Decision Support for Manage Flood Risks in Gelderland's IJssel River

Employing an Exploratory Modeling Approach within a Broader Political Context

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Group 13

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Executive Summary

The Netherlands, especially the region surrounding the upper branch of the IJssel River, faces a critical need for robust flood risk management strategies to protect lives, livelihoods, cultural heritage, ecosystems, and businesses from the significant threat of floods. This complex system with deep uncertainties is analyzed within this report utilizing a novel approach of exploratory modeling and analysis.

This report illustrates how computer-based modeling approaches can be used to identify scenarios of interest and search for optimal robust policy spaces. The modeling is assisted with an analysis of the political arena, to provide a holistic approach that goes beyond a sole technocratic advice.

The report concludes that Gelderland will most likely mediate the conflict between local and national interests. This conflict was identified within the political decision arena and model analyses, and reflects the underlying ethical lens of a utilitarian (national) and egalitarian (local) problem understanding. Thus, we recommend that the province of Gelderland be aware of the conflicting perspectives and respective ways they influence the decision-making process. It recommends three final policies that reflect different interest prioritization in line with these concerns. Having these policy narratives allow Gelderland to be flexible within the decision arena when proposing policies to the Rijskwaterstaat.

The **Low-Risk Green Infrastructure** policy yields the highest protection for Gelderlands dike rings. With four Room for River projects it follows a nature based narrative and can be used when there is a strong need for climate adaptivity. The costs are estimated to be €784 million.

The **Green Infrastructure Co-Benefits** policy has similar characteristics to the Low-Risk Green Infrastructure one. However, due to a different Room for River project prioritization, security benefits are shifted towards a national perspective, resulting in a more affordable policy of around €578 million.

Low-Cost Gray Infrastructure policy is recommended if monetary constraints are prominent within the decision-making. The policy relies heavily on dike embankments in four out of the five dike rings. Building upon previous policy implementations is expected to limit the environmental adaptation capacity, trading it off to the lowest implementation cost of €335 million.

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1 Introduction

Floods pose a significant threat to communities worldwide, including the Netherlands. The region surrounding the upper branch of the IJssel River in the Netherlands is particularly vulnerable, making effective flood management crucial (Mens, Klijn, and Schielen, 2015). Lives, livelihoods, cultural heritage, ecosystems, and businesses all rely on robust flood management strategies (De Bruijn, Diermanse, and Beckers, 2014).

Gelderland, as the largest province in the Netherlands and located upstream, holds a critical position in the national landscape. Its flood risk reduction policies and measures have a significant impact within its boundaries and downstream regions. The province's approach to mitigating flood risks directly affects water levels and the safety of stakeholders further downstream. This multi-actor nature of the problem highlights the complexity, with different actors having diverse roles and responsibilities, all seeking to exert influence in the decision-making process.

Furthermore, diverging perspectives stemming from varying problem understandings further compound the challenges. It is important to recognize that these complexities extend beyond Gelderland's borders, encompassing budgetary constraints and national delta strategies. The interplay of uncertainties adds an additional layer of complexity.

Leading up to the upcoming discussions around the flood protection projects for the **IJssel River Shared Vision 2100** project, addressing these multifaceted challenges requires a comprehensive and collaborative approach, considering the broader implications for the entire basin. This report aims to tackle the critical flood risk management challenges faced by the province of Gelderland, considering its upstream position along the IJssel River and the multi-stakeholder nature of the decision problem. By focusing on the complex political decision arena, the report seeks to understand and accommodate the diverse interests and objectives of the involved stakeholders. Examining the interplay between political values and scientific considerations will shed light on how these factors shape policy planning.

Ultimately, the report aims to contribute to the development of a comprehensive flood risk management plan that effectively addresses the risks associated with flooding while navigating the complexities of the multi-actor decision-making process for Gelderland.

2 Problem Analysis

To offer strategic policy advice to Gelderland, it is vital to conduct a thorough analysis of the political decision arena, stakeholder engagement, and the uncertainties involved in the decision process. By understanding these complexities, we can provide customized recommendations that empower Gelderland to actively participate in the decision arena, thus helping them achieve their flood risk management goals.

2.1 Decision Arena: A Contested Political Process

Figure 1 depicts the political decision arena, categorizing stakeholders into three levels of governance: local (dike rings), regional (provinces Gelderland & Overijssel), and national (Delta Commission, Rijkswaterstaat, environmental and transport interest groups). Stakeholders at each level seek to influence policy decisions aligning with their interests and perspectives on the issue at hand. The Delta Commission and Rijkswaterstaat are expected to exert influence through financial resources and decision-making power. Provinces aim to participate in policy decisions, leveraging their democratic representation and local expertise, while local actors rely on the regional level for representation. Interest groups aim to leverage both perspectives to advance their interests, showcasing their ability to navigate the political landscape.

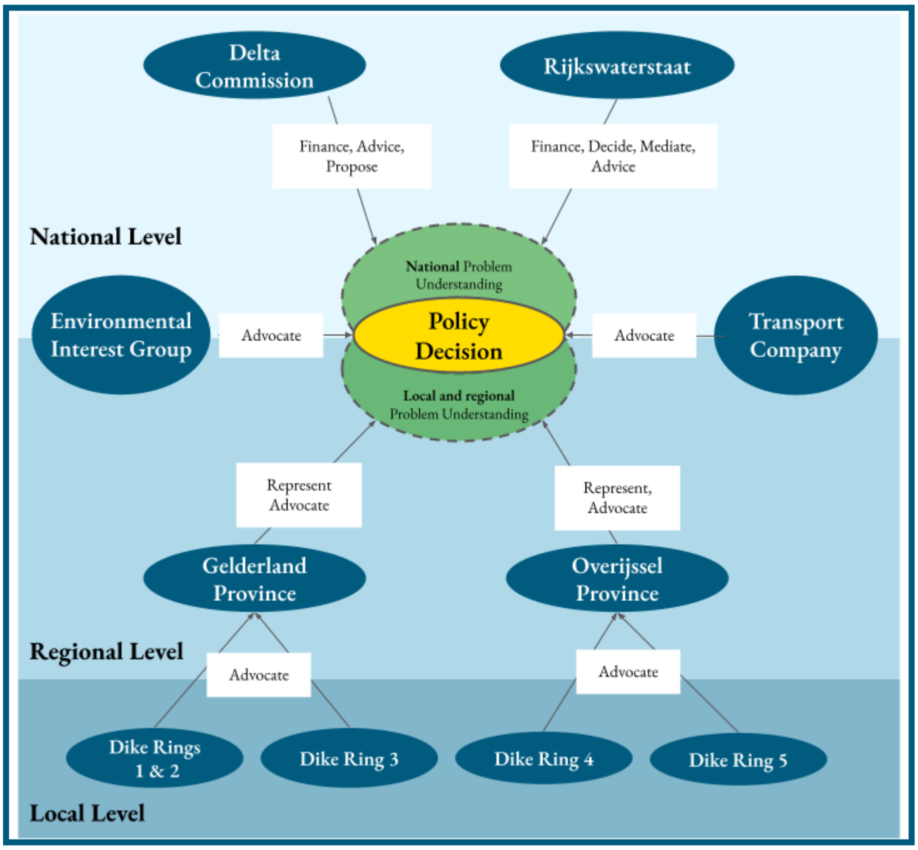


Figure 1. The Decision Arena of the IJssel River 2100 Shared Vision Project. The diagram showcases actors organized by their governance level, approach towards a policy decision and possible actions.

Conflicts within the decision arena are likely to arise from conflicting national and local perspectives on the issue. Historically, Dutch water management followed a top-down approach, with national institutions controlling water management policies (Roth et al., 2021). In the IJssel River basin context, this may result in Rijkswaterstaat prioritizing national interests over local concerns. A holistic perspective would ensure a comprehensive approach to flood risk mitigation but may overlook the specific needs of dike rings. Regional actors adopting a bottom-up approach challenge this broader scope and emphasize local interests.

The decision arena process is further complicated by inherent uncertainties., categorized as hydrological variability and knowledge limitations (Simonovic, 2000). Hydrological variability refers to fluctuations of hydrologic variables, while knowledge limitations arise from limited knowledge to precisely assess values of interest. In the context of Gelderland, the lack of knowledge becomes apparent in their public mandate (Akter & Simonovic, 2005), causing subjectivity when evaluating alternatives due to shifting priorities, power dynamics, and limited precise knowledge of goals, constraints, and consequences. Comparing and prioritizing non-commensurate objectives like flood damage and psychosocial impacts adds further complexity, while uncertainties persist in risk communication and public acceptance levels.

Conclusively, involving multiple stakeholders with diverse interests, objectives, and priorities at different governance levels in an uncertain system will complicate the decision-making process. Balancing these perspectives and finding common ground among stakeholders is crucial for developing an effective flood risk management plan.

2.2 Stakeholder Analysis

To overcome the challenges of a contested political decision arena with multiple actors and uncertainties, a thorough stakeholder analysis is essential. An extensive analysis can be found in Appendix A. The identified stakeholders in the analysis are mapped on a power-interest grid representing the relative position of each possible stakeholder in terms of their interest and power reflecting a spectrum (Eden & Ackermann, 2021) (Figure 2).

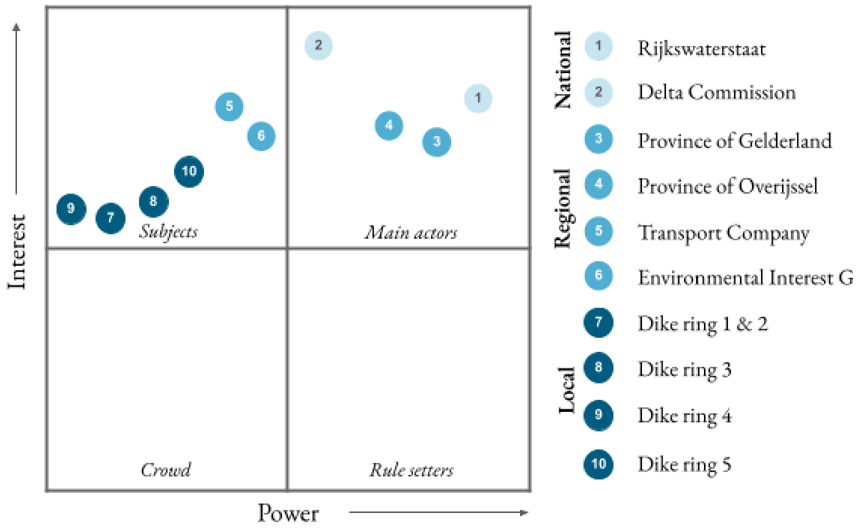


Figure 2. Power-Interest Grid of the stakeholders of the IJssel River 2100 Shared Vision Project. representing the relative power and interests of all stakeholders involved within the policy decision-making.

Based on the power interest grid, we can identify four key players in the political arena, specifically the top right of the high-power/high-interest quadrant (Eden & Ackermann, 2021). The key players are Rijkswaterstaat, the province of Gelderland, the province of Overijssel, and the Delta Commissioner. These players operate at two different political levels and hold significant power and interest in decision-making. Rijkswaterstaat and the Delta Commissioner represent the national level, while the provinces of Gelderland and Overijssel represent the local interests. The clear distinction between national and local players might lead to potential tensions within the political decision arena. As a result, different approaches, methodologies, and overall frameworks may be employed in developing an effective flood risk mitigation plan. Therefore, Gelderland must delve deeper into different problem understandings and their implications for the decision-making process to represent the local interests effectively.

2.3 Problem Framing

The previous analysis highlighted a potential conflict between national and local perspectives regarding problem understandings. A similar conflict arises when considering preferences for different policy options. Early warning systems are not deemed a viable policy option due to their potential for failure and the disproportionate reduction in expected loss of life compared to expected damages (Thieken et al., 2022). Therefore, only two infrastructure policy measures are recognized as effective in various forms:

- Increasing the height of existing dikes or investing in the development of new dikes.
- Implementing measures that provide space for the IJssel river near the dike rings (referred to as Room for River).

In the subsequent sections, we will explore the conflicting national and local perspectives, and formulate research questions that will guide this report.

2.3.1 Local Problem Perspective

The local problem perspective of Gelderland represents the interests of its three dike rings. In terms of general interests, ensuring the safety and security of residents is paramount, with a focus on preventing loss of life from flooding events. Additionally, there is a strong emphasis on enhancing economic development to support local businesses and maintain a high standard of living.

Rural dike rings 1 and 2, and urban dike ring 3, exhibit distinct concerns. Dike rings 1 and 2 prioritize the protection of farmland, which is crucial for farmers' livelihoods and contributes to the local economy. These stakeholders favor technological solutions that preserve their living standards and lean towards dike raising to prevent the conversion of farmland into Room for River (RfR) projects. However, they acknowledge their responsibility towards overall flood risk management in the IJssel River basin and are open to RfR projects as long as implementation is evenly distributed across provinces. Dike ring 3 aims to minimize flood risk and ensure the safety of its citizens, with compensation for potential relocation being another key interest in the area.

Furthermore, local stakeholders approach problem formulation from an egalitarian perspective. Dike rings emphasize the equitable distribution of costs and benefits among all rings and their residents rather than disproportionately burdening a specific ring.

The local problem perspective in Gelderland shapes three key objectives for the regional player:

1. Prioritize the physical safety and security of residents to prevent loss of life from flooding events.
2. Ensure the robustness of the economy by supporting businesses and maintaining a high standard of living.
3. Emphasize cost-effective and efficient solutions to address uncertainty and the effects of climate change.

2.3.2 National Problem Perspective

The national problem understanding emphasizes a science-based approach grounded in technical expertise and national interests. It prioritizes cohesive and integrated flood risk reduction strategies based on a utilitarian problem perspective, favoring an aggregated understanding of the problem. While it may appear less attentive to local needs, the national perspective aims to protect the entire country from flood risks, contributing to a comprehensive and coordinated strategy for effective flood risk management.

In contrast to the local perspective, national actors recognize the significance of unified decision-making and coordinated efforts on a national scale. They prioritize flood risk reduction policies that align with expertise, considering technical feasibility, cost-effectiveness, and long-term sustainability. As a result, they favor climate-adaptive policies, such as RfR projects, which are nature-based solutions and inherently climate adaptive.

2.3.3 Rival Framing: Local versus National

The consideration of the rivaling problem framings, with their underlying ethical principles of utilitarian and egalitarian perspectives is crucial for Gelderland to effectively influence the complex political decision process. To address both framings, three non-negotiables are identified considering local and national interests (Appendix B).

Additionally, it is important to acknowledge that the contrasting perspectives reflect parallel views on the role of value driven politics and science-based solutions. The local problem framing emphasizes community interests, public opinion, and the accountability of political representatives. It recognizes the political factors and values involved in decision-making, ensuring that flood risk management strategies align with the specific needs and aspirations of local communities. On the other hand, the national problem framing places greater emphasis on science, technical expertise, and national interests. It aims to develop comprehensive strategies based on scientific knowledge, considering the broader welfare of the entire country.

The tension between political and technical problem understandings is closely tied to local versus national dynamics. By considering both perspectives, Gelderland can navigate the complexities of flood risk management and develop inclusive policies that balance national and local interests. Hence, we ask:

> *Q1) How can Gelderland reconcile the regional and national perspectives in flood risk management to develop a robust policy decision that effectively balances the needs and priorities of local communities with the broader national objectives?*

To answer this question in greater detail, we developed two subquestions that focus on Q2) political decision-making and Q3) finding a robust policy.

> *Q2) How do existing power dynamics affect the decision-making in flood mitigation policy for Gelderland?*

> *Q3) What focus would potential robust policies under deep uncertainty set and how do they perform in the political arena?*

3 Methodology

To support the province of Gelderland in finding a robust policy decision that effectively balances the needs of local communities with the broader national objectives, we have implemented a methodology that integrates widely used techniques for model-based decision support for environmental policies. These techniques have been proven to aid in making decisions even in highly complex and uncertain conditions (Kasprzyk et al., 2013; Kwakkel, 2017).

The analysis is conducted in two stages (Figure 3). First, an open exploration process is implemented to understand the model's behavior and limitations using sensitivity analyses and scenario discovery methods. The exploration was conducted by contrasting the local and national perspectives to understand the implications of these two opposing political lenses toward resilience building. This exploration produced a set of constraints and insights that were used as the basis to conduct a directed policy search.

A multi-objective evolutionary algorithm (MOEA) was implemented that generated a set of over 8,000 policies that optimally balance the levers to find the safest and least costly combinations of levers. These large sets of policies were then filtered using political constraints derived from the stakeholder analysis resulting in 9 viable optimal policies. Finally, these nine policies were evaluated under deep uncertainty to identify three robust policies, considering the limited knowledge of the system and its future behavior.

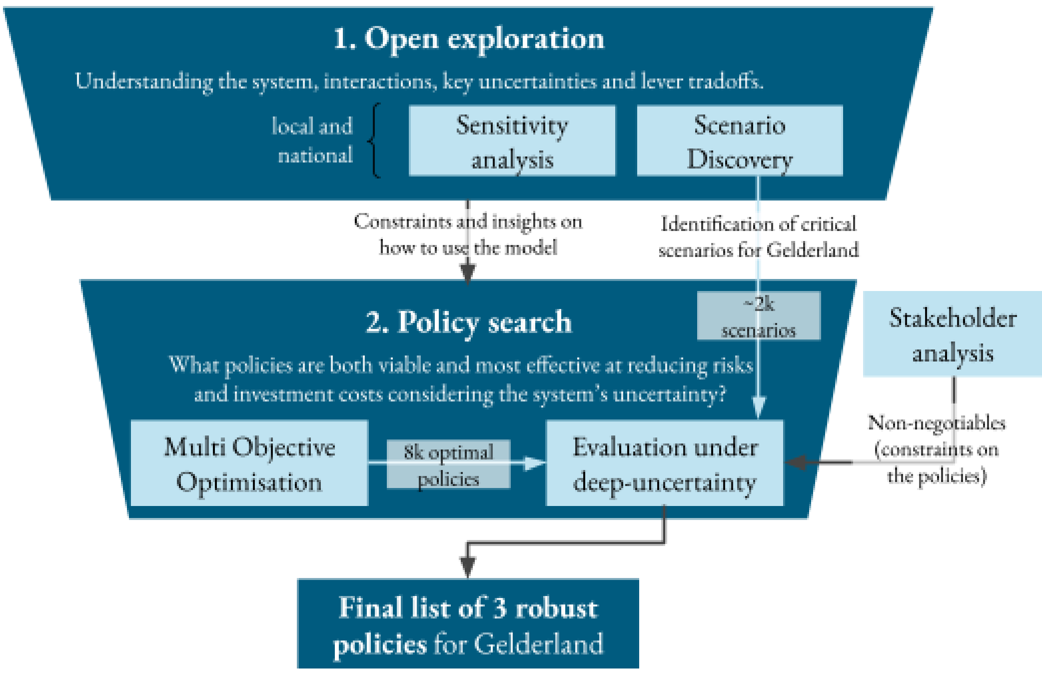


Figure 3. Methodological Overview of the Analysis Workflow. The diagram illustrates a two-step process resulting in a final list of policy recommendations. The initial open exploration phase informs the subsequent directed search analysis.

3.1 Model-Based Decision Support

The approach towards using models for decision-making support used in this report follows the XLRM framework designed by Lempert et. al. (2003). This framework consists of categorizing all the variables in a model in external factors (X), levers (L), relations (R) and measures (M) (Table 1). This framework was applied to an adapted version of the Dike *model*, developed by Alessio Ciullio of Deltares to identify optimal policies under uncertainty. The complete description of the model's modifications can be found in Appendix C.

Table 1. Components of the model based on the XLRM approach

Components		Definition	Variables in the model
X	**Eternal factors** or **uncertainties**	Factors that influence the behavior of the system but are outside of the policy-maker's control and its numerical values are unknown and dynamic.	Economic (discount rate), hydrologic (flood shape) and hydraulic variables (probability of dike failure, breach rate growth, dike breach final width).
L	**Levers**	Set of variables that the policy-maker could modify. A specific combination of levers is called a policy.	What room for the river projects are implemented and how much dikes will be increased in each dike ring.
R	**Relations**	Set of equations that define how the measures are calculated based on the levers and uncertainties.	A set of hydrologic, hydraulic and economic equations to estimate flooding risks and potential impacts.
M	**Measures** or **outcomes**	Indicators assessing the performance of the policies calculated by the model	Expected damage in every dike ring and the investment costs of the policies.

Note. See the full descriptions of the variables in Appendix D.

At its most basic level, the *Dike model* has three stages of simulation (Appendix C Figure C.1). First, a hydrologic submodel simulates how high water-level events flow through the canal system. Then, a hydraulic submodel estimates whether that water flowing through the canal can cause a breach on each dike rings' dikes and what is the extent of that breach. Finally, an economic submodel estimates how much damage would that breach generate in each dike ring as well as the investment costs of the policies.

The Dike model is a simplified representation of reality. As such, to use it for advising policy-making requires robust scientific approaches like modeling under deep uncertainty and responsible modeling which are described in the following section.

3.2 Decision-Making Under Deep Uncertainty

As climate change makes extreme weather events less predictable, devising long-term solutions for flood protection is increasingly challenging. Mathematical models that test potential solutions against possible futures have been increasingly used to deal with climate change uncertainty. However, no mathematical models, huge socio-environmental ones, are perfectly accurate. This twofold uncertainty, where we do not know how the future will be or all the details of the system's behavior, is called deep uncertainty (Walker et al., 2013).

Decision-making under deep uncertainty arises as a comprehensive set of tools designed to face these challenges. The basic idea behind the framework is that instead of reducing uncertainty by having more precise values for the uncertain parameters, we try to devise solutions that work no matter the exact values of those parameters. To do so, tools are implemented to create tens of thousands of combinations of all the possible values of the uncertain parameters. Policies are then assessed using the model for all these combinations of uncertainties, called scenarios. Then insights are provided from that ensemble of outcomes instead of only using likely scenarios. These types of solutions are called robust (Lempert, 2019).

Deep uncertainty also arises from different interpretations of the problem and the stakeholders' values in the decision-making process. Most notably, we have identified two conflicting framings for resilience building in the political arena: the local and national perspectives. To face this challenge, all the analyses are conducted from these two main perspectives giving the policy-maker a wider view of the problem. As such, the report follows a comprehensive methodology supporting the analysis of solutions for multiple futures and scenarios and different actors (Appendix E).

4 Results

Based on our presented methodology, we first conducted an open exploration to gain a better understanding of the uncertainties and levers and furthermore, discover interesting scenarios. These insights were then used for a directed search that results in specific policy recommendations. The used model and further code for analysis can be found on GitHub.

4.1 Open Exploration

With such a complex problem of high value commensurability and uncertainty, there is a strong need to use computer-assisted reasoning to draw deeper insights about the behavior of the model, the interaction between inputs and outputs. The top-down and bottom-up perspective was introduced as they are perceived to be the two most dominant and polarized frames expected in the political discussions.

4.1.1 Local Perspective

From a local perspective, the effects of dike rings' policies and uncertainties on the dike ring outcomes are analyzed through feature scoring. This would be the main interest of local actors to understand the specific benefits and risks they bear. The observations are as follows:

- It is **generally observed** that dike ring outcomes are primarily linked to the uncertainties and policies associated with its specific dike ring as shown from their high feature scores which implies a stronger influence on the outcome variable.
- In the **policy space**, it is apparent that the dike increase policies have a much larger influence than RfR for both outcomes of expected deaths and damages (Figure 4). Additionally, it is observed that EWS only influences deaths and not damages.
- In the **uncertainty space**, probability of dike failure (p_{fail}) is the primary uncertainty that seems to have any influence on any outcome. This uncertainty influences both the damage and deaths in its area. Additionally, a spillover effect is observed as seen from the faint upper triangle on the uncertainty space (Figure 4 right). The probability of A1's failure has influenced outcomes on A1-A5 but A5 only influences outcomes on itself. This implies that upstream dike rings seem to have cascading effects on the downstream dike rings.

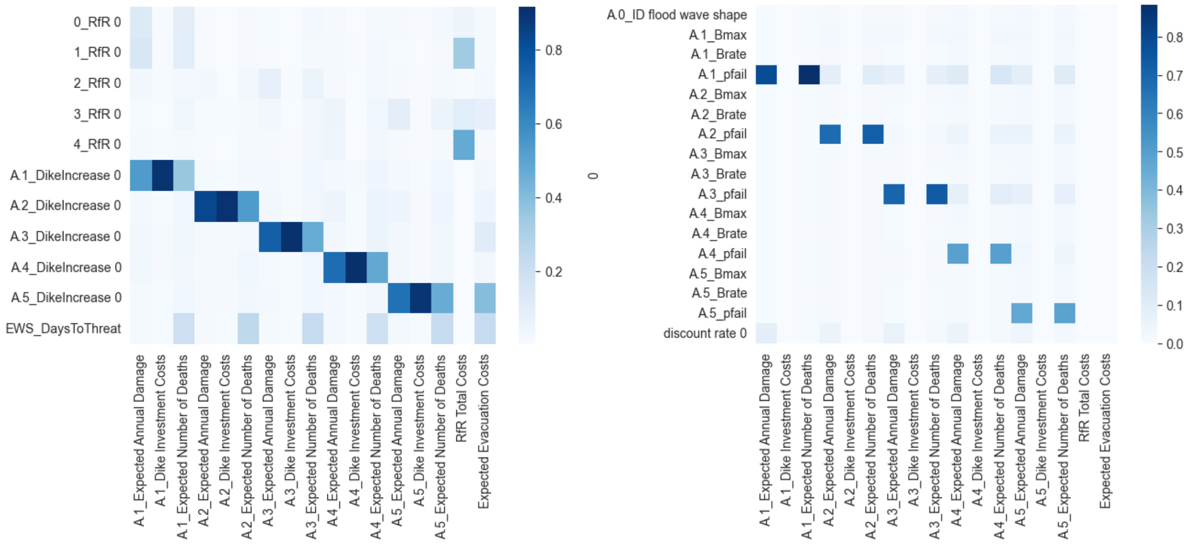


Figure 4. Feature Scoring of Policy Space (left) and Uncertainty Space (right) respectively.

These observations translate to 3 main implications about the perspective of local actors:

Firstly, the **dominant approach** for local actors is prominent. As the model shows that outcomes of a dike ring are attributed to its uncertainties and policy solutions, there is a narrative of equality since a dike ring should bear the cost of a solution to prevent undesirable outcomes on their land.

Secondly, with regard to the **policy space**, it draws attention to political implications of the EWS policies beyond the model. The observation that EWS helps with deaths but not damage reaffirms our earlier decision to exclude EWS as it cannot be seen as a critical nor comprehensive solution.

Lastly, with regard to the **uncertainty space**, it acknowledges the presence of interaction effects through over the observation of spillovers in of the dike failure probabilities. Practically speaking, it will imply a complexity in distribution of cost and benefits, i.e. funding the solution and compensations, if a collaborative solution is created.

4.1.2 National Perspective

From a national perspective, the effects of dike rings' policies and uncertainties on the nation-wide outcomes are analyzed. Lobby groups and Governmental actors would be interested in deriving the most effective cumulative solution of all dike rings. This perspective is analyzed to understand potential key aspects in their political arguments.

- From an aggregated perspective, the **interaction effects** are observed to be more prominent on an aggregate. This is illustrated in Figure 5 where total-order indices (ST) are significantly higher than first-order indices (S1) values which shows that total effects have much greater influence as opposed to direct effects.
- As such, **combination pairs of policy levers** (2nd order effects) are also analyzed to draw hints as to what fundamental interactions could create significant impacts. For expected annual deaths (see Figure 6), A3 dike increase coupled with EWS has an uncontested top effect. Upon inspection of exogenous model input data, it is likely because A3 is by far the densest by citizen population. For expected annual damage (see Appendix F), any combination of A1 dike increase with another dike increase or RfR (0 and 1) has high effects. This could be because of spillover effects where upstream A1 has the ability to reduce flood risk for all downstream dike rings.

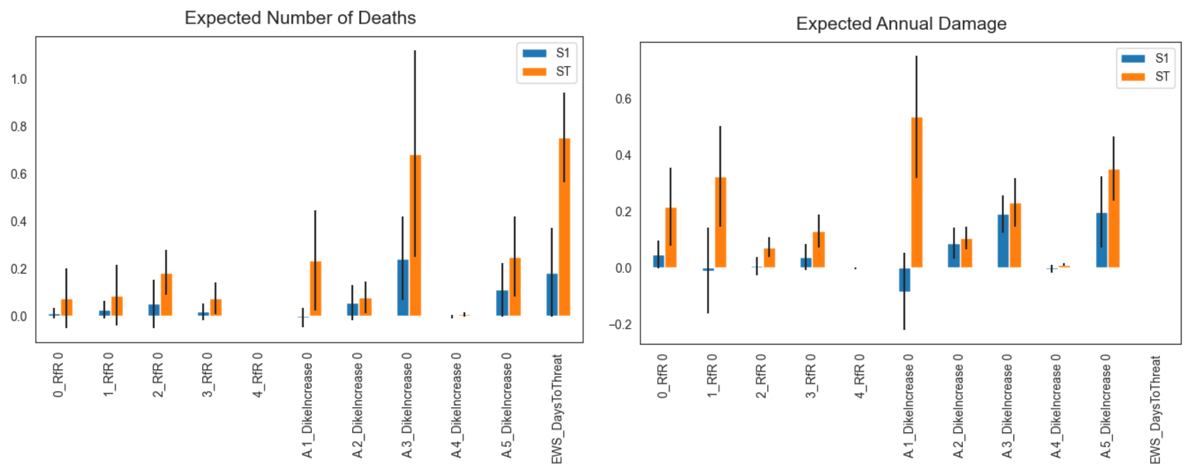


Figure 5. Sobol indices of Annual Deaths (left) and Annual Damages (right). The overall greater ST values over S1 values illustrates the importance of interaction effects on aggregate level outcomes.

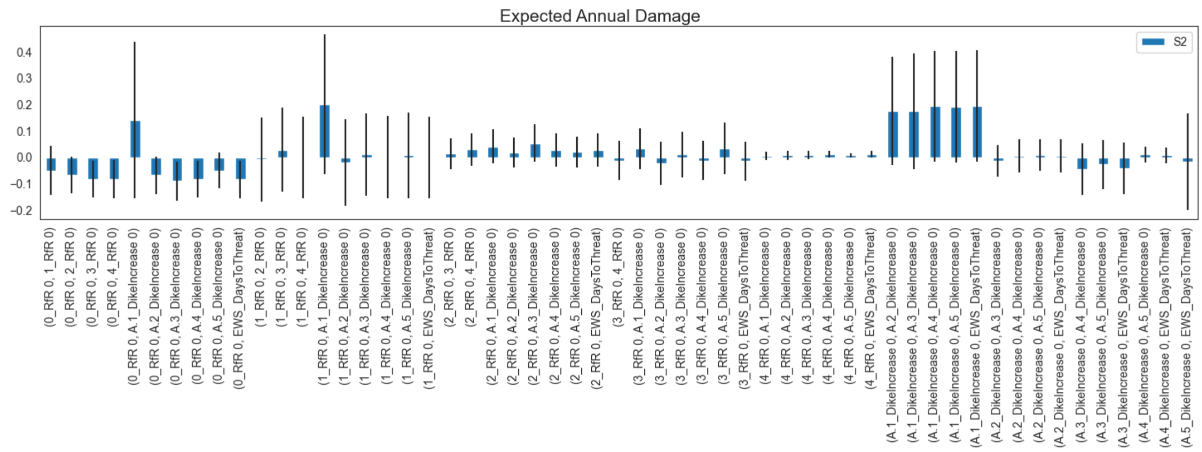


Figure 6. 2nd Order Effects of Annual Damage – A1 Dike Increase with any combination of dike increase or RfR (0 and 1) has high influence. See Appendix G for the Effects of Expected Deaths.

These observations translate to two main implications about the perspective of national actors:

Firstly, from understanding **interaction effects**, it is clear that the most efficient national-level outcomes will have a multi-levers collaborative.

Secondly, from studying the **most influential levers**, a system understanding is formed where focusing on certain dike rings would allow for a much greater cumulative effect because of their vulnerability such as population density and geography (upstream/downstream).

Finally and conclusively, there is an evident **conflict in perspectives** between local and national actors. Local actors tend to advocate for egalitarian solutions, where each dike ring is treated equally due to their direct involvement in costs and benefits with their respective areas. On the other hand, national actors may allow a specific dike ring to bear a disproportionate cost if it greatly benefits the other dike rings. In policy search it is crucial to find a balance where the consideration of all dike rings is prioritized while maintaining overall efficiency on an aggregate level.

4.1.3 Uncertainty Space

From the two above perspectives, we saw some common areas of uncertainties in the model that we saw a need to address.

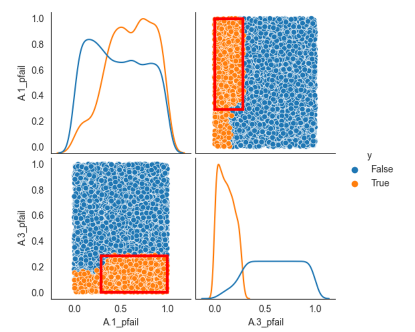
Firstly, the inclusion of EWS in the model appears to be a red herring. The policy is generally understood to be ineffective due to it being a final safety net and reactionary mechanism that does not reliably mitigate overall risk (Cools et al, 2016). Yet it creates a disproportionately high influence on our outcomes, which distracts the dominant local frame of proactive flood management.

Hence, the model is adjusted for a more realistic approach. Based on the results of the open exploration, the EWS lever was removed. We did so by setting the impacts for EWS to zero on all potential outcomes.

Secondly, uncertainties in probability of dike failure (p_{fail}) play a significant influence in the outcome, especially with the spill-over effects. Thus, scenario discovery is conducted to search for crucial uncertainty spaces to test as part of the policy search. The Patient Rule Induction Method (PRIM) was used to partition the uncertainty space based on the top 20% of different dike ring outcomes (expected annual deaths and expected annual deaths). Only dike rings in Gelderland were analyzed because of political self-interests as well as the comparatively important role as the upstream actor.

Table 2. Summarized results of PRIM which was applied to explore the range of uncertainties that causes the top 20% of Deaths and Damages for each dike ring in Gelderland. The primary uncertainty variable explains the variances in outcomes more than the secondary. Complete PRIM results in Appendix H.

Outcomes (Top 20% of)	Primary Uncertainty	Secondary Uncertainty
Deaths A.1	$0.00 < A.1\_p_{fail} < 0.31$	-NIL-
Deaths A.2	$0.00 < A.2\_p_{fail} < 0.28$	$0.27 < A.1\_p_{fail} < 1$
Deaths A.3	$0.00 < A.3\_p_{fail} < 0.28$	$0.21 < A.1\_p_{fail} < 1$
Damage A.1	1.5 < Discount Rate 0 < 3	$0.00 < A.1\_p_{fail} < 0.34$
Damage A.2	$0.00 < A.2\_p_{fail} < 0.25$	$0.19 < A.1\_p_{fail} < 1$
Damage A.3	$0.00 < A.3\_p_{fail} < 0.23$	$0.21 < A1\_p_{fail} < 1$



Example on A.3 Deaths

In general, a significant amount of density and coverage can be explained with 2 dimensions of uncertainties or less (results are found in Appendix I).

As described by Table 2, the PRIM results also validates the feature scoring results (in Section 4.1.1); the lower bound of $\_p_{fail}$ (higher likelihood of breaching) in one's own dike ring explains the most undesirable outcomes. It is also observed that the upper bounds of A.1$_p_{fail}$ (lower likelihood of failure) is the secondary variable; this describes a zero-sum interaction where more upstream has to flood in order for downstream to flood less.

4.2 Policy Search

This section aims to identify appropriate policy options for effective flood management through a structured policy search methodology. Our approach is split into three parts. First, we use directed search to optimize a range of potential policies based on a reference scenario. Afterwards, we narrow a policy subgroup based on political constraints (Section 4.2.2). Lastly, we test the selected policies for their robustness and vulnerabilities over relevant scenarios that were identified in the open exploration. This overall approach is based on the idea of robust decision-making (RDM) (Lempert, 2019).

Our open exploration showed the need to find balanced trade-offs between the competing perspectives. All dike rings ought to be protected while maintaining overall efficiency. As such, the directed search would run on disaggregated problem formulation to initially account for the wide range of trade-offs comprehensively. However, outcomes at local, regional and national levels of aggregation are considered and addressed in the final evaluation process.

4.2.1 Directed Search

For our directed policy search, we followed a multi-objective robust decision-making (MORDM) process as it is a state-of-the-art approach to handle deep uncertainty over multiple objectives (Kasprzyk et al., 2013). The approach was implemented using the python package ema-workbench (Kwakkel, 2017). We used multi-objective evolutionary algorithms (MOEA), as this class of algorithms is especially suitable because it gives Pareto optimal solutions while handling multiple objectives. The algorithm has an evolutionary characteristic which lets it iterate over the population and is generally speaking also regularly used in water resource management (Zatarain Salazar et al., 2016). Given the fact that MOEA is stochastic we provide a reference scenario, which illustrates an average case scenario. The scenario can be found in Appendix J.

A key component of the optimization progress is the number of functional evaluations (nfe). A high number of nfe ensures that all potential policies will be assessed. Due to a trade-off with the available computing resources and the scope of this project, we settled for a nfe of 50.000. Additional model configurations are explained in Appendix E. Our first directed search resulted in a policy space of 8107 pareto-optimal policies.

4.2.2 Policy Constraints and Selection

This high amount of policies is not yet suitable for a concrete recommendation and further robustness assessments. Hence, we applied a set of political non-negotiable constraints to create a more specified subspace. Policies were filtered for the following political non-negotiables that can be found in Appendix B.

With these steps, 19 Pareto-optimal policies remained that would be politically feasible as seen in Appendix L. However, to further narrow down the list, a robustness assessment was conducted to identify the best policies under deep uncertainty.

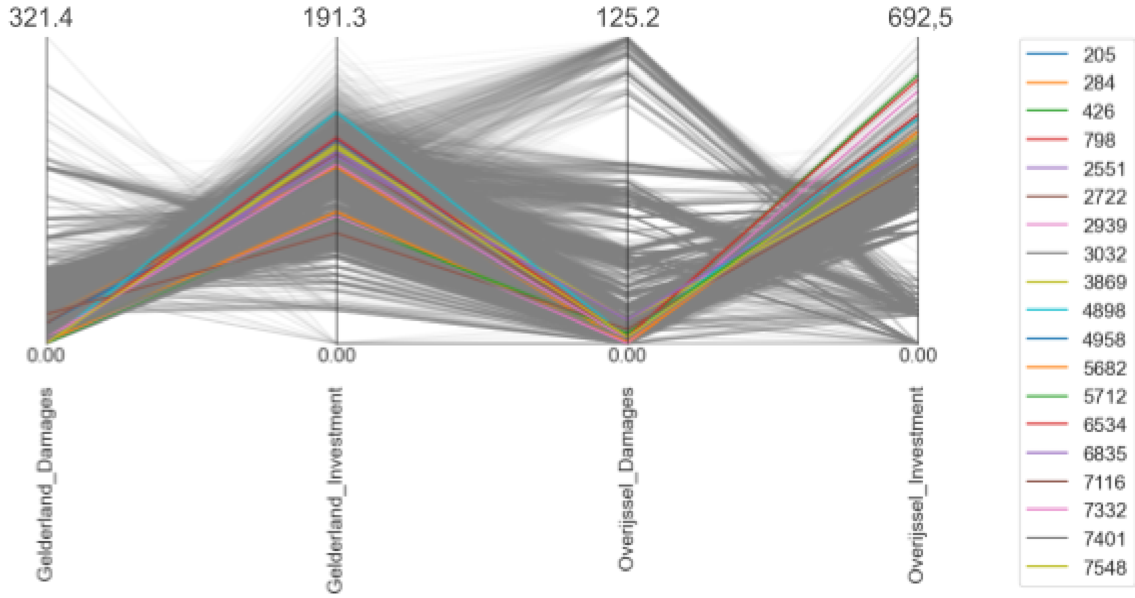


Figure 7. Damage and Investment Trade-offs of Optimized Policies (grey) and Politically Feasible Optimal Policies (colored). Outcomes are presented in million EUR.

The graphs highlight the trade-off between dike investments and expected damage. Moreover, it is visible that Gelderland tends to invest more in limiting damages compared to Overijssel. This interaction shows the different power levels actors have in the problem and the complication on finding a suitable policy option for all involved stakeholders. Overall, the selected constraints perform well in also choosing policies that are limiting the effects on damages for the two provinces.

4.3 Robustness Assessment

To further assess the previously selected policies, we used two robustness metrics and evaluated our selected policies over a range of 2,326 scenarios that resulted from the open exploration. For our metrics, we first chose to use the Signal-To-Noise Ratio (SnS) which can be used to investigate the relation between the expected value and standard deviation. As all our outcomes are minimized, the optimal SnS values are as low as possible as this indicates a low expected value and low standard deviation, hence, high robustness (McPhail et al., 2018).

In addition, we applied a regret matrix to investigate the impact if one policy would be chosen over another. We took the difference of something and normalized the values. Thus, a value of 1 indicates the most regretful policy and a value of 0 the least regretful.

4.3.1 Signal-to-Noise Ratio

For the first metric, we investigated all three aggregation levels (local, regional, national) to fully understand the volatility on different outcomes and what different stakeholders would value and argue for.

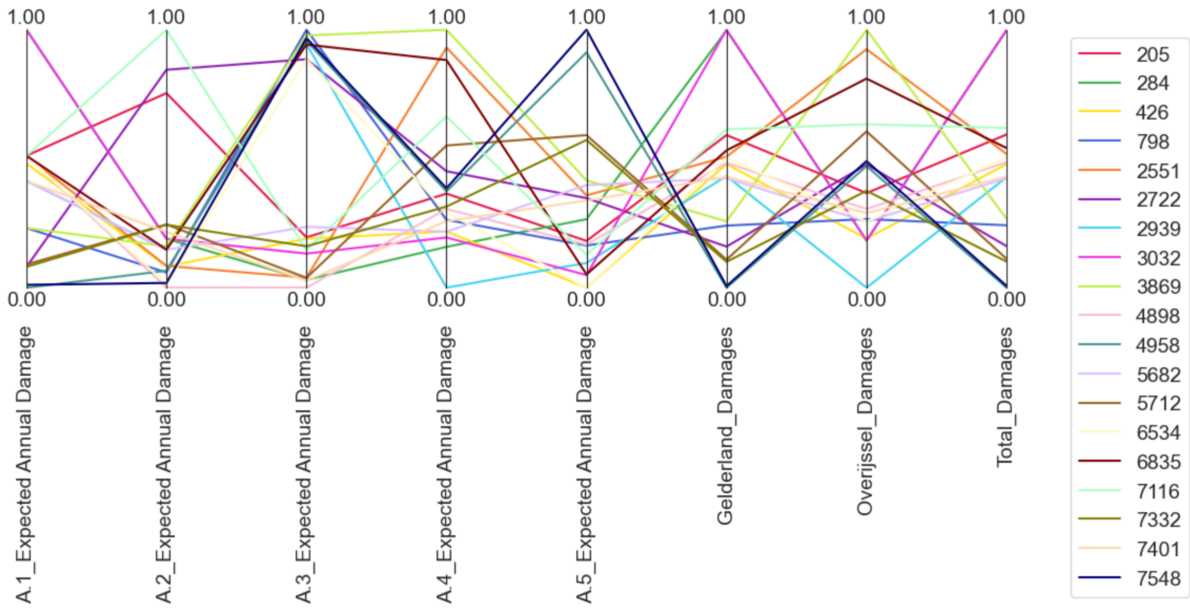


Figure 10. Parallel Axis Plot Analyzing Policy Robustness for Gelderland. The plot visually represents the interaction between variables, specifically focusing on the robustness of a policy for Gelderland and providing a comprehensive view. The legend includes the corresponding colors and policy identifiers. The y-axis has been normalized and ranges from 0 to 1, facilitating the comparison of values.

No policy presents a low score on all outcomes. We analyzed the data by looking at the local, regional, and national perspective and determined that all policies that have a SnS-Ratio close to 1 are too volatile and hence, cannot be used for a robust policy. It is evident that policies with high volatility for damages in one of the provinces tend to have less in the other province, and vice versa. Thus, we excluded 10 non-robust from further analysis and have 9 remaining policies (Table 3).

4.3.2 Maximum Regret

To further scope down the number of preferred policy options, robustness is further assessed using maximum regret indicators. These indicators calculate how often a policy is outperformed by the others in each scenario. A high value means that in most scenarios you would regret implementing that policy as other policies would have yielded better results. The values of regret for each one of the 9 policies for each dike ring can be found in Appendix K. However, to assess the policies with a single regret value that captures the information of all dike rings, a spatial aggregation must be made to create relevant robustness indicators for this specific case.

We analyzed the aspect from both national and local perspectives to account for all stakeholder perspectives. Hence, we introduced two risk indicators. From the national perspective, we calculated a utilitarian risk indicator that is based on the normalized maximum regret of the total damages of a policy. In addition, we provide for the local perspective an egalitarian indicator that is calculated by the sum of squared maximum regrets of the individual dike rings which punishes unequal distribution of regret. As such, we put a higher emphasis on the individual outcomes for dike rings and argue from the standpoint of distributive justice. For both indicators, it is optimal to have low scores. The data is displayed in Table 3; further visualization and explanation can be found in Appendix L.

Table 3. Overview on selected policies with their respective levers, cost, and regret indicators. Egalitarian is seen as the local perspective, Utilitarian as the national.

Policy		RfR					Dike Increase [dm]					Total Investment [million EUR]	Regret Indicator	
Name	ID	0	1	2	3	4	1	2	3	4	5		Local	National
Perspective Tradeoff	7548	1	1	0	1	1	1	5	6	1	6	850	0.0	1.0
Low-risk Green Infrastructure	7332	0	1	1	1	1	2	2	6	1	6	784	0.1	0.4
Green Infrastructure Co-Benefits	5712	1	1	1	1	0	0	2	7	1	6	578	0.2	0.4
Low-Cost Gray Infrastructure	5682	1	0	0	1	0	0	3	7	2	6	335	0.5	0.2
Low-Cost Gray Infrastructure 2	2939	1	0	0	1	0	0	3	6	6	7	342	0.6	0.2
Utilitarian	426	0	1	1	1	0	0	3	6	2	9	509	0.6	0.0
Utilitarian Green Infrastructure	7401	1	0	1	1	1	0	2	7	1	6	616	0.7	0.2
High Regret	4898	0	0	0	1	1	2	6	9	1	7	572	1.0	0.8

Note. The 3 selected policies due to their low regret in the egalitarian perspective are highlighted in bold and further discussed in the Section 5.1.

It is evident that there is not one policy that has the least regret on both a utilitarian and egalitarian approach. These tradeoffs highlight another unavoidable conflict between the national point of view, that seeks to minimize risks over the whole region, and the local one where the priority is reducing risks in each one of the dike rings. On a utilitarian level, it is more beneficial to have less room for river projects and have no dike increase on dike ring 1. Moreover, policies tend to have lower costs. On an egalitarian level, the most desirable policies have dike increases on all dike rings and tend to have more RfR projects. These results illustrate again the inherent conflict between the rival problem framings of national and local actors. A feasible policy needs to take this into account and find possible compromises between both sides.

5 Discussion

Considering the complexity of model-based decision-making in general as well as the complexity of the specific case of flood protection for the IJssel River, we present our main findings in a four points discussion. These recommendations can guide the province of Gelderland in the upcoming discussion with local and regional discussion for the IJssel River shared vision 2100.

5.1 Policy Recommendation

Based on our optimization and robustness assessment, we argue that the Gelderland province should build a narrative that focuses on a bottom-up egalitarian approach to ensure that those who bear the risks, the dike rings, are equally represented. The proposed policies focus on minimizing damage over a wide range of risky futures for all dike rings in the IJssel region and the investment costs. Three policies were selected based on these criteria. The values of damages are assessed over all the scenarios as shown in Appendix M and can be used in future conversations about compensations due to risk transfer. The proposed policies are the following:

- **Low-Risk Green Infrastructure (7332)**
  This policy could yield the most protection over all dike rings as it has the lowest egalitarian regret score. This policy proposes 4 RfR projects offering the region a nature-based solution approach towards flood prevention. The high costs of this policy derive from the RfR 4 project is costly and affect the urban dike ring 5.
- **Green Infrastructure Co-Benefits (5712)**
  This policy yields also very low egalitarian regret scores meaning that most dike rings would benefit from it over most future scenarios. Four dike ring projects are also proposed offering high environmental and climate change adaptation co-benefits. Additionally, the swap of RfR4 to RfR0 from the Egalitarian Green Infrastructure policy not only reduces costs by approximately €200 million but also further protects the high ecological value area present in dike ring 1.
- **Low-cost Grey Infrastructure (5682)**
  This policy mostly relies on dike increases to protect the dike rings. Two RfR projects are implemented, one in the high ecological area of dike ring 1 and another one in dike ring 4 where there might be a potential overflow area. This approach might limit environmental and adaptation co-benefits but presents the lowest cost of the set of optimal, non-volatile and low-regret policies. This policy is particularly risky for dike ring 1 where damages could reach up to €150 million (Appendix M). If this policy is implemented due to budgetary limitations, a comprehensive compensation scheme.

Other policies have been excluded from is final risk for their high relative egalitarian regret (4898, 7401, 426), similarity with other preferred policies (2939) or exceeding tradeoff between the perspectives (7548).

5.2 Acknowledging Stakeholder Interests

Understanding various interests and non-negotiables in a model is proven to be important in achieving a politically acceptable but effective policy. From open exploration, it is clear that because the aggregate levels of objectives are different for local and national actors, the policies in which they would support will be likewise quite different.

Our results showed how different policies focus on competing stakeholder interests. Local actors would go for solutions of self-protection where benefits and costs are contained within their boundaries, national actors tend to push for more utilitarian outcomes; and as a result regional actors like Gelderland have to navigate between these two policy approaches as a middleman.

Because consensus on the outcome cannot be drawn due to rival framings, the final solution would be a compromise on policy preferences – likely to result in a lose-lose outcome. Hence, the modeling approach of integrating interests from both local and national actors addresses this by drawing focus to the negotiation of goals but yet guarantee that policies on the table will deliver pareto-optimal outcomes.

5.3 Model Limitations: Boundaries in Science and Political Values

The validity of the model is rather limited in understanding social-hydrological interactions. As inferred by the structure, the hydrological dynamics of the model are endogenously modeled while the social impacts such as deaths and costs are exogenously modeled based on lookup inputs. However, all of the outcomes are measured in social impacts as a proxy to understand risk in the hydrological, but does not capture the complexity between social and hydrological factors that would be important in designing local and regional scale policies.

Additionally the model is limited in representing temporal dynamics. Most variables relating to demographic, hydrometeorological are assumed to be static; this does not provide enough space to account for long term population dynamics and climate change variability respectively. Also, policies could be lacking in detail like construction delays and specific policy interactions like dike increase and room for rivers in the same dike ring, which limits the range of policies explored. Hence, the model could be insufficient in achieving sustainability which was thought to be important considering the default 200 year time horizon. Producing adaptive pathways would also be difficult because of these constraints. Future work could improve on this.

The model has limited representation that is able to cover all politically relevant factors extensively in the decision arena comprehensively. For example, the interests of German actors are not represented in the model since it is scoped within the national boundaries even though the IJssel river is transboundary. Hence, we argue that most parts of the modeling process is exploratory in nature, where it reflects on the important and necessary conditions needed to reach a more desirable solution.

The policy search methodology also assumes an organized stepwise process in which policies are incrementally narrowed down based on considerations to objectives, uncertainties and robustness. However, in the heuristics of "nothing is agreed until everything is agreed", our process of negotiating trade-offs in simulations will not be reflective of complex multi-agenda negotiations in political settings.

All in all, these limitations are a reminder that even though these methods have the potential to be prescriptive, such a technocratic approach would not hold up in a real-world political decision-making process where complex value discussions are dominant. Thus, this reinforces the primary purpose of scientific models to be descriptive and evaluative, to inform the consequences of policies and draw greater consensus on knowledge.

In our context, the model allows us to gain a better system understanding of conflicting objectives, address trade-offs in policy and clarify deep uncertainties to enrich political discussions.

5.4 Dynamic Adaptation For Future Challenges

Within Decision-Making under Deep Uncertainty there are two approaches towards the implementation of the policies found via MOOA and scenario discovery. On the one hand, we can seek to find a policy today that could work best for every possible future. However, this approach only superficially recognizes the irresolvable uncertainties as well as core model limitations. On the other hand, a dynamic approach can be implemented, offering the tools to react to the changing environment in order to implement solutions that work best considering what future we are starting to move into. This is a more cautionary approach towards planning under uncertainty as it gives the opportunity to decision-makers to navigate the changing environmental, social and political and physical environment as they evolve which is more in-line with Gelderland's approach towards resilience building. This process is called Dynamic Adaptation Policy Pathways (DAPP) developed by Haasnoot et al. (2013).

DAPP is a methodology that has been implemented for planning and informing decision-making effectively in similar cases all around the world (Deltares, 2023). Although the current implementation of the Dike model, which lacks a better representation of climate and demographic uncertainties, is not suited to develop a DAPP, we consider that the IJssel River could benefit from such an approach. The scenario discovery and MOOA results that can be found on the supplementary material can serve as a baseline for such future efforts (Kwakkel, Haasnoot & Walker, 2016).

6 Conclusion

With this report, the province of Gelderland can reconcile the regional and national perspectives in flood risk management to develop a robust policy decision that effectively balances the needs and priorities of local communities with the broader national objectives. We have shown that the policy is placed in a multi-actor system that covers various political, social, and economic aspects leading to a high level of complexity and uncertainty.

Through state-of-the-art model-based approaches, two main narratives influencing an agreement between actors were identified. On the one hand, there are national actors, like Rijkswaterstraat, that focus on an utilitarian approach using a high level of aggregation on all outcomes. On the other hand, regional and local actors, like Gelderland and their respective dike rings, aim for an egalitarian approach that is based on the concept of distributive justice. Based on the understanding of the model and the political context, a robust policy search under deep uncertainty resulted in a set of optimal and politically-feasible policies that were then further assessed for their robustness across critical scenarios and ranked against each other. This analysis showed again the trade-offs between national, regional, and local actors based on their respective narratives.

We recommend that the province of Gelderland pushes a narrative that is based on local interests and that is agreed upon with the province of Gelderland to obtain a stronger position in the decision-making process. Having these policy narratives allow Gelderland to be flexible within the decision arena when proposing policies to the Rijskwaterstaat.

The **Low-Risk Green Infrastructure** policy provides maximal protection to the dike rings in Gelderland. This approach, underscored by a nature-oriented narrative, includes four Room for River projects and is particularly suitable in scenarios demanding high climate adaptivity. Financially, this policy demands an investment of approximately €784 million.

The Green Infrastructure Co-Benefits policy shares many traits with the Low-Risk Green Infrastructure approach. However, a shift in the prioritization of Room for River projects directs security benefits on a broader, national scale. This adjustment contributes to making it a more cost-effective policy, requiring an estimated investment of around €578 million.

The Low-Cost Gray Infrastructure policy is advised in scenarios where budgetary constraints significantly influence the decision-making process. This approach heavily leans on dike embankments across four of the five dike rings. By building on the foundations laid by previous policies, this strategy is likely to reduce environmental adaptation capacity, a trade-off for its comparatively minimal implementation cost of €335 million.

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Appendix A - Stakeholder analysis

The identified stakeholders are mapped on a power-interest grid representing the *relative* position of each possible stakeholder in terms of their interest and power reflecting a spectrum (Eden & Ackermann, 2021) (Figure A.1).

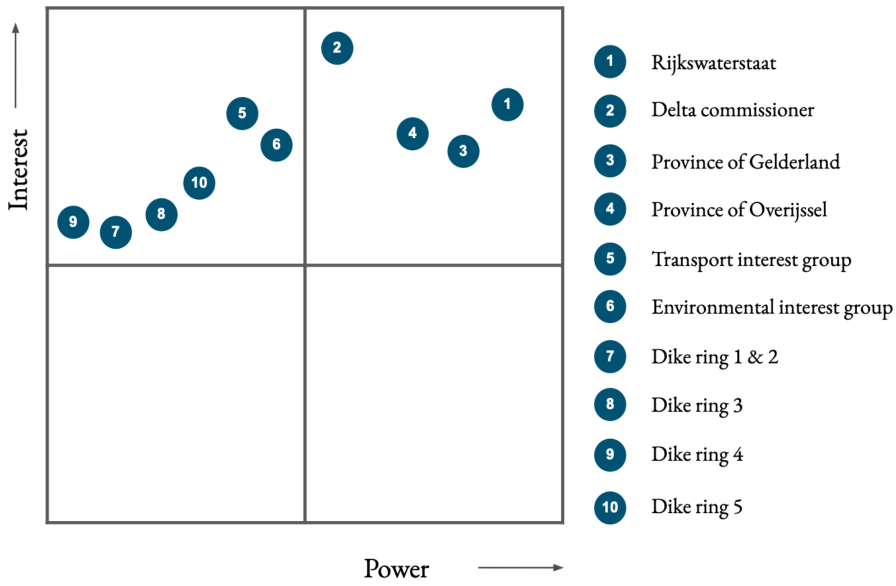


Figure A.1. Power-Interest Grid

Ranking the positions of Power

The actor with most power is the national water management agency (**Rijkswaterstaat**). This actor has the highest political power, as it is the executive organization of the Ministry of Infrastructure and Water Management (Rijksoverheid, 2021). In this capacity, Rijkswaterstaat assumes the responsibility for making final decisions regarding flood mitigation measures along the upper branch of the IJssel River. Crucial for the success are the provinces **Overijssel** and **Gelderland**, ranking second and third in terms of power, respectively. Their approval is essential for the proper implementation of policy levers, considering their control over financial resources and territory. Gelderland, being the upstream province, holds a slightly higher level of power. It can take measures that impact Gelderland, but not vice versa. Ranked fourth is the **Delta Commissioner**, a national actor that makes proposals for the national Delta Programme, including the financial consequences thereof (Deltaprogramma, n.d.). Due to the authoritative nature of their advice, the Delta Commissioner wields significant power. The **environmental** and **transport** interest groups hold the fifth and sixth positions, respectively, in the power ranking. As interest groups, they can only exert some influence on the decision-making process, hence, they are generally regarded as subjects. Among the two, the interest group for the environment is deemed to possess slightly more power due to its larger membership base and greater financial resources (Milieudefensie, n.d.). Lastly, the **dike rings** hold the lowest position in terms of power. They are ranked based on their population size, with the dike ring having the largest population holding the most power.

Ranking the positions of Interest

Determining the relative positions of interest can be more subjective and open to interpretation. To provide a classification, a broader categorization approach has been adopted, without placing undue emphasis on small differences observed in the PI-grid. Among the actors involved, the **Delta Commissioner** holds the highest level of interest since their primary responsibility revolves around ensuring the proper execution of the Delta Programme (Deltaprogramma, n.d.). As a result, flood risk mitigation interventions receive the utmost attention from the commissioner. Both **provinces**, the **Rijkswaterstaat**, and the two **interest groups** also demonstrate significant interest. However, it is important to acknowledge that these actors have multiple other matters to address, preventing them from solely focusing on this issue. Conversely, the **dike rings** exhibit the lowest level of interest, primarily due to the typically limited citizen participation in decision-making processes related to them.

Actor mapping

According to Hermans & Thissen (2009) there are four basic dimensions that help understand and explain actor behavior: networks, perceptions, values, and resources. In order to apply this framework, Table A.1 has been constructed, where each dimension is utilized to provide insights into the behavior and characteristics of the actors involved.

Table A.1: Actor mapping

Actor	Networks	Perceptions	Values	Resources
Rijkswaterstaat	Central position in the network, collaborates with government departments, regional water authorities and provinces, takes a leading role.	Takes into account the wishes of all actors, emphasizes the importance of long-term planning, risk assessment and scientific research in making informed decisions.	Safety above all, but also sustainability and accessibility.	Political power, they have the final say in what flood mitigating measures are taken, also large financial resources from national government funding
Delta Commission(er)	Collaborates closely with Rijkswaterstaat, international experts, universities, research institutes, can function as coordinator	Aims for integrated water management solutions. Considers long-term climate change projections and scientific data to guide decision-making.	Safety, sustainability and resilience in the face of climate change.	Influential recommendations which every actor takes seriously, financial funding by national government,
Province of Gelderland	Represents own dike rings and local municipalities.	Strong emphasis on providing what is best for residents, as it wants to win again at next elections.	Safety. Also quality of life, economic growth, and sustainability. Strives to support local communities.	Allocates budget for water management projects. Support from the province is essential for the success of measures.
Province of Overijssel	Represents own dike rings and local municipalities.	Strong emphasis on providing what is best for residents, as it wants to win again at next elections.	Safety. Also quality of life, economic growth, and sustainability. Strives to support local communities.	Allocates budget for water management projects. Support from the province is essential for the success of measures.
Transport interest	Collaborates with	Emphasizes the importance of	Values economic growth,	Financial resources through

Actor	**Networks**	**Perceptions**	**Values**	**Resources**
group	transportation companies and skippers, engages with policymakers to influence decisions.	efficient mobility and transportation, infrastructure development to support economic growth and connectivity.	improved connectivity and efficient transportation systems. Sustainable transport solutions.	membership fees, industry contributions, utilizes for research, advocacy and influencing transportation and infrastructure policy.
Environmental interest group	Collaborates with other NGO's, engages with policymakers to influence decisions.	Environmental conservation is crucial for the well-being of ecosystems and communities. Advocates for sustainable practices and protection of biodiversity and Natura 2000 areas.	Values biodiversity, ecosystem health, environmental justice. Long-term view.	Donations from supporters, campaigns, community programs.
Dike ring 1&2	Local citizens collaborate with each other, there is no formal representative of a dike ring.	Farmland needs to be protected. Like technological solutions. Keep the current living standard.	Values safety and economy.	None.
Dike ring 3	Local citizens collaborate with each other, there is no formal representative of a dike ring.	Minimizing flood risk, ensuring safety of their citizens.	Safety above all.	None.
Dike ring 4	Local citizens collaborate with each other, there is no formal representative of a dike ring.	Ensuring the land-use for agriculture.	Economic growth. Safety.	None.

Actor	**Networks**	**Perceptions**	**Values**	**Resources**
Dike ring 5	Local citizens collaborate with each other, there is no formal representative of a dike ring.	Minimizing flood risk, ensuring safety of their citizens.	Safety above all.	None.

Appendix B - Political Non-Negotiable Constraints

Table B.1. Political constraints on the possible policies demanded by the stakeholders

Constraint	Stakeholder	Definition
Environmental and climate change adaptation co-benefits	Delta Commission and Rijkswaterstaat	At least one RfR project to be implemented in the IJssel River
Room for River equity	Rural dike rings	If Gelderland is affected by RfR project, then there should be at least one RfR project in Overijssel as well
Dike increase in urban areas	Urban dike rings	The urban dike rings 3 and 5 should have at least a dike increase of 5 dm

Appendix C - Model Description - XLRM Diagram

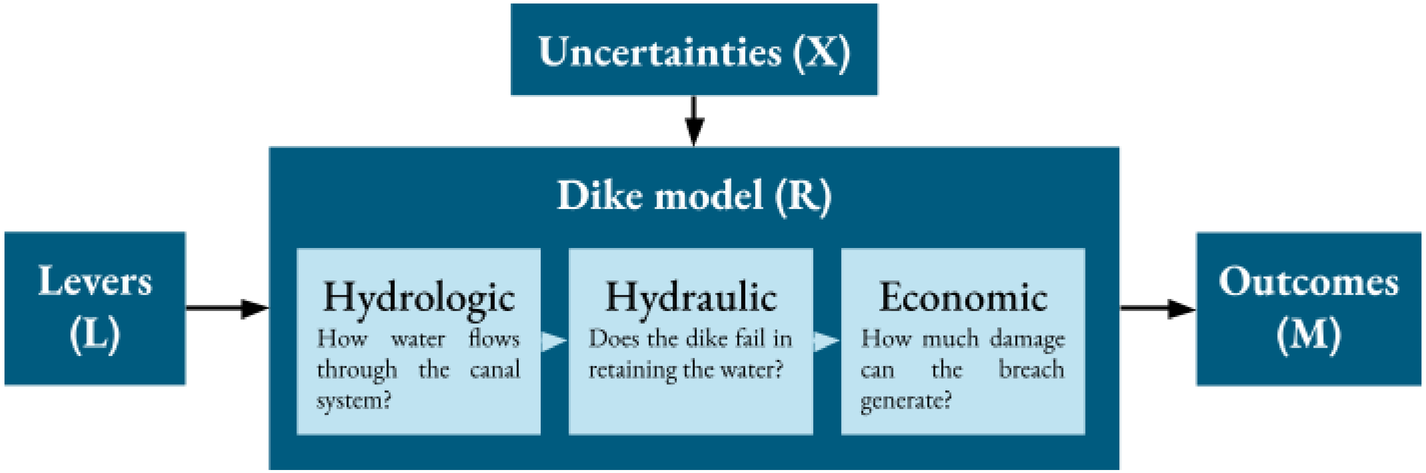


Figure C.1. Dike Model Description representring the relation between Uncertanties (X), Levers (L) Relations (R), and Outcomes (M). The Relations are simulated within three submodels (hydrologic, hydrologic and social/economic).

Appendix D - Model Variables Description

The uncertainties (X) of the simulation model. Note that elements between curly braces represent variables.

type	name	values	description	Unit	notes
categorical	discount rate {timestep}	1.5, 2.5, 3.5, 4.5	Discount rate for calculating present day value of damages	dmnl	
integer	A.0_ID flood wave shape	0-132	A normalized curve describing the shape of the incomming flood wave over time. There are 132 predefined curves.	dmnl	
real	A.{dike_ring}_Bmax	30-350	The final extent of the breach width. The greater the width, the larger the volume of water that enters the floodplain per unit of time	meters	Dike ring 1-5
real	A.{dike_ring}_pfail	0-1	Probability that the dike will withstand the hydraulic load	dmnl	
categorical	A.{dike_ring}_Brate	0, 1.5, 10	How fast the breach grows over time.	1/day	
integer	{location}_RfR {timestep}	0-1	Whether to activate the RfR project at the specified location or not. Once activated, the project remains active.	dmnl	0-4 locations
integer	EWS_DaysToThreat	0-4	Number of days prior to threat to give a warning. False warnings can undermine trust in the system. The earlier the warning the more time to evacuate, but also the more chance of a false warning.	days	
integer	A.{dike_ring}_DikeIncrease {timestep}	0-10	amount of dike raising	decimeter	

The levers (L) of the simulation model. Note that elements between curly braces represent variables.

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

The Outcomes (M) as calculated by the model. Note that elements between curly braces represent variables. Also, note that all outcomes are arrays indexed by timestep.

type	name	description	Unit
array	a.{dike_ring}_Expected Annual Damage	discounted expected annual flood damage	euro
array	a.{dike_ring}_Dike Investment Costs	investment costs of dike raising	euro
array	a.{dike_ring}_Expected Number of Deaths	expected annual number of casualties due to floods	person
array	RfR Total Costs	Investment costs for Room for the River	euro

		projects	
array	Expected Evacuation Costs	Costs of evaluation based on number of people and the duration they have to leave their home	euro

Appendix E - Model Modifications

Derived from the initial steps of open explorations as well as the actor scanning process conducted, several adaptations to the initial definition of the Dike model were made in order to generate simulations useful for the present use case.

Using 1 time step

The way that the Dike Model simulates time is limited as the evolution of socio-environmental or climatic variables is not accounted for. Thus, implementing a policy in the first 30 years or the last 200 is indifferent on a per-year basis. Moreover, the discussion we intended to open with this report is about what project should be implemented in the IJssel River, not what would be the optimal implementation pathway of such a policy. Thus, considering the limited time accountability of the model, as well as the overall purpose of the project, we only used 1 time step and discussed the limitations it implies in the discussion.

Using an 80-year simulation period

The reason why we designed a policy recommendation focused on a shared vision for the next 80 years and not 200 years as it was set in the baseline model is twofold. First of all, a 200 year planning period is extremely challenging from a political perspective as there's an overall reluctance to make such long-term compromises. On the other hand, as mentioned before no demographic or climate trends, variability or scenarios are considered. Thus the uncertainty of the estimated outcomes grows exponentially as the time horizon grows. Although we recognize the importance of devising a solution that works in the long term, we decided to reach a compromise on the time-scope considering the model's limitations and the political imperatives influencing the decision. Discussions around compensation amounts, financial responsibilities or implementation pathways could further benefit for a longer time-horizon if a more detailed depiction of time is incorporated into future models.
By adapting this variable on the model, we also modified the variable num_events to 36 in order to maintain the initial density of events from the initial model formulation.

Tailor-made problem formulation

The approach considered in this report required us to be able to discuss between outcomes disaggregated over dike rings and the total regional agregation derived from the sum of the outcomes of all dike rings. To do so, we required a fully disaggregated problem formulation for both damage and investment costs that we could later aggregate freely after running the simulations. This formulation was named problem formulation 6.

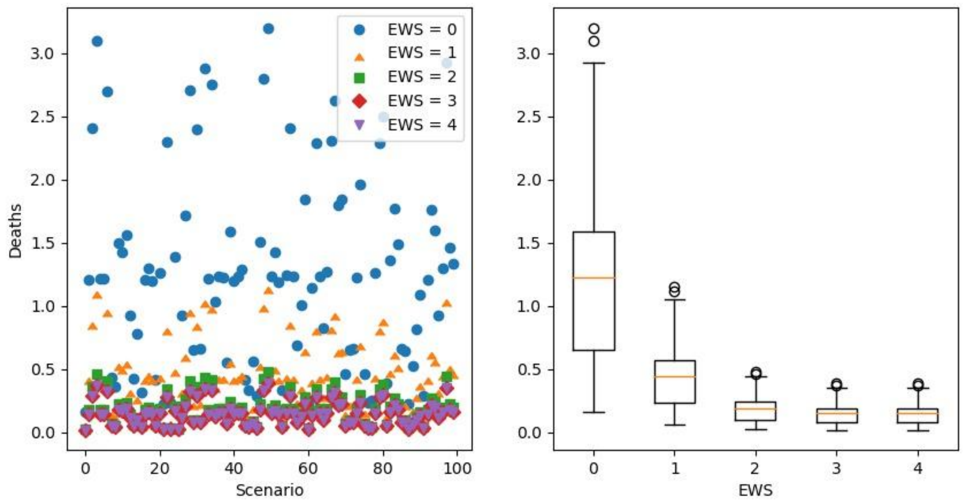
Focusing on damage more than deaths

The two outcomes from the model that depend on the uncertainties are damages and deaths. The results for total deaths over all scenarios range from 0 to 3 person over the 80-year simulation process. These values are up to 3 orders of magnitude below the values presented by other similar models such as Haasnoot et al. (2012) which has values of up to 1,500 deaths over a single region for a model of the Waal River. Thus, it is considered that the base Dike model might require further calibration for expected death estimation. Using a precautionary approach to model use, we focused mainly on assessing and communicating damage as it provides results that are in intuitively acceptable orders of magnitude. Moreover, expected costs and deaths showed a very high correlation if no EWS were implemented, thus focusing on damage does not imply a loss of information on flooding risks for this specific model and planning process.

Planning exclusively on built environment solutions, not on soft solutions such as EWS

The nature of the planning exercise presented in this report was to find a robust decision for the IJssel River. Within the Dike Model, besides RfR and Dike Increase levers, you could also implement Early Warning Systems (EWS). Although we consider that EWS should be a part of any decision-making process around flood resilience, we argue that the way these systems are currently modelled in the Dike Ring is still not mature enough to be integrated into a model-based decision. In practice, we observed a very high impact of EWS in expected deaths of up to 100 times with a cost up to 1000 times smaller than the built environment solutions.

Figure D.1. EWS impacts on deaths



Appendix F - Methodological Flow Chart

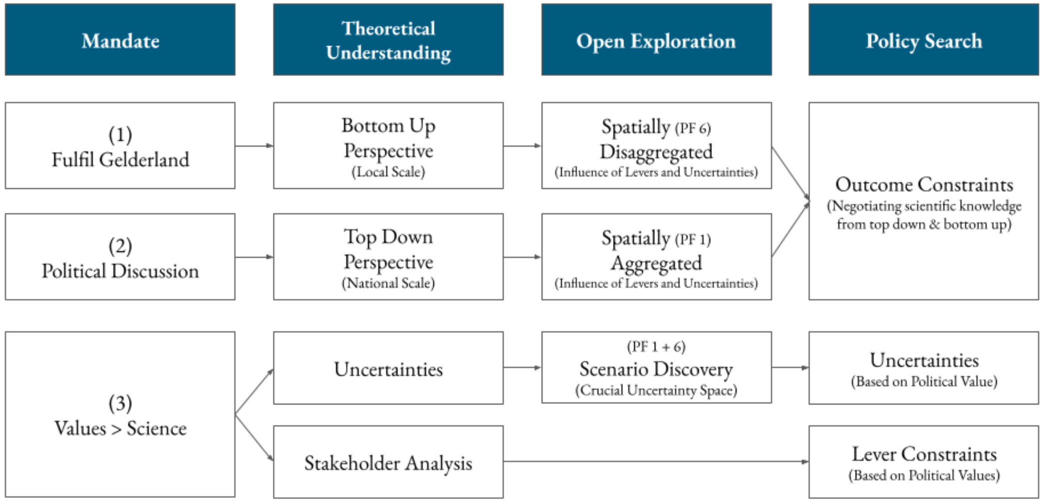


Figure F.1. Flow chart of the methodology where the influence of Gelderland's mandate influence on the research process is described.

Appendix G - Sobol 2nd Order

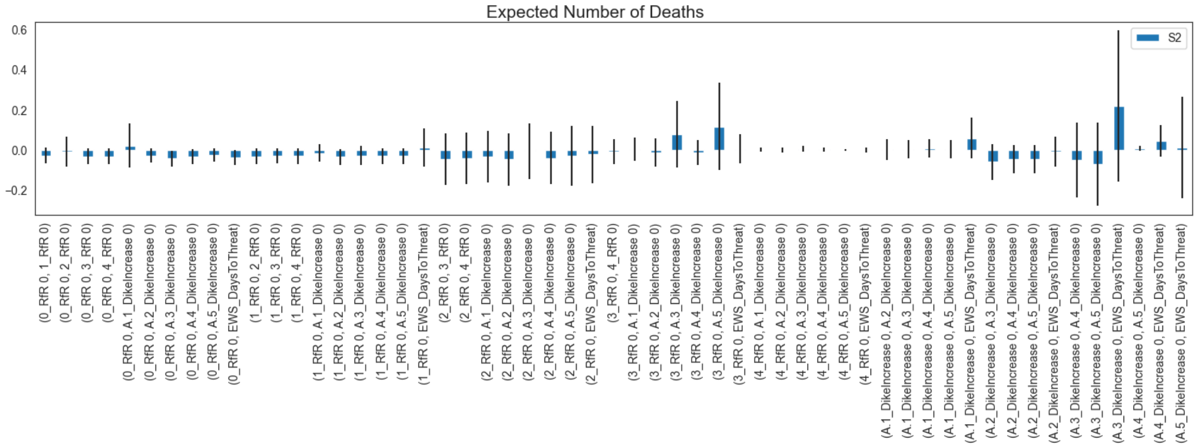
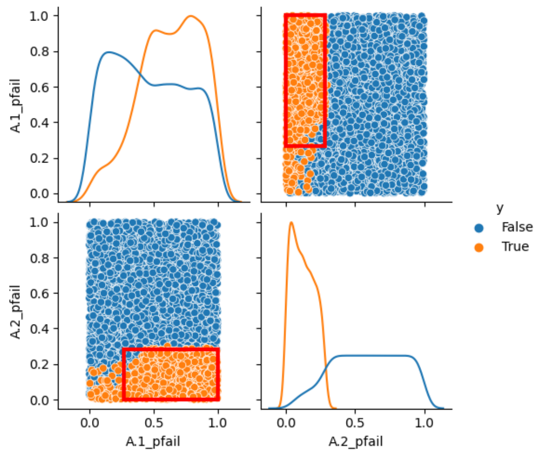


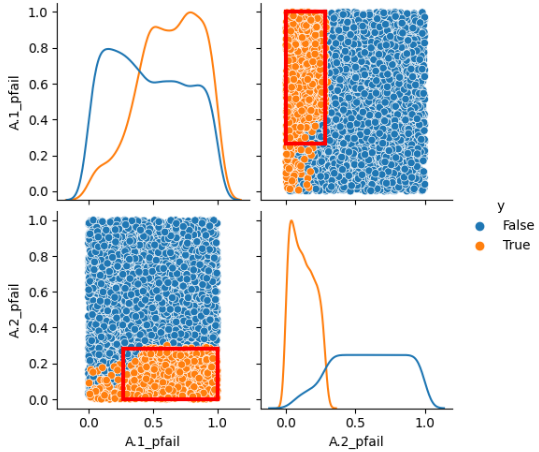
Figure I.1: 2nd Order Effects of Annual Deaths – A3 Dike Increase with EWS has the greatest influence.

Appendix H - Scenario Discovery

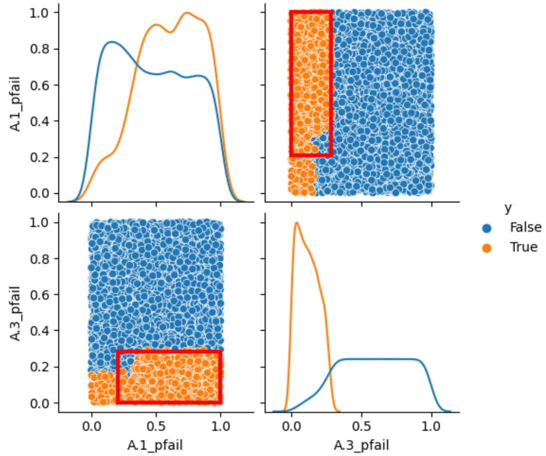
Prim for top 20% of Expected Annual Deaths - Dike Ring 1 (a), Dike Ring 2 (b), Dike Ring 3 (c)



(a)

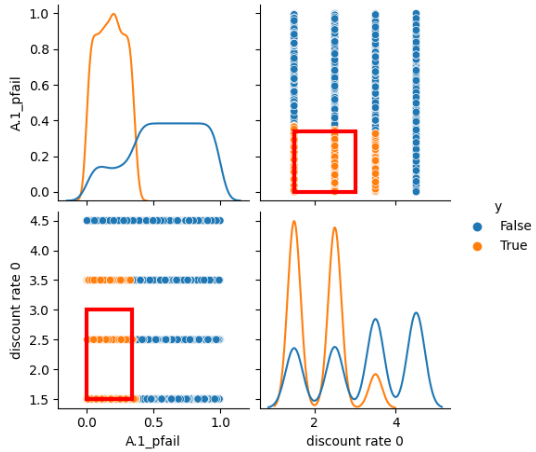


(b)

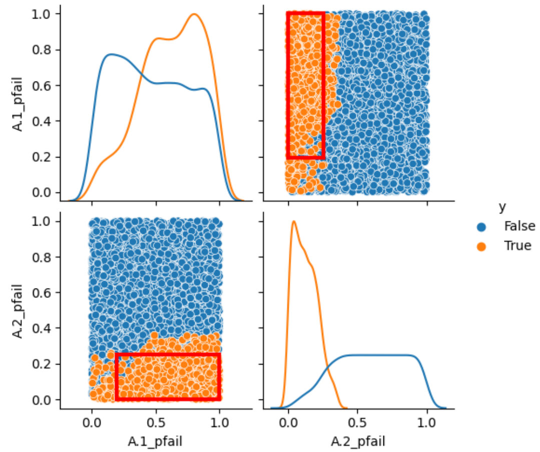


(c)

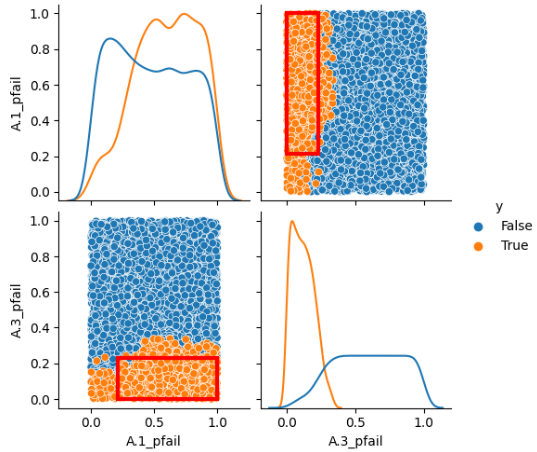
Prim for top 20% of Expected Annual Deaths, Dike Ring 1 (d), Dike Ring 2 (e), Dike Ring 3 (f)



(d)



(e)

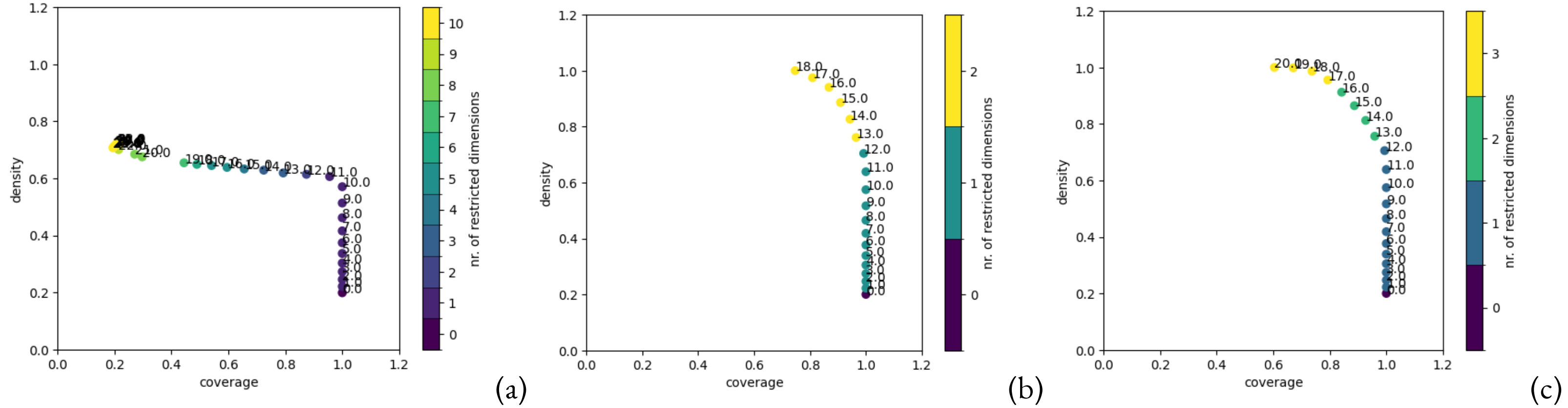


(f)

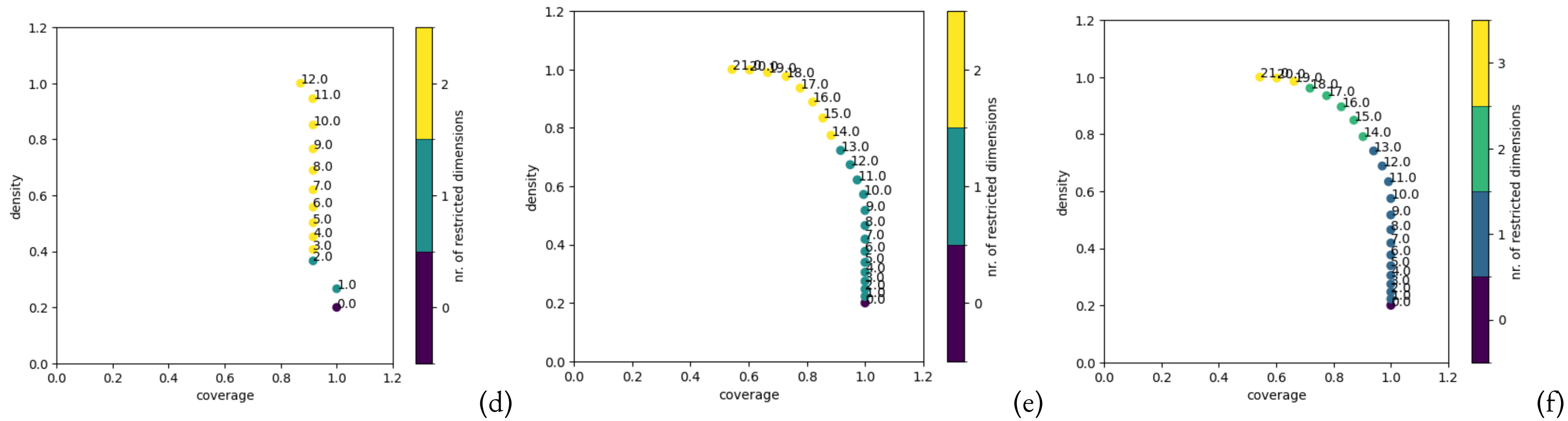
Appendix I - PRIM Coverage and Density Tradeoffs

2 Dimensions are sufficient in getting a fair density and coverage.

PRIM Trade offs for top 20% of Expected Annual Deaths - Dike Ring 1 (a), Dike Ring 2 (b), Dike Ring 3 (c)



Prim Trade offs for 20% of Expected Annual Deaths, Dike Ring 1 (d), Dike Ring 2 (e), Dike Ring 3 (f)



Appendix J - Directed Search

Table J.1: Reference Scenario used for Directed Search

B_{max}	175
B_{rate}	1.5
p_{fail}	0.5
Discount Rate	3.5
Flood Wave Shape	4

Appendix K - Maximum Regret

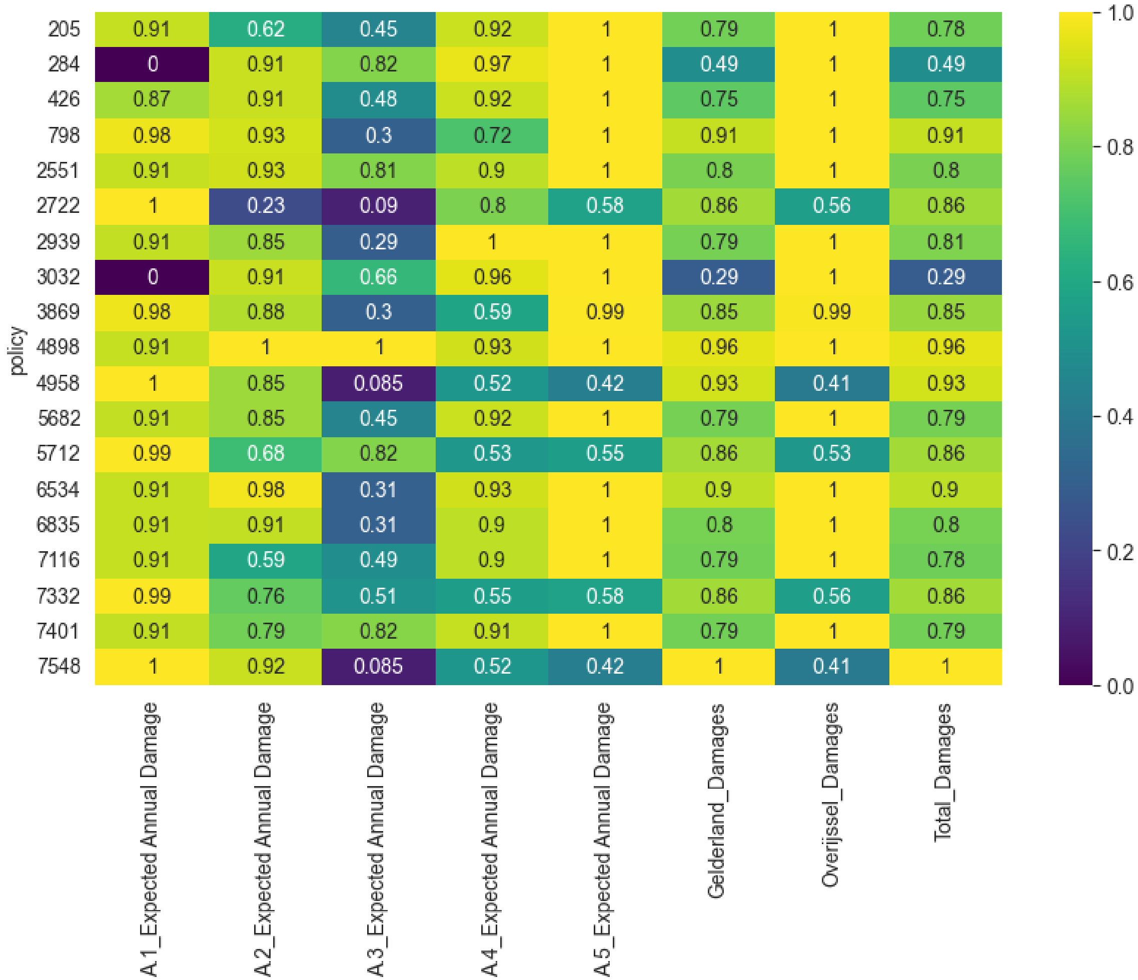


Figure K.1: Maximum Regret Matrix over all 19 selected policies.

Appendix L - Selected Policies

Table L.1: Overview on selected policies with levers, cost, and signal to noise ratio

Policy				Rom for the river					Dike increase					Total Expected Cost [million EUR]	Signal to noise							
	ID	S/n	Regret	0	1	2	3	4	1	2	3	4	5		A1	A2	A3	A4	A5	Gelderland	Overijssel	Total
205	0	0	0	0	0	0	1	0	2	1	7	1	6	278	0.5	0.8	0.2	0.4	0.2	0.6	0.4	0.6
284	0	0	1	0	0	1	1	0	1	2	7	2	6	309	1.0	0.2	0.0	0.2	0.3	1.0	0.2	1.0
798	0	0	0	0	0	0	1	0	3	4	6	2	7	300	0.2	0.1	1.0	0.3	0.2	0.2	0.3	0.2
2551	0	0	1	0	0	1	1	0	2	3	7	0	6	311	0.5	0.1	0.0	0.9	0.4	0.5	0.9	0.5
2722	0	0	0	0	0	0	1	0	4	1	6	1	6	285	0.1	0.8	0.9	0.5	0.3	0.2	0.5	0.2
3032	0	0	1	0	0	1	1	1	1	2	6	1	7	565	1.0	0.2	0.1	0.2	0.0	1.0	0.2	1.0
3869	0	0	0	0	0	0	1	0	3	3	6	0	6	283	0.2	0.2	1.0	1.0	0.4	0.3	1.0	0.3
4958	1	0	0	1	0	0	1	1	3	4	6	1	6	636	0.0	0.1	1.0	0.4	0.9	0.0	0.5	0.0
6534	0	0	0	0	0	0	1	1	2	5	6	1	9	565	0.5	0.0	0.9	0.3	0.0	0.5	0.3	0.5
6835	0	0	0	0	0	0	1	0	2	3	6	0	7	282	0.5	0.1	0.9	0.9	0.1	0.5	0.8	0.5
7116	0	0	1	0	0	1	1	0	2	0	6	0	6	261	0.5	1.0	0.1	0.7	0.1	0.6	0.6	0.6
426	0	1	1	0	1	1	1	0	0	3	6	2	9	509	0.5	0.1	0.2	0.2	0.0	0.5	0.2	0.5
2939	1	0	0	1	0	0	1	0	0	3	6	6	7	342	0.4	0.1	0.9	0.0	0.1	0.4	0.0	0.4
4898	0	0	0	0	0	0	1	1	2	6	9	1	7	572	0.5	0.0	0.0	0.3	0.2	0.5	0.3	0.5
5682	1	0	0	1	0	0	1	0	0	3	7	2	6	335	0.4	0.1	0.2	0.2	0.4	0.4	0.3	0.4
5712	1	1	1	1	1	1	1	0	0	2	7	1	6	578	0.1	0.2	0.0	0.6	0.6	0.1	0.6	0.1
7332	0	1	1	0	1	1	1	1	2	2	6	1	6	784	0.1	0.2	0.2	0.3	0.6	0.1	0.4	0.1
7401	1	0	1	1	0	1	1	1	0	2	7	1	6	616	0.4	0.2	0.0	0.3	0.3	0.4	0.3	0.4
7548	1	1	0	1	1	0	1	1	1	5	6	1	6	850	0.0	0.0	1.0	0.4	1.0	0.0	0.5	0.0

Appendix M - Expected Annual Damage

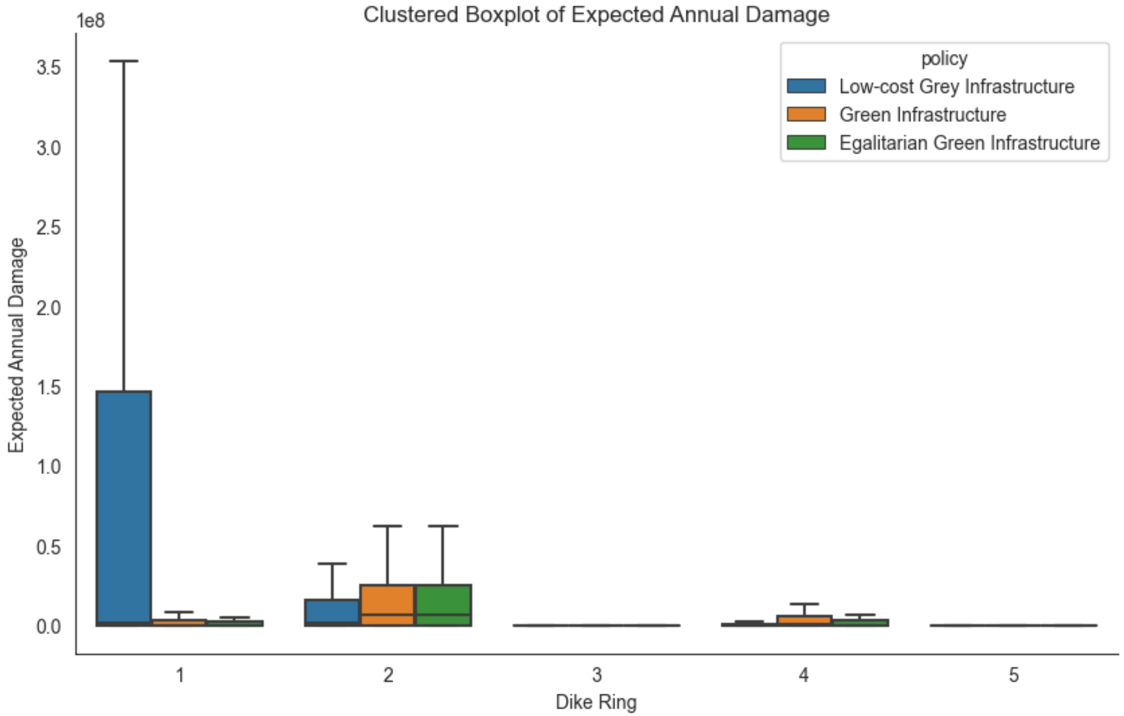


Figure M.1. Chosen policies are illustrated in a box plot to which their respective influences to the Expected Annual Damage of each dike ring are visualized. Over the 2,300 scenario evaluation.