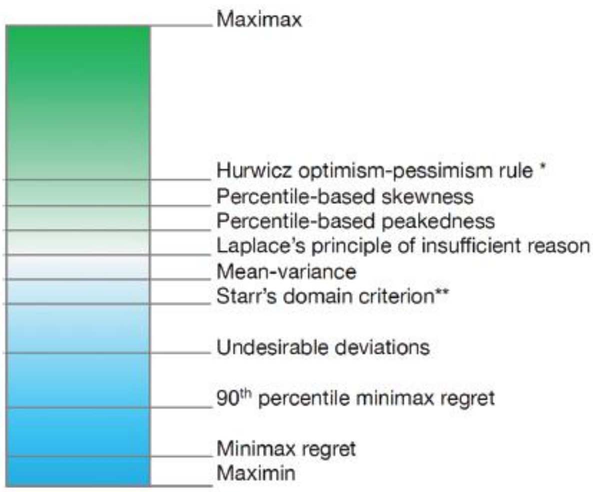


Figure 2: Robustness classification (from McPhail et al., 2018)

Table 4: Constraints applied after every step in both the formulations

| Steps | Problem Formulation 1 (PF1) | Problem Formulation 3 (PF3) |
|---|---|---|
| Step 1: Searching through lever space using one reference scenario | The obtained policies were not constrained and directly used for uncertainty analysis | The obtained policies were constrained by filtering out policies that did not include any RfR implementation, and that resulted in the 5th and 15th percentiles of death and evacuation costs respectively. |
| Step 2: Uncertainty Analysis | A set of worst case scenarios were picked for the next step using PRIM, based on annual damage being in the top 70th percentile. | The worst case scenarios were picked for the next step based on the expected number of deaths at Dike Ring 2 being in the top 80th percentile, after several iterations of scenario discovery. |
| Step 3: Searching through lever space | The optimized levers were limited for uncertainty analysis using hard constraints on RfR being implemented at least in one place. | The levers were filtered for uncertainty analysis, where only levers that resulted in the lowest 10th percentile of deaths and evacuation costs were selected. |

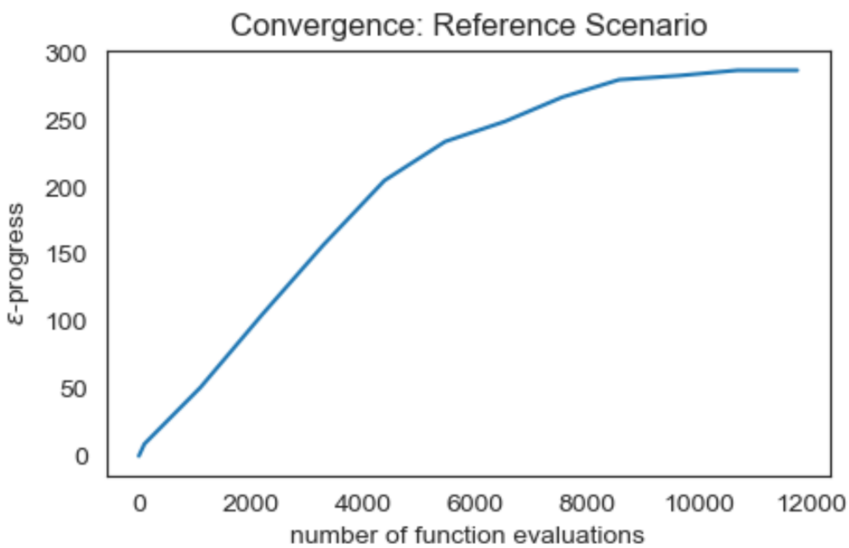


Figure 3: Convergence results for reference scenario

Details of modelling choices for each problem formulation are mentioned in Table 5. Please see "3-Multi-scenario MORDM PF1.ipynb" and "3- Multi-scenario MORDM PF3.ipynb" for complete code documentation of the multi-scenario MORDM modelling workflow.

Table 5: Rules applied for each problem formulation

| Steps | PF1 | PF3 |
|---|---|---|
| Step 1 | Optimized search for levers using 12000 nfe, resulted in 24 policies and apparent epsilon convergence (see figure 3). Epsilon values determined through iteration. | Optimized search for levers using 12000 nfe, resulted in 717 policies and no epsilon convergence. Policies filtered as described in Table 4. |
| Step 2 | Run experiments for 8000 scenarios and 24 policies. Perform scenario discovery to identify worst case reference scenarios. | Run experiments for 2000 scenarios and 24 policies. Perform scenario discovery to identify worst case reference scenarios. |
| Step 3 | Optimized search for levers using 12000 nfes with 3 reference scenarios, resulted in 81 policies and unclear convergence. Policies filtered as described in Table 4. | Optimized search for levers using 12000 nfes with 4 reference scenarios, resulted in a total of 2338 optimized levers and no epsilon convergence. Policies filtered as described in Table 4. |
| Step 4 | Run experiments for 8000 scenarios and 6 policies. | Run experiments for 8000 scenarios and 24 policies. |

# 3.0 Results & Discussion

## Open Exploration

In order to explore the uncertainty space and lever space, open exploration is performed. The open exploration results show that certain outcomes invariably perform worse in the event that no policy is implemented. Beyond demonstrating the need for policy intervention, the results also provide insight on the effect of uncertainties on desired outcomes as well as the locations that may be most critical in terms of desired outcomes.

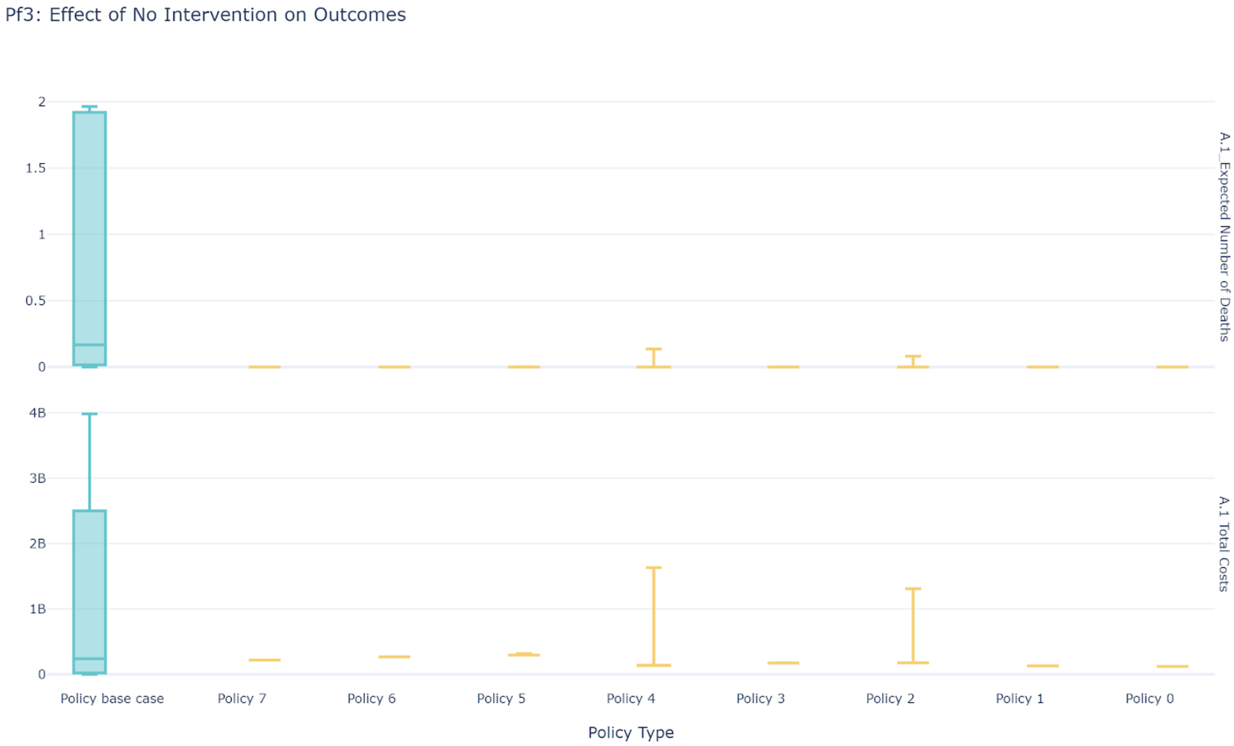


Figure 4: Open Exploration results for total costs and expected number of deaths in location A1 (Dyke Ring 1): base case situation and eight policy situations

Figure 4 demonstrates the comparison of total costs and expected number of deaths outcomes between policy and no policy implementation. It clearly indicates that, in the case of expected number of deaths and total costs for location A1 (Dyke Ring 1, Doesburg), the outcomes resulting from applying any policy is more desirable than a situation in which no policy is implemented. Appendix E illustrates that a policy intervention is always better for the expected number of deaths, whereas total costs are higher in the majority of locations when a policy is applied. RfR total costs and expected evacuation costs are also higher with policy interventions. Unexpectedly, however, Figure 4 illustrates that total costs in location A1 (Dyke Ring 1, Doesburg) are always lower when a policy is implemented which is not the case at the other locations. This means that more will be spent especially in dike ring 1 over and above any dike investment costs that may be incurred.

With regards to total number of deaths and total costs, location A1 (Dyke Ring 1, Doesburg) experiences the most number of extreme scenarios. A3 (Dyke Ring 3, Zutphen) which also experiences more scenarios with higher death numbers. The deaths in A3 can be attributed to a higher population density at that location. Locations A2 (Dyke Ring 2, Cortenoever), A3 (Dyke Ring 3, Zutphen), A4 (Dyke

Ring 4, Gorssel)), and A5 (Dyke Ring 5, Deventer) have considerably fewer scenarios associated with high numbers of deaths and costs. Please see Appendix E for detailed figures illustrating distribution of outcomes for each location.

## Robust Decision-Making (RDM)

RDM allows for a comparison of previously identified policy alternatives and for the discovery of how various uncertainties affect the performance outcomes of each alternative. The application of an RDM approach to two different problem formulations (Pf1 and Pf3) allows to compare and contrast policy alternatives from a high level (aggregated) perspective and from a low level (disaggregated) perspective.

From a high level (aggregated) perspective, Figure 5 and Figure 7 illustrate that "All RfR" and "Upstream RfR and downstream dykes" are associated with the highest overall expected number of deaths. "Upstream dykes and downstream RfR" and "All dykes" both yield a considerably lower expected number of deaths, the lowest number being achieved through "All dykes". This same ordering of policies is observed for every outcome, with "All RfR" and "All dykes" always being situated at the extremes. The analysis also shows that, with the All RfR policy, an increase in the expected number of deaths is linked to a smaller increase in expected annual damage, particularly compared to the policy with upstream dikes and downstream RfR.

From a low level (disaggregated) perspective, it is observed that costs and deaths need to be borne by different actors, a view not available in the aggregated view provided by Pf1. In contrast with results from Pf1, Figure 6 illustrates that there is only a negligible difference in expected number of deaths across policies for locations A1 (Dyke Ring 1) and A4 (Dyke Ring 4). Additionally, total costs in location A1 (Dyke Ring 1) are higher for policies "Upstream dykes and downstream RfR" and "All dykes". Finally, despite total investment cost being a fixed amount for each policy, expected annual damage is always dependent on the scenario considered.

Overall, the all RfR policy appears to be the least desirable policy, whereas the all dikes policy appears to be the most desirable policy.

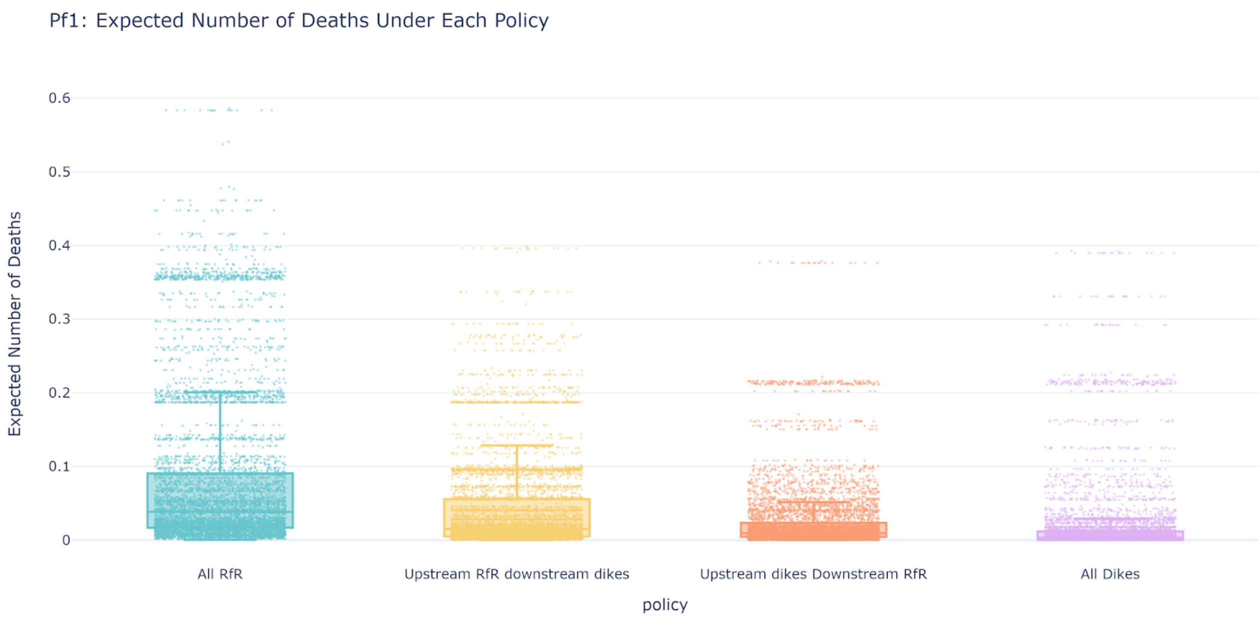


Figure 5: Aggregated RDM results for expected number of deaths under each identified policy intervention (Pf1)

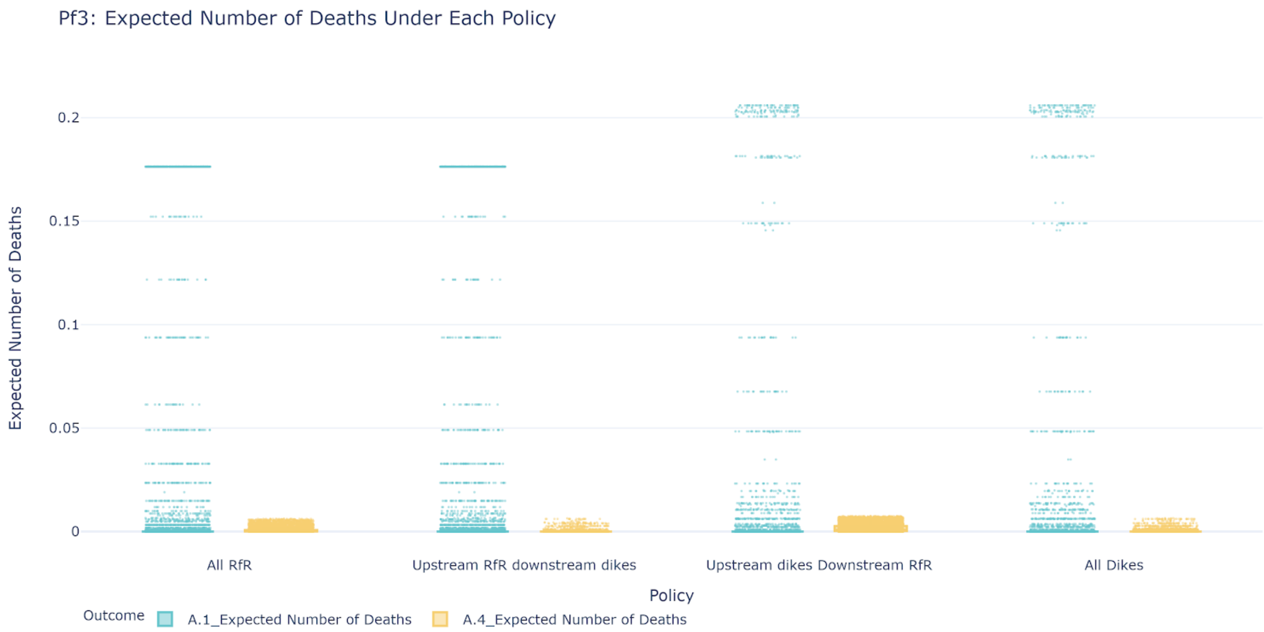


Figure 6: Disaggregated RDM results for expected number of deaths in two locations (Dyke Ring 1 and Dyke Ring 4) under each identified policy intervention (Pf3)

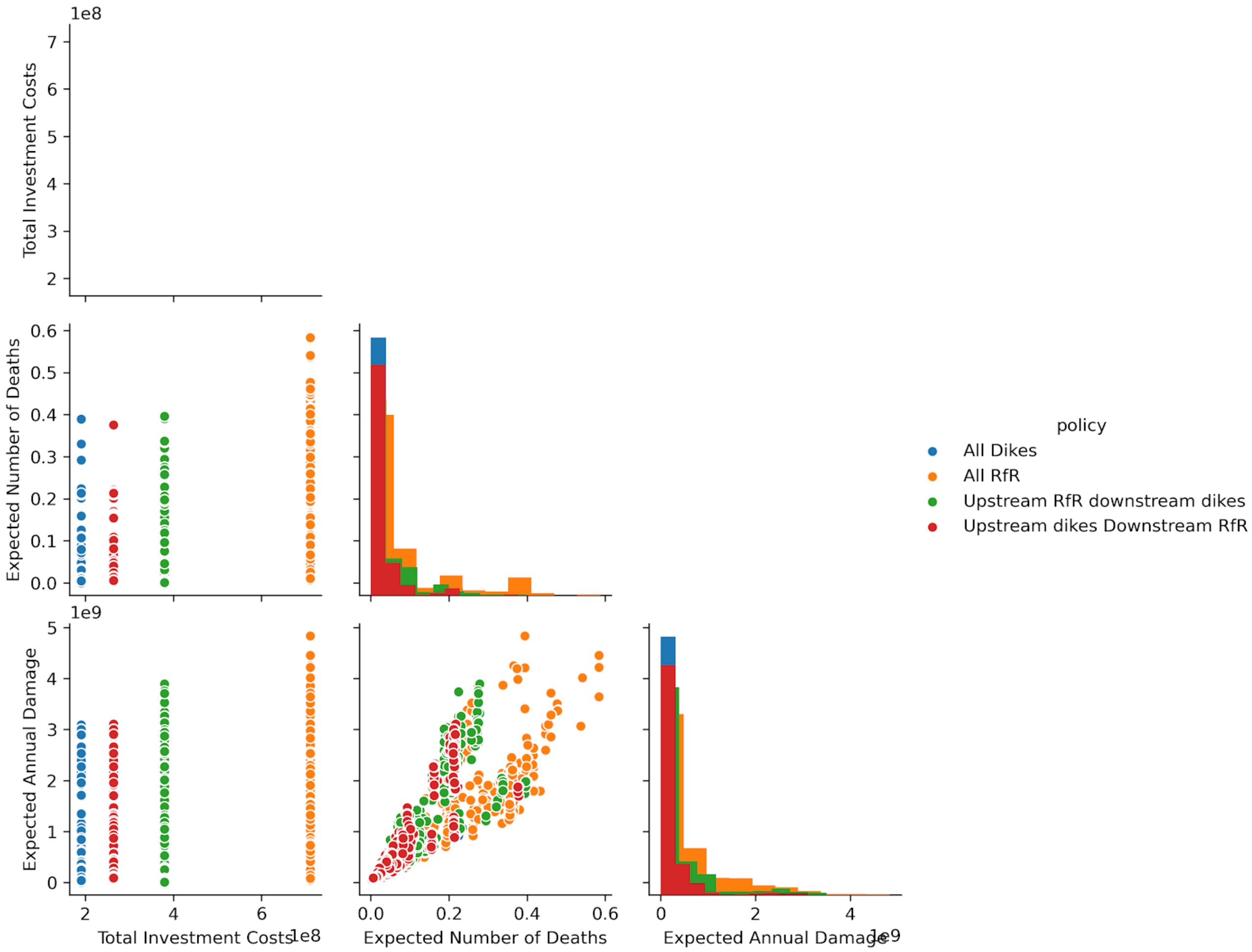


Figure 7: Aggregated RDM results for expected number of deaths, total investment costs, and expected annual damage under each identified policy intervention (Pf1)

## Sensitivity Analysis

The sensitivity analysis shows the overall sensitivity of the outcomes to the uncertainties using SOBOL indices. The sensitivity split by policies is visualized from the extra trees analysis.

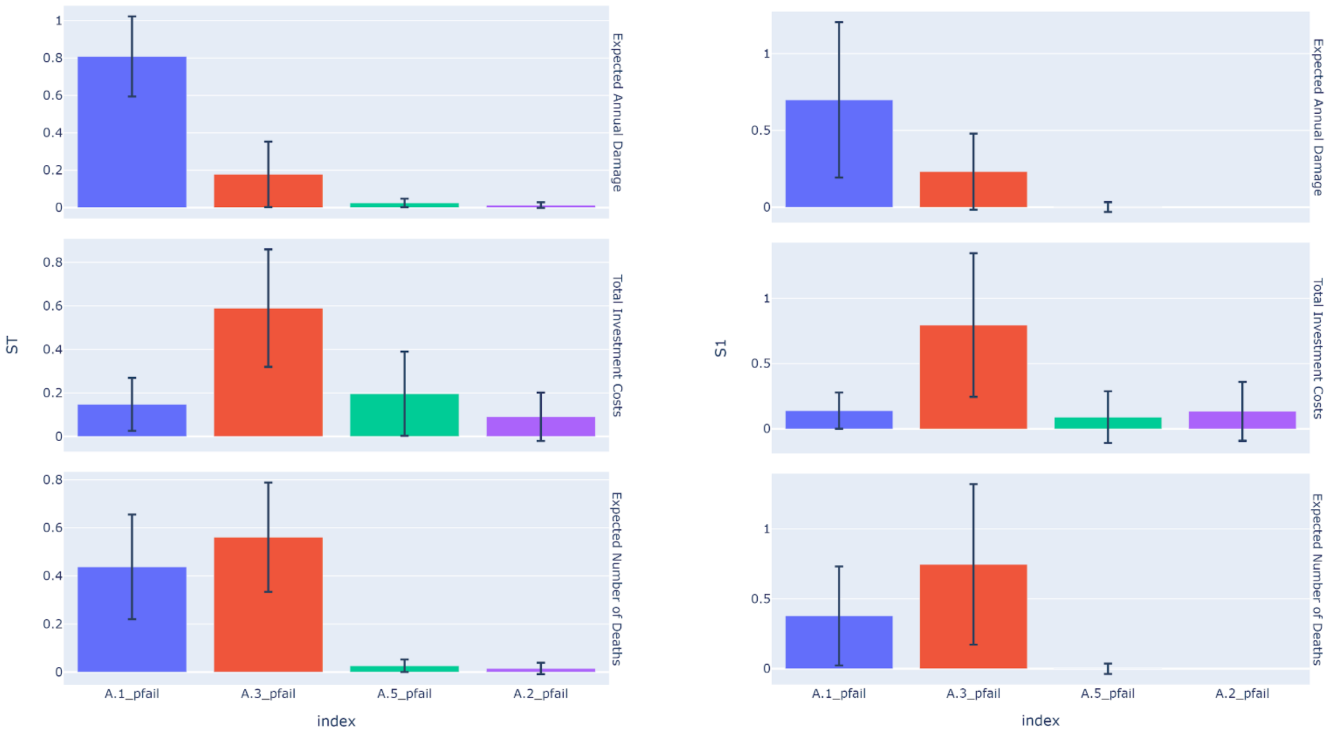


Figure 8: (Left) Sobol Total Indices for PF1 (Right) Sobol first order indices for PF1

The results show that of all the uncertainties, the outcomes are most sensitive to the probability of dyke failure. Overall, the sensitivity to failure of Dyke Ring 1 and Dyke Ring 3 is higher than the rest, both in terms of first order indices and higher order indices.

The sensitivity of the outcomes where the 'all RfR' and 'all dykes' policies are implemented are similar to each other with respect to Dyke Ring 3. However, with RfR measures, it can be noted that the sensitivity to Dyke Ring 1 is seen to reduce. This same change, however, is not seen when using the disaggregated formulation where each dyke ring remains sensitive to the probability of failure in the said dyke ring (see Appendix E).

RfR increases the sensitivity of death and costs to the probability of dyke failure wherever it is implemented. The increase in costs is expected, as RfR is more expensive. However, it is important to note here that the number of deaths is significantly low in all cases and any change in sensitivity does not translate to very high real world consequences. It must also be noted that the margin of error of these sensitivities are also high.

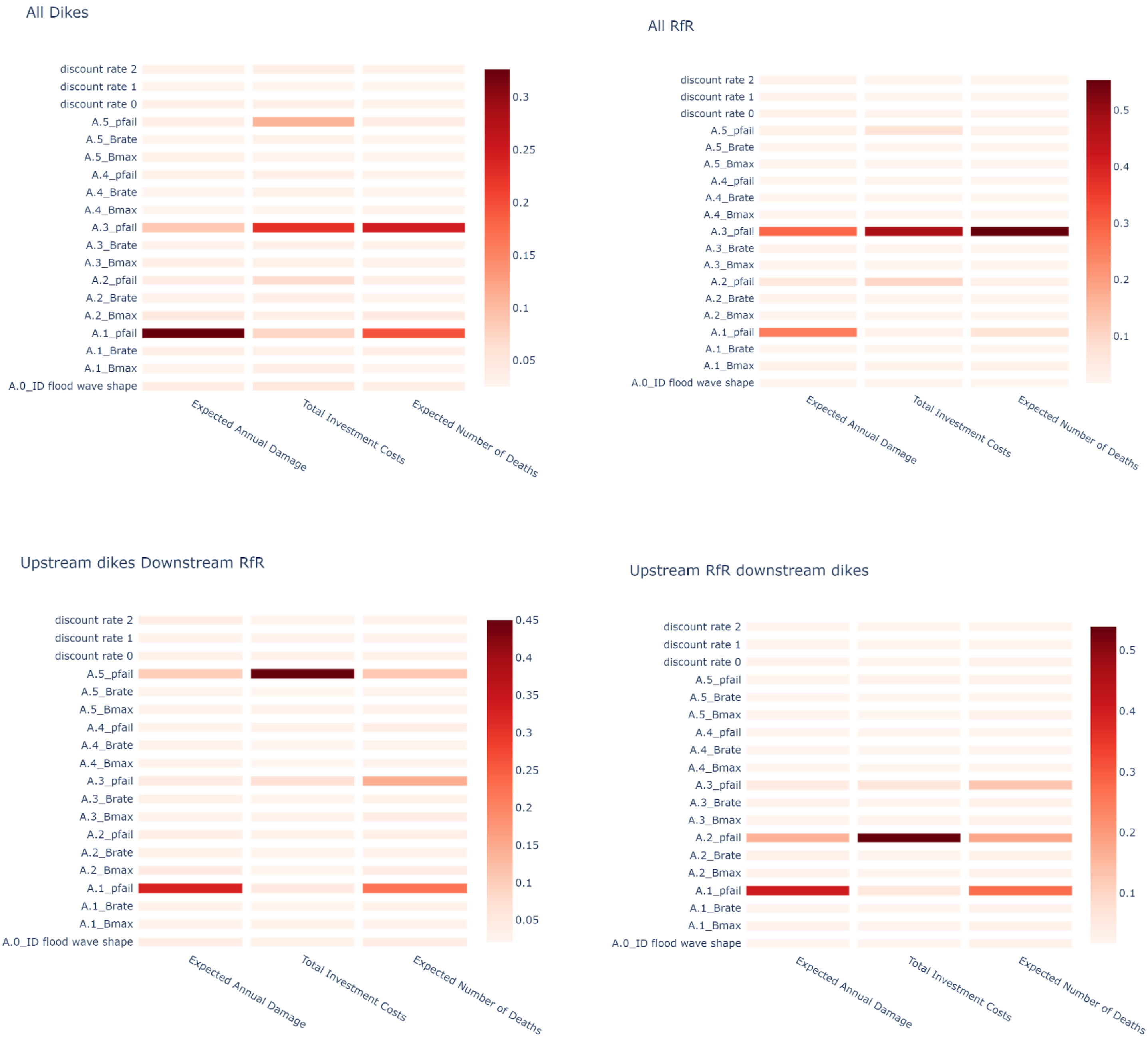


Figure 9: Extra trees sensitivity of outcomes to uncertainties when different policies are used

## Multi-Scenario Multi-Objective Robust Decision-Making

Figure 10 illustrates that there are clear tradeoffs between different outcomes. For PF1 (Figure 10, left) the tradeoffs are clearly shown to be between investment costs and expected number of deaths/ expected annual damages. However, the disaggregated formulation shows that the optimised policies may potentially yield a relatively higher number of deaths in A2 and A3 than at other locations, and that stakeholders at different locations will face the varying magnitudes of effects (i.e., in terms of costs and expected number of deaths) from the same policies. The evacuation costs however, reduce with the increase in RfR costs.

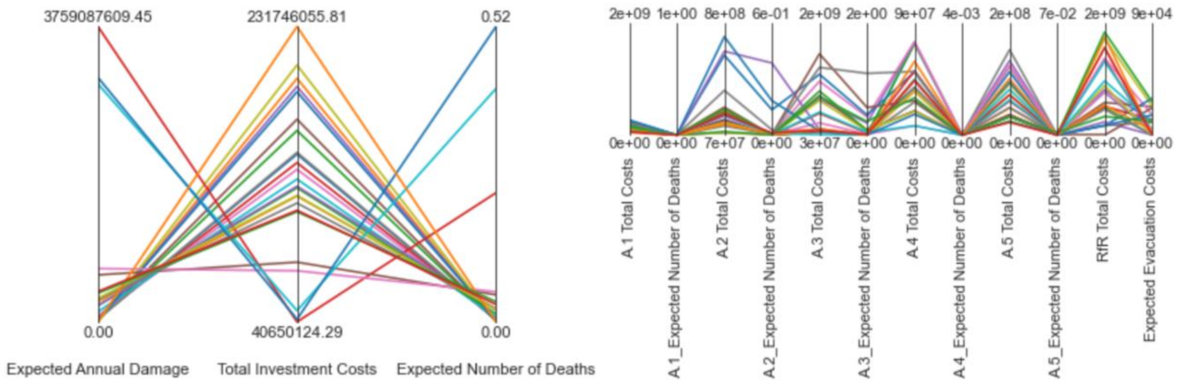


Figure 10: Tradeoffs for optimised policies based on 1 reference scenario for PF1 (left) and PF3 (right)

Similarly to Figure 10 above, Figure 11 demonstrates that there are various tradeoffs between the optimised policies for both PF1and PF3. The parallel coordinates chart for PF1 (Figure 11, left) indicates that there are some policies that yield relatively low expected annual damage, total investment costs, and expected number of deaths. The parallel coordinates chart for PF3 (Figure 11, right) shows the tradeoffs between all disaggregated outcomes for the final optimised levers, as well as the highlighted levers selected based on conditions outlined in Table 4.

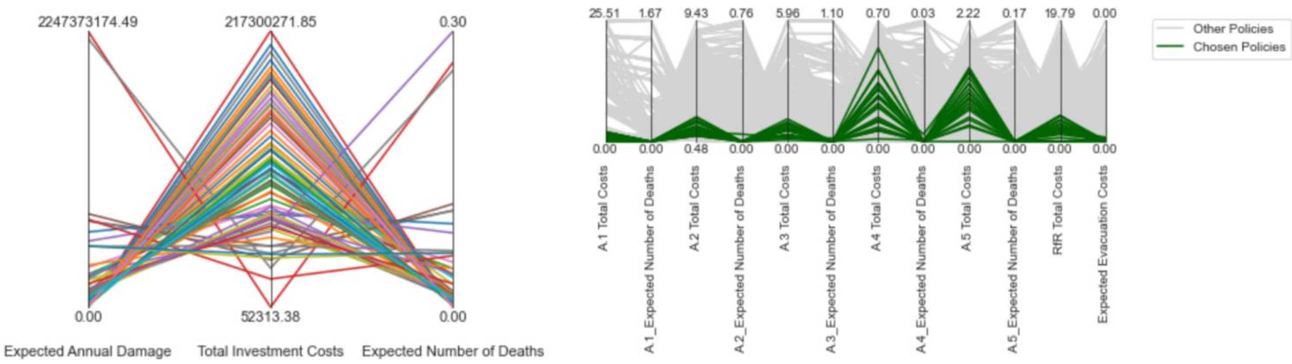


Figure 11: Tradeoffs for optimised policies based on multiple reference scenarios for PF1 (left) and PF3 (right)

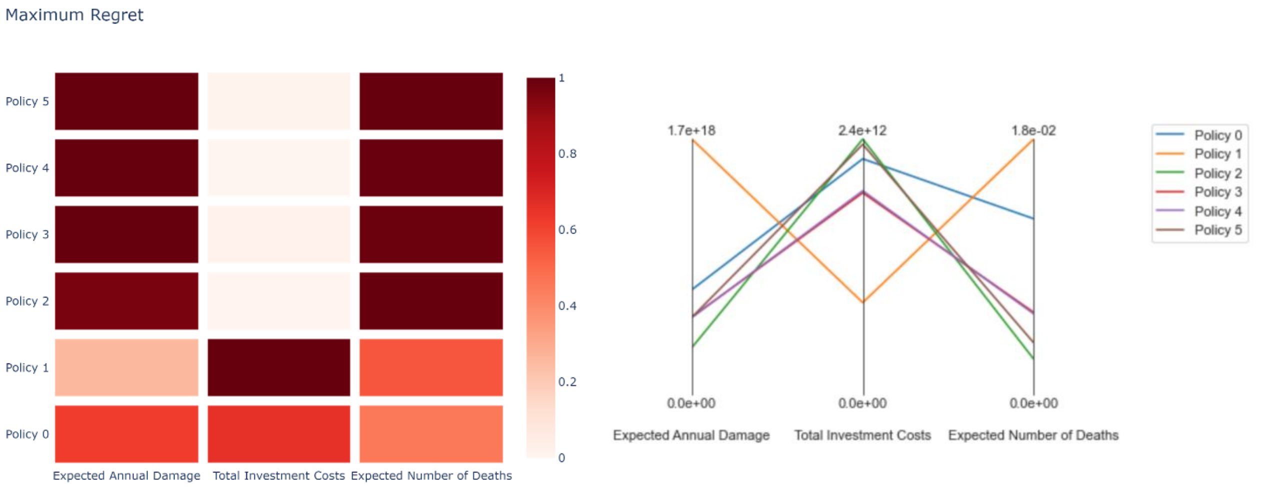


Figure 12: Heatmap for maximum regret (left) and parallel coordinates chart for signal-to-noise ratio (right) of selected policies from analysis of PF1

In reviewing the Maximum Regret of the finally selected policies in PF1 (Figure 12, left), it appears that Policies 2, 3, 4, and 5 perform robustly in terms of Total Investment Cost. Therefore, these policies may be of interest to a decision-maker for which Total Investment Costs are the only priority. However, these policies may not perform as well in terms of Expected Annual Damage and Expected Number of Deaths. Thus, the high likelihood of lower total investment costs comes with a low likelihood of achieving favorable outcomes in terms of Expected Annual Damage and Expected Number of Deaths.

The signal-to-noise ratio indicators show that all policies except Policy 1 are more robust in terms of providing favorable outcomes on Expected Annual Damage and Expected Number of Deaths, while it is less robust in terms of Total Investment Costs. This is in direct contrast to what is shown by the maximum regret metrics for the policies. However, both metrics similarly show that Policy 1 is more robust in yielding favorable performance in terms of Expected Annual Damage and Expected Number of Deaths, but not in terms of Total Investment Costs.

There are some policies that can be identified as robust based on the signal-to-noise ratio. A review of the robustness metrics for the policy reveals that Policies 15, 24 and 26 are robust in terms of both metrics. The detailed analysis of signal to ratio is mentioned in the Appendix E.

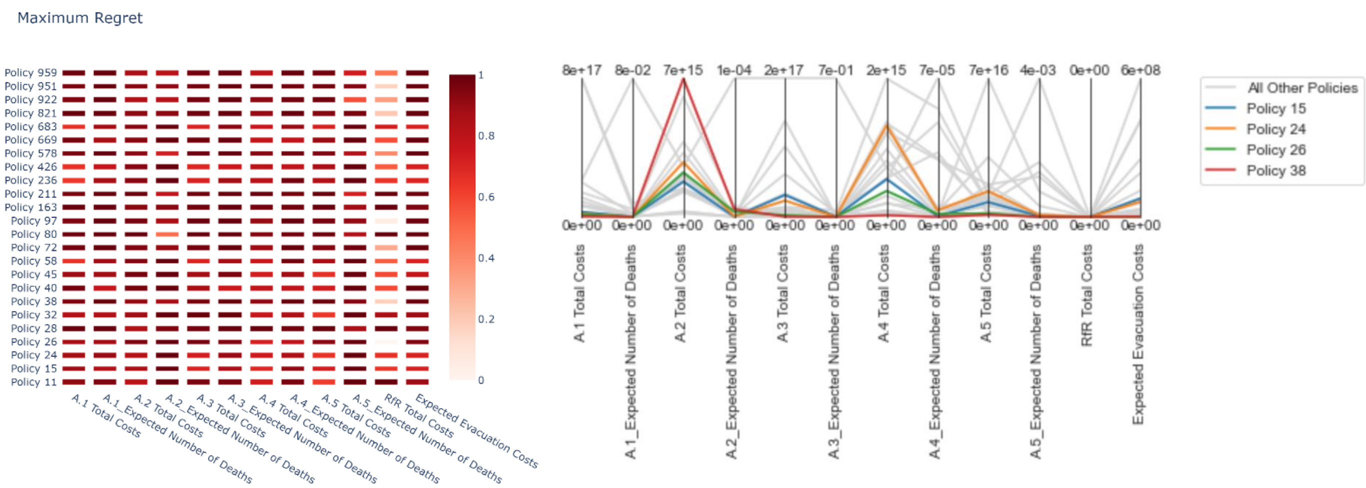


Figure 13: Heatmap for maximum regret (left) and parallel coordinates chart for signal-to-noise ratio (right) of selected policies from analysis of PF3

In reviewing the robustness of the finally selected policies from PF3, Figure X shows that Policies 15, 24, and 26 are highly robust policies when considering both maximum regret and signal-to-noise metrics. If cost is not a high-priority consideration for the client, Policy 38 can also be considered a robust policy in terms of the prioritized outcomes. Policy 38 may also be of interest to the client given that it includes RfR implementation in the short-term.

The final policies after the analysis for PF1 are as follows:

Table 6: Final policies after the analysis for PF1

| Policy Number | Policy |
|---|---|
| Policy 2 | RfR in Dyke Ring 3 (now), dyke heightening in Dyke Ring 1 (now), dyke heightening in Dyke Ring 3 (now), dyke heightening in Dyke Ring 4 (now), and dyke heightening in Dyke Ring 5 (now) |
| Policy 3 | RfR in Dyke Ring 3 (25 years), dyke heightening in Dyke Ring 1 (now), dyke heightening in Dyke Ring 3 (now), dyke heightening in Dyke Ring 4 (now), and dyke heightening in Dyke Ring 5 (now) |
| Policy 4 | Same as Policy 3 with different dyke heightening levels |
| Policy 5 | Same as Policy 2 with different dyke heightening levels |

The final policies from PF3 ar as follows:

Table 7: Final policies after the analysis for PF1

| Policy Number | Policy |
|---|---|
| Policy 15 | RfR in Dyke Ring 3 (25 years), RfR in Dyke Ring 4 (25 years), dyke heightening in Dyke Ring 1 (now), dyke heightening in Dyke Ring 2 (now & 25 years), dyke heightening in Dyke Ring 3 (now), dyke heightening in Dyke Ring 4 (now, 25 years, & 50 years), and dyke heightening in Dyke Ring 5 (now, 25 years, & 50 years) |
| Policy 26 | RfR in Dyke Ring 2 (now), RfR in Dyke Ring 3 (now, 25 years, & 50 years), RfR in Dyke Ring 4 (25 years), dyke heightening in Dyke Ring 1 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 2 (now & 50 years), dyke heightening in Dyke Ring 3 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 4 (now, 25 years, & 50 years), and dyke heightening in Dyke Ring 5 (now, 25 years, & 50 years) |
| Policy 24 | RfR in Dyke Ring 1 (50 years), RfR in Dyke Ring 3 (25 years & 50 years), dyke heightening in Dyke Ring 1 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 2 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 3 (25 years & 50 years), dyke heightening in Dyke Ring 4 (now, 25 years, & 50 years), and dyke heightening in Dyke Ring 5 (now, 25 years, 50 years) |
| Policy 38 | RfR in Dyke Ring 1 (now & 25 years), RfR in Dyke Ring 3 (now & 50 years), RfR in Dyke Ring 4 (25 years), dyke heightening in Dyke Ring 1 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 2 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 3 (now, 25 years, & 50 years), dyke heightening in Dyke Ring 4 (now & 25 years), and dyke heightening in Dyke Ring 5 (now) |

# 4.0 Assumptions, Limitations, & Future Research

The limitations of the analysis have been broken down into limitations of model boundaries, approach and modelling choices.

The first identified limitation is that the model boundaries are not in line with clients' objectives. Multiple outcomes that are relevant and are likely to be advantageous to RfR have not been included in the scope of the model. This is likely to require the client to defend their position using qualitative evidence in addition to model-based analysis. A synthesis of all the outcomes that can be included and are relevant is mentioned in Appendix D.

In the approach, Multi Scenario MORDM was used. A limitation of MS-MORDM is that it does not consider robustness during the policy and scenario search phase, and that robustness metrics are only evaluated when policies are selected at the end of the process. This makes the process of obtaining the first reference scenario very important. The reference scenario was obtained by picking out the worst case scenario through visual discovery. This can be a significant limitation in the analysis. Furthermore, more systematic ways of selecting reference scenarios before the second optimization step has been introduced by Eker & Kwakkel (2018) which allow for the selection of a more diverse range of policies. The current method used is PRIM followed by worst case scenarios which can be considered as an ad-hoc approach. This limitation can be mitigated by using better methods to identify reference scenarios, which may be computationally expensive but can be explored in future research.

With respect to modelling choices, multiple choices and constraints were used based on iterative selection processes. Hard limits were used to constrain policies in light of client preferences and computational handicaps. These constraints can be used as points of discussion in a decision arena where different actors may provide different constraints, and various policies can be filtered out to check for robustness.

Scenario discovery methods used in the model did not produce easily identifiable boxes using PRIM. Alternate methods like PCA PRIM or directed search for worst case scenarios can be performed to improve this aspect. Convergence was not obtained in MS-MORDM for PF3 which demands more number of runs to identify more optimal policies. This however, in the bigger picture may not be as important because multiple optimal policies can be generated with different problem formulations.
Sobol sampling technique is recommended to run for greater than 150,000 (Jaxa-Rozen & Kwakkel, 2018). It would be beneficial to perform the vulnerability analysis and RDM using a greater number of runs to better evaluate robustness.

Lastly, there can be a limitation in the chosen formulation itself. Disaggregating it even further to include considerations of time steps and locations based on the priorities of specific actors may be done. This would have proven extremely computationally expensive. However, the current level of abstraction may also lead to criticism of premature abstraction. It would be advisable in future research to create a new problem formulation that better represents all relevant actors and combines outcomes by province. A further improvement would be to use adaptive planning pathways to understand how policy interventions can be made.

In the process of understanding pathways, there should be greater stakeholder engagement and expert judgement to determine thresholds within the system. This can help the client operationalise some more environmentally relevant objectives and include them to a greater degree in the decision making process.

# 5.0 Conclusion & Recommendations

Multiple approaches have been used to search for and evaluate optimal policies and consequently understand their robustness. We advise that the results be used in tandem with stakeholder interaction as well as expert opinion which can address some of the broader limitations. In line with Stirling's (2010) view, the nature of policy recommendations included in this analysis are plural and conditional.

To begin with, not implementing any policy is demonstrated to yield the worst case outcomes in Section 4. Although this is not the intention of any actor, it is an important backdrop around which policy negotiations may take place. In terms of costs (especially for Dyke Ring 1) and safety, inaction will not be favourable.

To incorporate the participatory governance aspect of Room for the River, the problem formulation has been considered with outcomes at two levels - the national abstraction level and at the level of each of the Dyke Rings (i.e. a more local abstraction). We anticipate a discussion around the formulation itself, and the choice of formulation can change the kind of results obtained.

From both PF1 and PF3 formulations, four policy alternatives were built based on stakeholder objectives and biodiversity considerations on the Ijssel River. One of them, RfR in all the dike rings, is considered to be the most favourable to the client while the policy 'all dykes' (i.e. dyke heightening everywhere) is considered most favourable for the most powerful opposing actor, the Transport Company, and less favorable to the client. Two other policies are considered that alternates RfR between upstream and downstream locations while avoiding the urban areas (Dyke Ring 3 and Dyke Ring 5).

Based purely on the model, it can be argued that "all dykes" are better in terms of safety and costs. The model is extremely sensitive to dyke failure, while showing that opting for RfR measures increases the investment costs significantly. Disaggregated outcomes at each location remain sensitive to whether RfR is implemented at that location. Here, it is recommended that if the client wishes to seek implementation of RfR immediately in either upstream or downstream locations, it would be advisable to shift the focus away from the expected number of deaths. This is because, even though the expected number of deaths in cases with RfR implementation are relatively high, they remain within safe and acceptable thresholds. Thus, it would be favorable to the client's negotiations to instead build a narrative that justifies the investment costs and focus on forwarding hybrid policies can be worked with.

Given the high number of uncertainties and policy alternatives within the model, a more sophisticated technique of MS-MORDM was used to search for optimal and robust policy levers. All the modelling choices made in this method were based on the objectives of the client being favoured to RfR and prioritising safety over investment costs. It can be concluded that there are optimal policies that include RfR at least in one location and where the tradeoffs between cost and safety are minimised. The highlighted policies include minimal tradeoffs between investment and safety (e.g., death, evacuation, damage). These policies can be considered robust if a higher investment cost is sufficiently justified in the negotiation.

The fact that policies exist that provide RfR implementation while minimizing tradeoffs between investment and safety is important in two contexts: firstly, that narratives on optimal policies excluding RfR measures are more likely to be rooted in modelling choices than the lack of optimal solutions. Secondly, it cannot be denied that a policy with more RfR will fare worse than policies with more dykes when evaluated in terms of investment costs. Thus, the potentially higher costs must be carefully considered and justified in terms of qualitative returns that may not be currently included in the model.

Finally, circling back on formulations, it can be seen that the solutions obtained while using PF3, which is more disaggregated, have a lot more policies that involve implementing RfR in the first time step. This goes to show that the choice of problem formulation (keeping in mind the limitations) plays a significant part in the kind of outcome that is considered optimal. Each formulation has been considered to be a quantitative abstraction of actor preferences (Quinn et al., 2017). The client operates in high-level strategy debates that involve actors that represent provinces as well as the country. This two-fold analysis can be used for more iterations of robust decision-making which involve constraints and hard limits suggested by the stakeholders.

Andy Stirling, in his 2010 opinion piece about complexity in the policy making arena raises an important observation that the process of measuring an array of specialist views and explaining underlying reasons for different interpretations of evidence is consistent with scientific rigour and democratic accountability. Instead of simply focusing on one model or another, a preferable strategy might be to discuss the formulations, hard choices, constraints and methods used for the analysis such that agreement on flood risk management strategies may be implemented as one country where required, while keeping in mind the needs of every province.

All code relevant to this report is available here: https://github.com/jwrap/EPA1361-G21

# 6.0 Political Reflection

The insights from the model-based approach are not envisioned to become the centre of negotiations, but to create a strong evidence base in order to provide strategic direction for policy or build a favourable narrative (Boa et al., 2010). This section is aimed at enriching the model-based advice with a reflection on how it can be used in favour of (or against) Free the Blue Foundation (the Environmental Interest Group actor in which we, Group 21, represented in the debates). It is believed that the Free the Blue Foundation favours the Room for the River initiative. They will, henceforth, be referred to as the client.

## 6.1 Tensions & Challenges

The general consensus in the Netherlands is that resilience to natural disasters is an important value, thus leading to the introduction of consideration for measures like 'Room for the River' (RfR). However, what the value of resilience entails and how it can be implemented is often a point of contention (de Bruijn et al., 2015). Multiple challenges and points of tension have been identified that can potentially affect or deflect the narrative away from the client.

RfR initiatives are sustainable and ecologically resilient. Thus, it is expected that an environmental interest group such as Free the Blue Foundation would support it. An actor's stance as well as their inherently derived objectives and goals are strategic information that can be used to strengthen their network position (de Bruijn, 2018). It can therefore be assumed that such an advantage is only to Free the Blue Foundation given their inherent bias towards RfR. Inclusion in pre-negotiation discussions and the negotiation itself can be a political decision, once actor stances are known. Precedent shows that ecological teams and environmental actors have purposefully not been invited to negotiations, as they are known to potentially delay the process (Schut et al., 2010).

While this is a challenge, environmental issues can obtain a consensus, while simultaneously stimulating a Not-In-My-Backyard (NIMBY) reaction from individual actors when it comes to implementing measures like RfR in their provinces.

Another challenge is that of the contradicting values that the client, Free the Blue Foundation, holds with the Transport Company. Notably, the Transport Company holds a greater power in the arena than Free the Blue Foundation due to their considerable contributions to the national economy. For their benefit, the Transport Company would want to maintain the status quo. They could make the environment an issue that they prioritise, while emphasising on dyke heightening. This must be deframed.

Lastly, the most important challenge is that what gets measured, gets managed. Not only is the model limited in its boundary, but it may also be used to scientifically back any value-based decision (Sarewitz, 2004). This makes it imperative not to rely on a single scientific truth or model.

## 6.2 Political Strategy

Given that the client is less powerful than some of the other actors, such as the Transport Company, who are known to firmly stand against RfR measures, it would be in the best interest of Free the Blue Foundation to garner support from other actors. In efforts to garner such support, the problem could be framed as an investment in the long-term resilience of the Netherlands. In doing so, a multi-issue game can be created (de Bruijn, 2018). With a broader agenda, the game can be changed from a narrowly-focused dike heightening vs RfR situation.

It is at this juncture that the disaggregated and aggregated problem formulations will be useful. The disaggregated formulation (PF3) can be used in discussions with the provinces, while the aggregated formulation (PF1) can be used with actors who operate at a country level and who are dealing in abstractions.

With the multiple formulations, the split incentive structure can also be recognised. Some dyke rings, such as Dyke Ring 3 and Dyke Ring 1, tend to be more affected than the ones downstream or spend more in case of implementing RfR while the benefits will be reaped throughout the delta. This is likely to cause unrest (de Bruijn et al., 2015). Therefore, understanding the difference in magnitude of cost and benefit can help provide insight if some provinces need to be focused on or compensated in order to convince them on the benefits of measures like RfR.

Once again, by broadening the agenda and including other advantages of RfR like 'spatial quality' and tourism and new methods of organic farming, incentive can be created for those actors who would undertake RfR. In order to inform the actors of such incentives flyers and information documents were sent out to them.

The model is not meant to provide a specific set of solutions, but instead it is meant to create windows of opportunity for the client to create a favourable narrative and push for inclusive decision-making. Given that is the case, the model must be supplemented with expert opinion. Environmental information and scientific information in general can sometimes be difficult to grasp for a wider audience. The advantages of RfR for soil fertility and biodiversity may not fully be understood by the room in general. To counter this, information flyers were sent out to the actors and calls were conducted to engage them with the idea of RfR (see Appendix D).

## 6.3 Reflection

The strategy is meant to provide a starting point to the discussion around Room for the River on the Ijssel delta. It discusses the policy for flood risk management through model-based advice that is supplemented with a policy strategy. However, the discussion around governance of the undertaken policy or specific details of compensation for losses have not been reflected upon.

Once the policy is suggested, in case of opting for dike rings, a biodiversity offsetting strategy must be discussed. The client can also utilize the window that opens up with losing a political debate by requesting for compensation. More importantly, if RfR is chosen as a policy in any of the locations, its governance must be discussed as it will be a long process of implementation involving customized solutions for the dyke and quality assurance studies.

The other important limitation is if a policy has been agreed upon for a future time step. This will come with its own challenges of a potential change in government by the future time and discounted benefits and amplified losses in postponing the decision to implement RfR.

All in all, given the success of The Netherlands in implementing Room for the River and the general political will inclined towards sustainable development, there is no better policy window to discuss resilient disaster mitigation plans. Writing this report from the dark corners of a quarantined mind also suggests that actors will be more open to discussing black swan incidents and engaging in longer dialogue.

# Appendix A

Table A1: Model Uncertainties

| Variable Name | Factor | Description | Range | Location |
|---|---|---|---|---|
| ‘A.0_ID flood wave shape’ | Flood Wave Shape | “A normalized curve describing the way discharges at the most upstream location change over time. There are 140 possible wave shapes” (Kwakkel, 2020) | 0-140 (unit-less) | Not Applicable |
| 'A.1_Bmax' | Final Breach Width | “The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain.” (Kwakkel, 2020) | 30-350 (m) | Dyke Ring 1 (Doesburg) |
| 'A.1_Brate' | Breach Width Growth Rate | “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.” (Kwakkel, 2020) | “(1, 1.5, 10) for 5, 3, 1 day respectively” (1/day) | Dyke Ring 1 (Doesburg) |
| 'A.1_pfail' | Dyke Failure Probability | “Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dyke.” (Kwakkel, 2020) | 0-1 (unit-less) | Dyke Ring 1 (Doesburg) |
| 'A.2_Bmax' | Final Breach Width | “The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain.” (Kwakkel, 2020) | 30-350 (m) | Dyke Ring 2 (Cortenoever) |
| 'A.2_Brate' | Breach Width Growth Rate | “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.” (Kwakkel, 2020) | “(1, 1.5, 10) for 5, 3, 1 day respectively” (1/day) | Dyke Ring 2 (Cortenoever) |
| 'A.2_pfail' | Dyke Failure Probability | “Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dyke.” (Kwakkel, 2020) | 0-1 (unit-less) | Dyke Ring 2 (Cortenoever) |
| 'A.3_Bmax' | Final Breach Width | “The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain.” (Kwakkel, 2020) | 30-350 (m) | Dyke Ring 3 (Zutphen) |
| 'A.3_Brate' | Breach Width Growth Rate | “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.” (Kwakkel, 2020) | “(1, 1.5, 10) for 5, 3, 1 day respectively” (1/day) | Dyke Ring 3 (Zutphen) |
| 'A.3_pfail' | Dyke Failure Probability | “Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dyke.” (Kwakkel, 2020) | 0-1 (unit-less) | Dyke Ring 3 (Zutphen) |
| 'A.4_Bmax' | Final Breach Width | “The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain.” (Kwakkel, 2020) | 30-350 (m) | Dyke Ring 4 (Gorssel) |
| 'A.4_Brate' | Breach Width Growth Rate | “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.” (Kwakkel, 2020) | “(1, 1.5, 10) for 5, 3, 1 day respectively” (1/day) | Dyke Ring 4 (Gorssel) |
| 'A.4_pfail' | Dyke Failure Probability | “Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dyke.” (Kwakkel, 2020) | 0-1 (unit-less) | Dyke Ring 4 (Gorssel) |
| 'A.5_Bmax' | Final Breach Width | “The final extent of the breach width. The larger the width, the greater the volume of water flowing into the floodplain.” (Kwakkel, 2020) | 30-350 (m) | Dyke Ring 5 (Deventer) |
| 'A.5_Brate' | Breach Width Growth Rate | “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.” (Kwakkel, 2020) | “(1, 1.5, 10) for 5, 3, 1 day respectively” (1/day) | Dyke Ring 5 (Deventer) |
| 'A.5_pfail' | Dyke Failure Probability | “Probability that the dike will stand the hydraulic load. The higher this number, the 'stronger' the dyke.” (Kwakkel, 2020) | 0-1 (unit-less) | Dyke Ring 5 (Deventer) |
| 'discount rate 0' | Discount Rate | “It determines the present value of the future expected damage. The lower the value, the more damage to future generations is valued.” (Kwakkel, 2020) | (1.5, 2.5, 3.5, 4.5) (unit-less) | Not Applicable |
| 'discount rate 1' | Discount Rate | “It determines the present value of the future expected damage. The lower the value, the more damage to future generations is valued.” (Kwakkel, 2020) | (1.5, 2.5, 3.5, 4.5) (unit-less) | Not Applicable |
| 'discount rate 2' | Discount Rate | “It determines the present value of the future expected damage. The lower the value, the more damage to future generations is valued.” (Kwakkel, 2020) | (1.5, 2.5, 3.5, 4.5) (unit-less) | Not Applicable |

# Appendix B

Table B1: Model Levers

| Variable Name | Factor | Description | Range | Location | Timestep |
|---|---|---|---|---|---|
| '0_RfR 0' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 1 (Doesburg) | 0 (25 years) |
| '0_RfR 1' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 1 (Doesburg) | 1 (50 years) |
| '0_RfR 2' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 1 (Doesburg) | 2 (75 years) |
| '1_RfR 0' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 2 (Cortenoever) | 0 (25 years) |
| '1_RfR 1' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 2 (Cortenoever) | 1 (50 years) |
| '1_RfR 2' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 2 (Cortenoever) | 2 (75 years) |
| '2_RfR 0' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 3 (Zutphen) | 0 (25 years) |
| '2_RfR 1' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 3 (Zutphen) | 1 (50 years) |
| '2_RfR 2' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 3 (Zutphen) | 2 (75 years) |
| '3_RfR 0' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 4 (Gorssel) | 0 (25 years) |
| '3_RfR 1' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 4 (Gorssel) | 1 (50 years) |
| '3_RfR 2' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 4 (Gorssel) | 2 (75 years) |
| '4_RfR 0' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 5 (Deventer) | 0 (25 years) |
| '4_RfR 1' | RfR | “RfR projects widen the river bed thus lowering the water levels associated with 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.” (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 5 (Deventer) | 1 (50 years) |

| | | | | | |
|---|---|---|---|---|---|
| '4_RfR 2' | RfR | "RfR projects widen the river bed thus lowering the water levels associated with 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." (Kwakkel, 2020) | 0-1 (unitless) | Dyke Ring 5 (Deventer) | 2 (75 years) |
| 'A.1_DikeIncrease 0' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 1 (Doesburg) | 0 (25 years) |
| 'A.1_DikeIncrease 1' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 1 (Doesburg) | 1 (50 years) |
| 'A.1_DikeIncrease 2' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 1 (Doesburg) | 2 (75 years) |
| 'A.2_DikeIncrease 0' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 2 (Cortenoever) | 0 (25 years) |
| 'A.2_DikeIncrease 1' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 2 (Cortenoever) | 1 (50 years) |
| 'A.2_DikeIncrease 2' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 2 (Cortenoever) | 2 (75 years) |
| 'A.3_DikeIncrease 0' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 3 (Zutphen) | 0 (25 years) |
| 'A.3_DikeIncrease 1' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 3 (Zutphen) | 1 (50 years) |
| 'A.3_DikeIncrease 2' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 3 (Zutphen) | 2 (75 years) |
| 'A.4_DikeIncrease 0' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 4 (Gorssel) | 0 (25 years) |
| 'A.4_DikeIncrease 1' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 4 (Gorssel) | 1 (50 years) |
| 'A.4_DikeIncrease 2' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 4 (Gorssel) | 2 (75 years) |
| 'A.5_DikeIncrease 0' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 5 (Deventer) | 0 (25 years) |
| 'A.5_DikeIncrease 1' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 5 (Deventer) | 1 (50 years) |
| 'A.5_DikeIncrease 2' | Dike Heightening | "Amount of dike raising. The higher the dike, the higher the hydraulic loads it can stand" (Kwakkel, 2020) | 0-10 (dm) | Dyke Ring 5 (Deventer) | 2 (75 years) |
| 'EWS_DaysToThreat' | Early Warning | "Early warning systems anticipate a threat and help limit damage and/or avoid 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 in 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" (Kwakkel, 2020) | 0-4 (days) | Dyke Rings 1, 2, 4, & 5 (Doesburg, Cortenoever, Zutphen, Gorssel,& Deventer) | Not Applicable |

# Appendix C

Table C1: Performance metrics representing outcomes of interest in the predefined model

| **Variable Name** | **Factor** | **Description** | **Unit** | **Location** | **Problem Formulation** |
|---|---|---|---|---|---|
| 'Expected Annual Damage' | Expected Annual Damage | "Expected annual value of flood damage over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | € | Not Applicable | PF1 |
| 'Total Investment Costs' | Total Investment Costs | The sum of dyke investment costs and RfR investment costs | € | Not Applicable | PF1 |
| 'Expected Number of Deaths' | Expected Number of Deaths | "Expected annual value of deaths over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | Not Applicable | Not Applicable | PF1 |
| 'A.1 Total Costs' | Total Costs | The sum of total Expected Evacuation Costs, total Dyke Investment Costs, and RfR Total Costs | € | Dyke Ring 1 (Doesburg) | PF3 |
| 'A.1_Expected Number of Deaths' | Expected Number of Deaths | "Expected annual value of deaths over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | Not Applicable | Dyke Ring 1 (Doesburg) | PF3 |
| 'A.2 Total Costs' | Total Costs | The sum of total Expected Evacuation Costs, total Dyke Investment Costs, and RfR Total Costs | € | Dyke Ring 2 (Cortenoever) | PF3 |
| 'A.2_Expected Number of Deaths' | Expected Number of Deaths | "Expected annual value of deaths over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | Not Applicable | Dyke Ring 2 (Cortenoever) | PF3 |
| 'A.3 Total Costs' | Total Costs | The sum of total Expected Evacuation Costs, total Dyke Investment Costs, and RfR Total Costs | € | Dyke Ring 3 (Zutphen) | PF3 |
| 'A.3_Expected Number of Deaths' | Expected Number of Deaths | "Expected annual value of deaths over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | Not Applicable | Dyke Ring 3 (Zutphen) | PF3 |
| 'A.4 Total Costs' | Total Costs | The sum of total Expected Evacuation Costs, total Dyke Investment Costs, and RfR Total Costs | € | Dyke Ring 4 (Gorssel) | PF3 |
| 'A.4_Expected Number of Deaths' | Expected Number of Deaths | "Expected annual value of deaths over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | Not Applicable | Dyke Ring 4 (Gorssel) | PF3 |
| 'A.5 Total Costs' | Total Costs | The sum of total Expected Evacuation Costs, total Dyke Investment Costs, and RfR Total Costs | € | Dyke Ring 5 (Deventer) | PF3 |
| 'A.5_Expected Number of Deaths' | Expected Number of Deaths | "Expected annual value of deaths over the planning period. Clearly, for each location, the lower this value, the better." (Kwakkel, 2020) | Not Applicable | Dyke Ring 5 (Deventer) | PF3 |
| 'RfR Total Costs' | RfR Total Costs | "Investment costs of the implemented Room for the river project." (Kwakkel, 2020) | € | Not Applicable | PF3 |
| 'Expected Evacuation Costs' | Expected Evacuation Costs | "Function of the number of people evacuated and the number of days they need to be out of home. The estimation is based on the 1995 evacuation in the Netherlands." (Kwakkel, 2020) | € | Not Applicable | PF3 |

# Appendix D

### Model Limitations: Outcomes

Below is a list of environmental outcomes that are not quantified in the predefined flood mitigation model. The omission of such environmental outcomes from the predefined model serves as a model limitation. Parameters that are easily quantifiable, in addition to more abstract properties of the natural environment, have been outlined.

Table D1: Environmental outcomes that are missing from the predefined flood mitigation mode

| Missing Outcome | Description | Modelable? | Measure |
|---|---|---|---|
| **Soil Erosion** | This would be directly correlated with the "Dike Failure Probability" and "Final Breach Width" uncertainties, and the "dyke heightening policy". Soil erosion would be dramatically minimised through a policy such as RfR as opposed to dyke heightening (Kondolf et al, 2008). | Yes | Total Tons of soil lost (m3) |
| **Nutrient Cycling** | Healthy river ecosystems play a vital role in nutrient cycling such as fixing nitrogen and maintaining soil fertility. The chosen policy should reflect its impact on the ability of the river to cycle nutrients properly. This could be translated into an outcome for soil fertility (Kondolf et al, 2008). | Yes | Rate of nutrient cycling (dmnl) |
| **Soil Acidification** | This can be measured as the effect of a policy on the pH level of the soil over time. This would be correlated with the "Dyke Failure Probability" and "Final Breach Width" uncertainties, and the chosen policy. | Yes | Soil pH |
| **Biodiversity Loss** | River ecosystems are rich in biodiversity, which could be affected by flood management policies. For example, raising the dykes instantly removes riparian habitat for species living at the intersection of water and land, while RfR creates new habitat types such as trees for insect and mammal species in the areas surrounding the river. This would be directly impacted by the chosen policy. The number of habitat types would be dramatically minimised through dyke heightening. RfR, in contrast, allows for the creation of stratified vegetation from the water itself to farmland, thus creating several types of habitats for aquatic and terrestrial species (Kondolf et al, 2008). | Yes | Net change in number of habitat types (dmnl) |
| **Carbon Sequestration** | River ecosystems are crucial in carbon sequestration, especially when they transition into land through wetlands. Wetlands have high carbon sequestration potential through soil, marshes, and vegetation (Kondolf et al, 2008). This could be captured by the model through an outcome of total CO2 sequestered/CO2 released, depending on the policy. | Yes | Net Carbon Storage (tCO2e) |
| **Water Pollution** | The flow rate of a river plays an important role in transporting waste water away from polluting sources and water purification (Kondolf et al, 2008). Water quality could be incorporated as an outcome. | Yes | Aggregated measure (pH, turbidity, toxicity etc.) |
| **Recreation Loss** | Attractive river ecosystems play a key role in providing recreational spaces for people (Vermaat et al., 2015). The effect of the chosen policy on the recreation potential of the river for local communities is not captured by the model. | No | Not Applicable |
| **Healthcare Cost** | Functional river ecosystems that can be used by people for recreation have been shown to greatly improve mental health and decrease conditions such as anxiety and depression (Vermaat et al., 2015). Decreased recreation value results in increased costs for local health support systems. This is not captured in the model. | Yes | $ |

# Appendix E

## Open Exploration


Figure E1: Open Exploration results for Pf3 outcomes: base case situation and eight policy situations

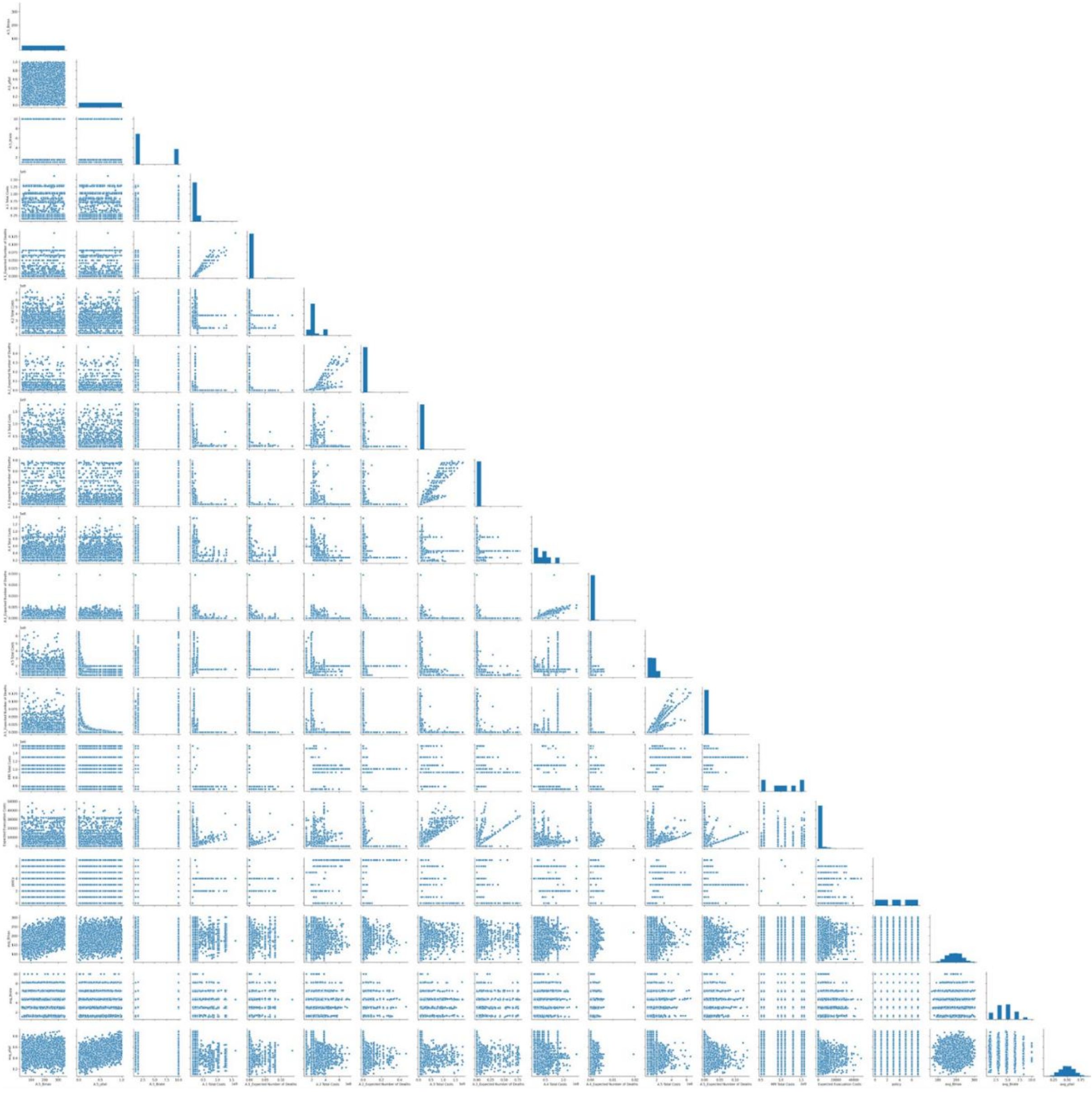

Figure E2: Open Exploration results for Pf3 outcomes: base case situation

## Robust Decision Making

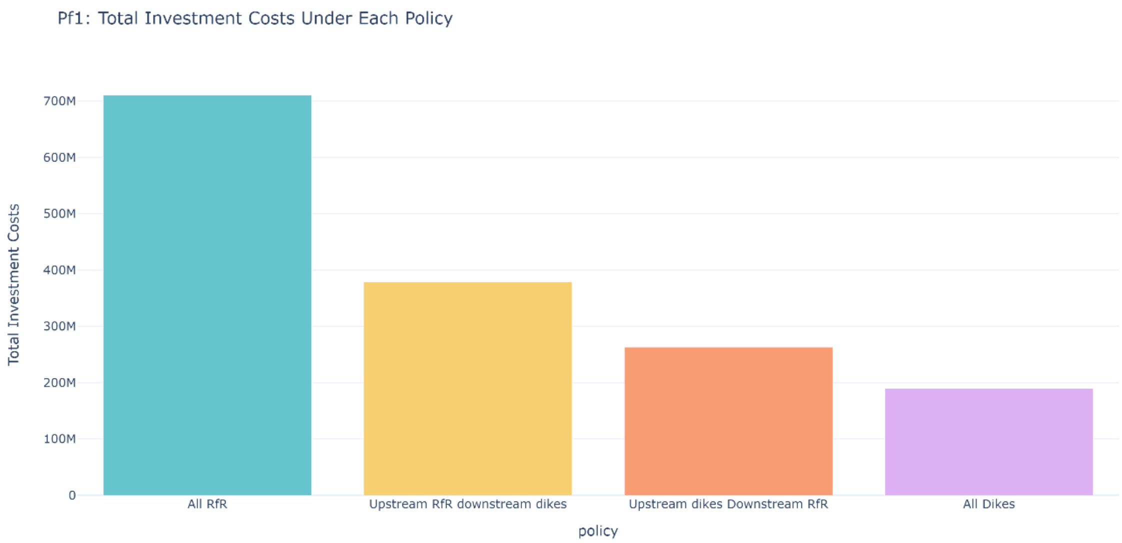


Figure E3: RDM results for total investment costs for four identified policies (PF1)

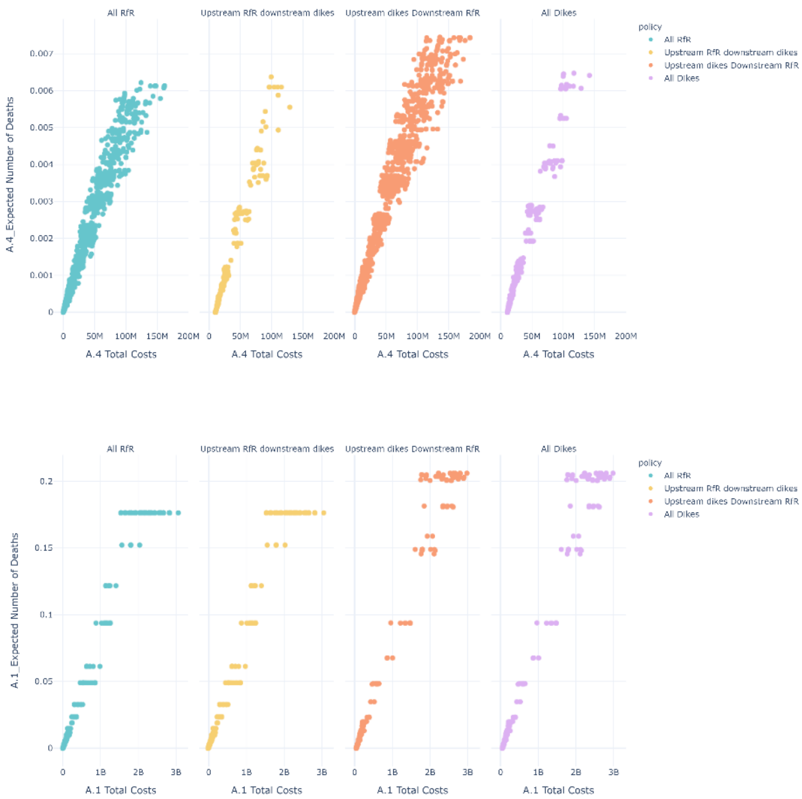


Figure E4: RDM results for total investment costs and expected number of deaths for four identified policies (PF1)

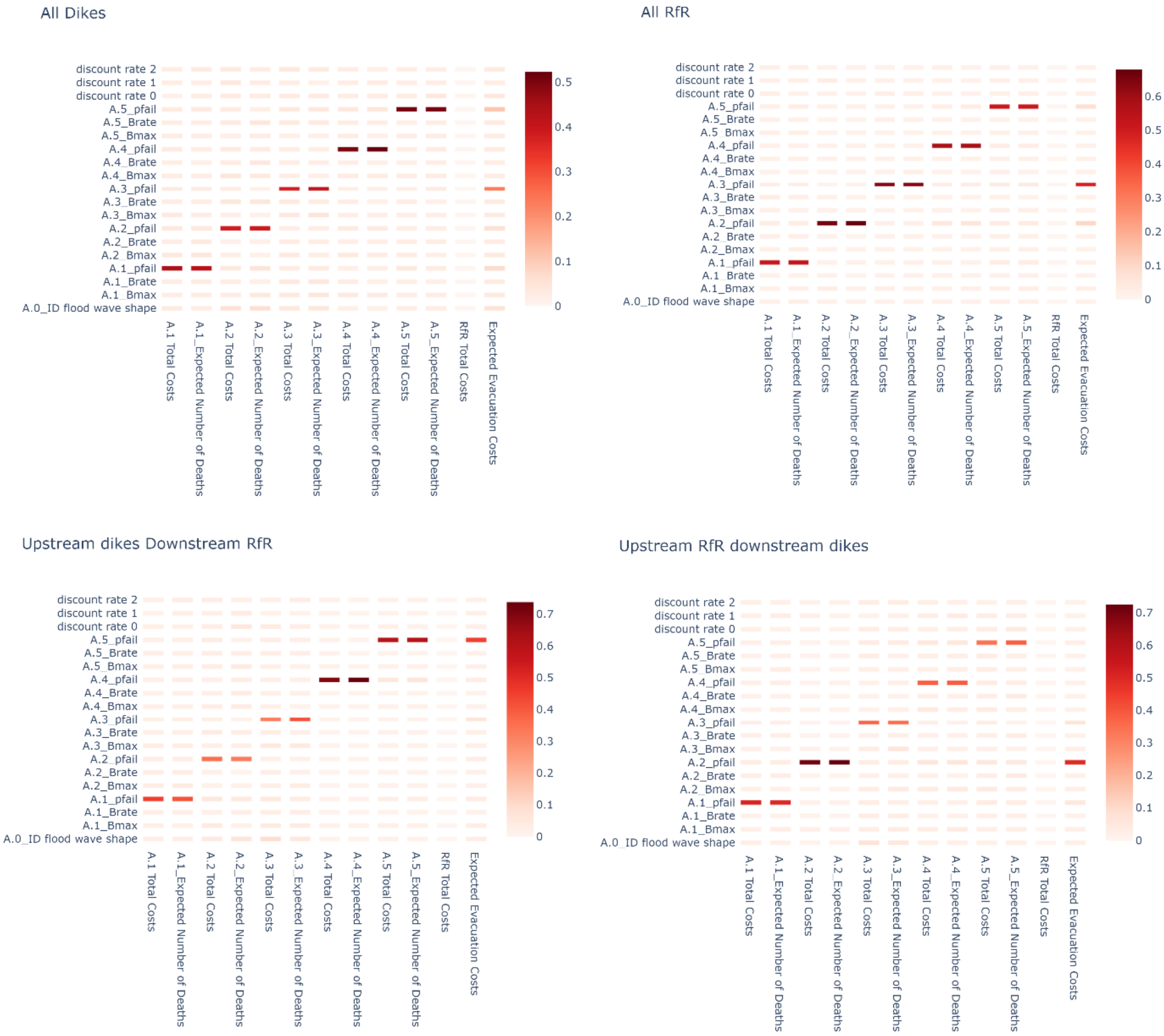


Figure E5: Feature scoring (extra trees) results for RDM analysis (PF3)

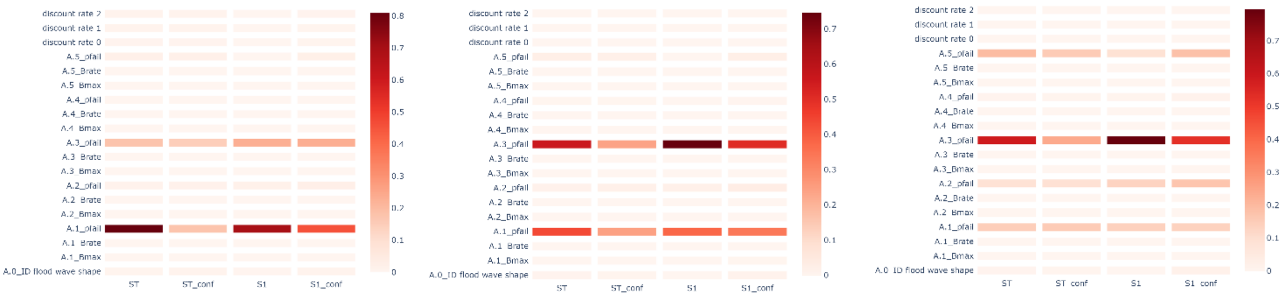

Figure E6: Sobol sensitivity analysis results for RDM analysis for total investment costs (left), expected annual damage (center), expected number of deaths (right) (PF1)


Figure E7: Sobol sensitivity analysis results for RDM analysis (PF3)

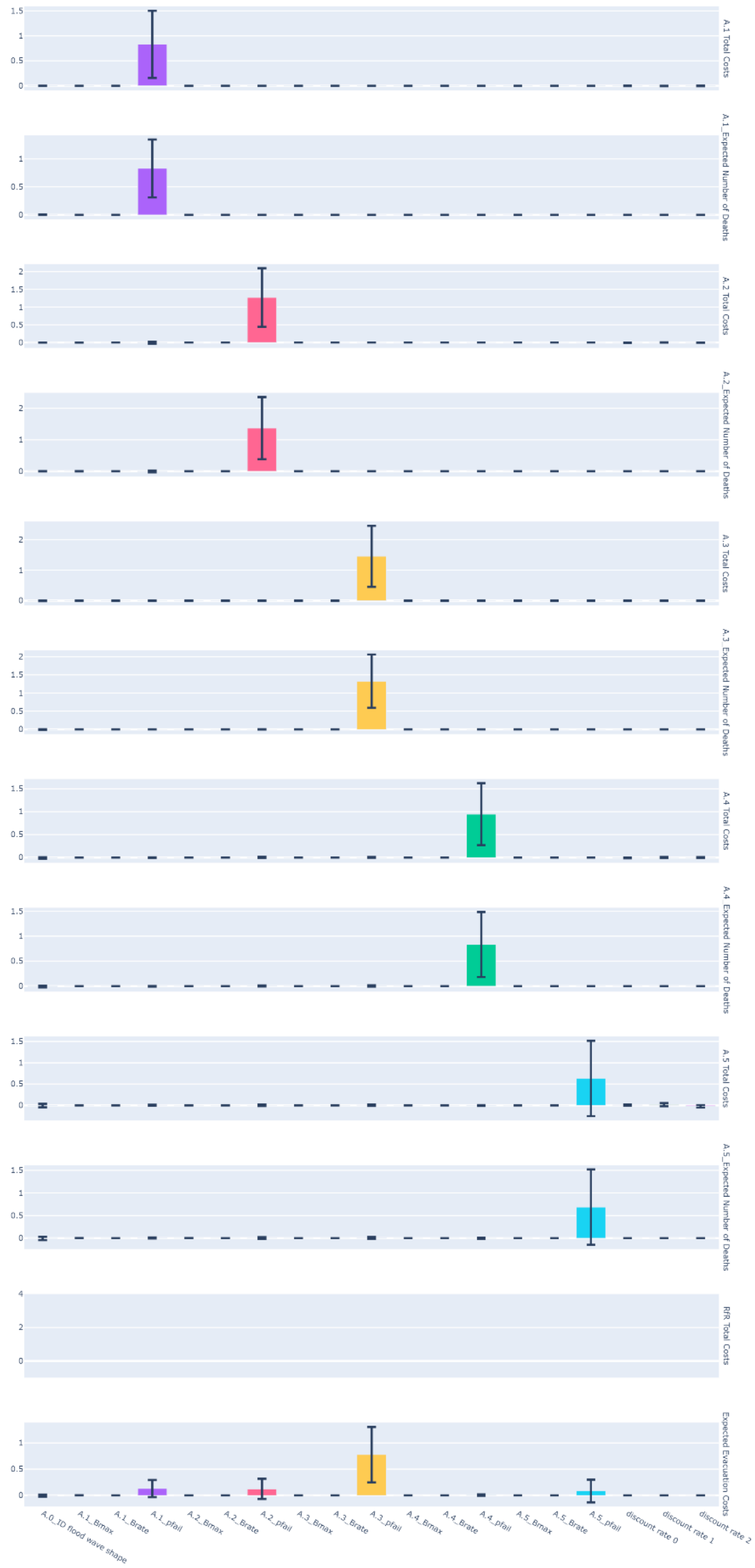


Figure E8: Sobol sensitivity analysis results (S1 indices) for RDM analysis (PF1)


Figure E9: Sobol sensitivity analysis results (ST indices) for RDM analysis (PF1)

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