Flood Protection and Mitigation:
A model-based study of the IJssel River

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Executive Summary

Water management has always been a prominent and challenging issue in the Netherlands. The ongoing climate change, the rising sea levels, the gradual sinking of the land, and the occasional flooding which occurs in several Dutch river deltas, put constant pressure to the Dutch rivers for handling more and more water flows. Additionally, sediments from the upstream that arrive in the river delta reduce the spaces to contain flood water. Hence, an resilient combination of effective policies and measurement will be needed to tackle the issues effectively. The ex-ante prevention of the damages became a necessity, urging for minimizing the damage caused by the river flooding. In other words, the need for handling the issues proactively instead of reactively. The Dutch Delta Works in 1954 can be classified as an example of a reactive response, acting as a countermeasure to disasters of great magnitude. Taking also into consideration the perpetual environmental challenges, a potential failure of such proactive approaches would cause substantial or irreversible damage over time.

In this modelling assignment, the client is Rijkswaterstaat which is part of Ministry of Infrastructure and Water Management in the Netherlands. The client's mandate is the safety of the citizens, being in charge of forwarding and executing policy implementations for their well-being. In the model, seven objectives are considered following the socio-economic factor of policy implementation. However, each of the defined objectives cannot be fully satisfied accordingly, which consists of a prominent challenge within the policy implementation, implying that several trade-offs need to be addressed by the decision maker. At this point, optimization methods will be needed. Moreover, human justification will be minimized within this assignment, due to the risk of selection bias. Hence, EMA workbench will be used as a supporting tool to assist the decision-making process. EMA workbench itself uses an exploratory modelling approach, making it possible to conduct uncertainty analysis.

The EMA workbench consists of several decision- making supporting tools such as sensitivity analysis, open exploration, optimization, and scenario discovery to the model (Kwakkel *et al.*, 2013). In this model, analysis begins with the identification of worst case scenario, which will be used as a reference scenario of the SOBOL sensitivity analysis. In this point, a better understanding of the vulnerabilities and opportunities is needed to comprehend the effectiveness of individual policy results, as well as the correlation between them. Afterwards, the identification of constraint variables and values will be used as an input for the following optimization step. In this case, MORDM optimization algorithm is used, having the worst-case scenario as a reference and getting the top quartiles from the results as a constraint value. These values will be used as MORO's threshold for each outcome of interest, assuming they are optimum as extracted by the optimization, and be further used to improve the result and get optimum policy results. On top of that, scenario discovery is used in the next step to identify proper triggers for adaptive policy. Finally, regret matrix and open exploration are used in the final step, in order to check the policy performance.

In general, there are two avenues of policy results. The first focusses on dike increase a long the entire IJssel river, while the second strategy focusses the allocation of compensation for damages on certain locations (location 1 and 2).

Introduction

Water management have always been a prominent and challenging issue in the Netherlands, where Europe's rivers discharge out to IJsselmeer and the North Sea though its river delta. Due to the rising sea levels, as well as the frequent rainfalls upstream to the rivers and the gradual sinking of the land, the rivers in Netherlands are incrementally dealing with larger amounts of water. On top of that, the growing population and numbers and reactive measures such as dike heightening result less room available for its rivers, where flood dangers are ensued with a great impact on infrastructure, livestock, economy and people (RfR, 2012).

Reactive measures and stricter dyke safety regulations for an improved flood protection for the river region have been forwarded over a half- century span after the passage of Storm Surge in 1953. This catastrophic combination of a high spring tide and a severe north-western storm inundated large areas of the southwest resulted 1,835 fatalities and the flooding of approx. 2000 m2 of land (RfR, 2012). Initiatives such as the Delta Project initiated afterwards, where the concept of dyke fortification became a priority and sea inlets closed off and compartmentalised (Vergouwe et al., 2016) . The new philosophy introduced by the Delta Commission had in its centre the proactive protection, rather than responding to flooding after its occurrence. Water defences, as well as the delivery of flood mitigation and resilience have been strongly emphasized by the Commission, arguing that the costs of reinforcement would be offset by the reduction in flood risk (Vergouwe et al., 2016). With more sensitivity towards scenic and cultural-historical values, the Delta Programme for increasing and strengthening the dykes was completed in 2007 (Dossier, 2012).

Targeting at an improved planning quality, 'Room for the River', an area-based development national programme, launched in 2007 to regulate the water distribution, affording more space for a recreated river region and economic potential. The scheme is now at the implementation phase along the Ijssel, branch of the Rhine River, where a strong change is taking place in the landscape morphology. A broad variety of measures and their combinations applied all along the river zones is ultimately having a significant impact on water levels, the likelihood of flooding and the total costs (de Bruijne, 2015). However, uncertainties in inundation characteristics related to possible dike breach processes have not been explicitly reported (Vorogushyn et al., 2010). Losses arising from subsequent inundation may be dramatic due to the high value concentration in the dike- protected floodplain, but also due to fast water level rise and high flow velocities caused by rapid breach outflow (Alkema et al., 2005).

Case introduction

The national agency which is part of the Dutch Ministry of Infrastructure and Water Management, namely Rijkwaterstaat (RWS), is having a strong interest in the flood protection case in the IJssel River. RWS aspires a well-functioning water management system which would not jeopardize public safety, following the protection policy drawn by the Delta Committee and the safety standards mentioned in the Flood Defences Act. RWS also urges to shift the focus from the probability of a failure of the water defences to the risk of actual flooding which denotes the risk of a widespread damage. Finally, the conclusions of the second Policy Document on Water Management are embraced by RWS, where it is argued that large-scale investments in the water infrastructure are not necessary and that good management would suffice to optimise the benefits of our water distribution system (RWS, 2015).

Among other actors in the policy arena, the Dutch Association of Regional Water Authorities, Deltares, International committees, Municipalities, Nature and Environmental Organisations, the Government Service for Sustainable Rural Development and private enterprises are uniting to implement “Room for the River”. The examined public programme received a positive response, while the negotiation process would lead to success, as long as the target focus is maintained, and each approach is treated seriously.

On the basis of the points mentioned above, it will be investigated how RWS can mitigate the expected annual damages and fatalities within the flood protection plan in the IJssel River region without exceeding the allocated budget. An integrated plan for the decision problem concerning the IJssel river case study will be developed, in order to manage the flood risk into acceptable levels. For this purpose, a simulation model will be used, using carefully selected exploratory modelling techniques. The report comprises of two parts: a model-based analysis resulting in an advice to RWS, and a reflection on this advice.

Method

In response to the research question, the IJssel Dike Model was used (Kwakkel, 2018). This model comprises an approximation of the real situation, and its correctness is arguable as for any model of the real world (Bankes, 1993). Therefore, the IJssel dike model focuses on only five locations along the IJssel river, from upstream to downstream: Doesburg, Cortenover, Zutphen, Gorssel and Deventern, indicated as A1 through A5 respectively (Figure 1). All of these locations belong to the Province of Gelderland, except for Deventer which is in the Province of Overijssel.

The IJssel Dike Model specifies three different types of measures which can be taken at each location. These are: Dike Heightening (DikeIncrease), Room for the River (RfR) and an Early Warning System (EWS). The measures can be taken under any combination at each location. It comprises of a simplification of the actual situation, where 34 different measures were implemented within the “Room for the River” project to reduce flood risk (Kwakkel, 2018).

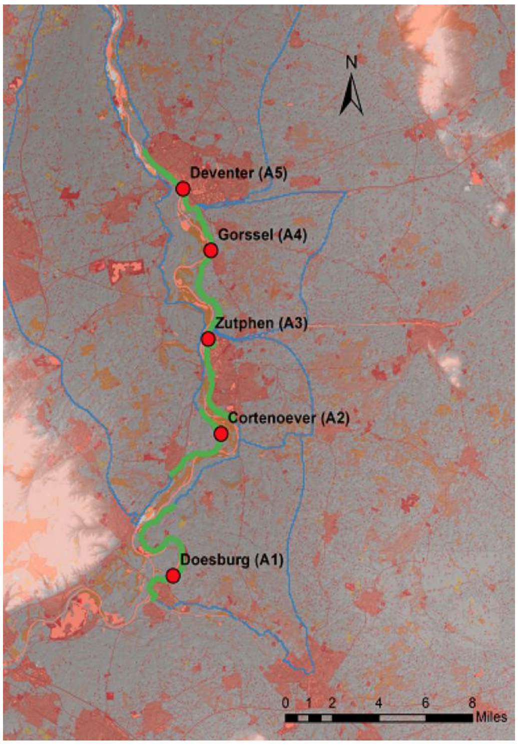

Figure 1. IJssel River and the case study locations

Dike Heightening

One of the possible measures to mitigate the flood risk at the locations along the IJssel river is the heightening of dikes. Dikes have been built in the Netherlands very since the early Middle ages and serve as protection against flood risk (Vis et al., 2004; Klijn et al., 2002). Dikes can be increased at each of the five locations providing additional safety against floods. The model allows an increase in dike height of 0.1 to one meter. The dike heightening lowers the probability of a dike failure and increases the discharge of the river in the model.

Room for the River

While minimising damages and maximising safety was the decree in the Netherlands, which was traditionally achieved by dike construction and dike improvement (Jonkman et al., 2004; Vis et al., 2004; Klijn et al., 2002). Nowadays there is a call for additional measures to prevent floodings without increasing dike height along the rivers. Room for the River (RfR) is such a measure that gives additional space to the river, including but not limited to areas that can be inundated in a controlled way to prevent uncontrolled flooding of other areas (Jonkman et al., 2004). For each of the locations in the model, a “room for the river” project can be implemented.

Early warning system

The final measure in the IJssel Dike model is the implementation of an early warning system (EWS). The main purpose of an EWS is to issue warnings when a flood is imminent or occurring (UNEP-DHI, 2016), resulting a significant reduction of the number of fatalities. As characterised by the model, the EWS gives the opportunity of choosing a warning period of zero to four days in front of a flood. The effectiveness of the EWS depends on the number of days people can be evacuated. The EWS measure is not location specific but is implemented for all locations (Kwakkel, 2018).

The IJssel Dike Model specifies 7 different objectives for decision- maker evaluation: *All Costs*, *Expected Annual Damage*, *Total Investment Costs, Dike Investment Costs*, *RfR Costs*, *Evacuation Costs* and *Number of Death*s. As one can see the objectives mainly revolve around costs and potential damages, nevertheless the model is a simplification of reality and does not include any environmental effects. In order to mitigate this lack of environmental impact in the model, policy documents and scientific literature will be used to assess some of the environmental impacts and their value to the IJssel area, in order to satisfy potential opponents of the policy proposal. In the analysis all objectives stated are used expect for the objective "*All Costs*".

The cities of interest aspire to improve the spatial quality of the area, taking advantage of the respective measures. Any combination of the measures above can be defined as a policy. This paper aims to provide decision-makers with policy advice on the basis of analysis under deep uncertainties with the IJssel Dike model. In order to achieve this, exploratory modelling and analysis (EMA) was used.

Exploratory Modelling and Analysis

Traditionally, uncertainty inputs to models were reduced as much as possible in order to come to the best estimate of model outcomes (Kwakkel & Pruyt, 2013). However, within the IJssel Dike Model there are seventeen identified uncertainties (see Table 1 and Appendix II) and seven objectives. Exploratory modelling approaches are favoured whenever critical information regarding these uncertainties is absolutely unavailable (Bankes, 1993). The model is clearly not a traditional model and thus requires an exploratory modelling approach for analysis.

Location	Uncertainties	
A.x	*A.x_Bmax*	The maximum size of opening in dike in case of dike failure
	A.x_Brate	Breach flow rate in case of a dike failure
	A.x_pfail	The probability of dike failure at location A.x
All	*Discount rate*	The rate at which the risks are discounted
	ID Floodwave shape	Generalized extreme value distribution for flood peaks

Table 1. Uncertainties in the model (see Appendix II for additional theoretical explanation about breach morphology).

Exploratory Modelling and Analysis (EMA) is an approach using computational experiments to analyse complex systems where there is significant uncertainty (Bankes, 1993; Kwakkel & Pruyt, 2013). EMA has mainly been developed for model-based decision making (Kwakkel & Pruyt, 2013), which is supportive with the aim of this report to render advice to policy makers on basis of a model with many uncertainty parameters.

Many-Objective Robust Decision Making

Given the multi or many objective nature of the model, additional analyses are required to optimise policies under the uncertainties. Many objective robust decision making **(MORDM)** is a method to generate alternatives for complex planning problems while enabling the discovery of the key trade-offs between the planning objectives (Kasprzyk et al., 2013). MORDM is used to quantify the number of conflicting objectives that characterize the IJssel.

Dike Model. Especially since the interest is to display a pattern of policy performance over the entire uncertainty space of the model and external scenarios (Walker *et al.*, 2013). In order to achieve this a worst-case scenario was constructed, based on the assumption that if a policy performs well in these worst-case scenarios, it will also have a robust performance (Kasprzyk *et al.*, 2013).

Adaptive Policies and Multi-Objective Robust Optimisation

The performance improvement of policies in the presence of deep uncertainty can be achieved by designing adaptive policies (Hamarat *et al.*, 2014). Adaptive policy making requires proper handling of parametric and structural uncertainties to develop robust policies, which makes robust optimisation methods excellent tools for decision making. Within this context, it is crucial to identify combinations of uncertainties which have substantial positive (opportunities) or negative (vulnerability) influence on the model objectives (Hamarat *et al.*, 2014) . Furthermore, the problem of identifying when the adaption of the policy should take place can be addressed using Multi-objective robust optimisation (MORO) (Hamarat *et al.*, 2014). This approach will be applied iteratively for achieving the best possible robustness. In the model, policy results from MORO optimization would be put into open exploration experiment.

Sensitivity Analysis

Sensitivity Analysis (SA) will be performed over the policy result extracted from MORO. The intention is to filter the best policy to be implemented based on MORO's results. While uncertainty analysis quantifies the variability of the output caused by the uncertainties in the model, SA aims at establishing the relative importance of input factors involved in the model (Cariboni *et al.*, 2007). In the analysis the **SOBOL method** was used which estimates sensitivity measures which summarise the entire model behaviour (Cariboni *et al.*, 2007).

Scenario discovery under deep uncertainty

Under deep uncertainty, scenarios can offer important benefits when used to support decision-making (Bryant & Lempert, 2010). Scenario discovery is a new approach to computer-assisted scenario development, it helps analysts and policy-makers in identifying policy-relevant scenarios (Bryant & Lempert, 2010). Scenario discovery does so by applying statistical and data-mining algorithms to large databases of simulation-model results. As mentioned by Bryant and Lempert the the scenario discovery approach defines a set of plausible future scenarios that represent vulnerabilities of proposed policies, i.e. scenarios where the policy fails to meet performance goals. In contrary to the classic exposition of how scenario axis analysis, which aims to reduce many futures in to a few, scenario discovery takes simulation that are run many times over a space defined by combinations of values for uncertain input parameters (Bryant & Lempert, 2010).

Analysis and Discussion

For the flood risk system under study, the peak of river water supply requires an area the size of the Betuwe to effectively accommodate the excessive water. The cross-section of a river is much broader than it is deep, even without those areas. Therefore, at equal water levels, extra drainage demands extra width, whereas it can be processed with limited increase of the river dykes (Dossier, 2012). Regarding the flood risk, studies show that a lower river level leads to lesser flood damage, since less water flows into the river area when it comes to a breakthrough, making river widening more favourable than increasing dike height (Nelson, 2016; Wright, 2007). In the upper river region, weak dykes become a priority, where strong water pressures and seepages can undermine the sand foundation, resulting the collapse of the dike (Dossier, 2012). This verifies why the locations upstream the river such as Doesburg and Cortenoever are more crucial, showing that initiatives such as “Room for River” can have an added value upstream but be less effective downstream.

When it comes to weak infrastructure in the river region, there is a likelihood of a breakage once every 100 to 500 years, instead of the agreed once in every 1,250 years (HNS, 2015). A lower water level with room for the river reduces this probability of failure by 1.5 to 3 times (Dossier, 2012). Room for the river results in reduced probability of breaching of the embankments due to a reduced load on the flood defences (Klijn et al., 2018). River widening, however, would be one and a half times more expensive than dike reinforcement, but cost estimation is “open to modification”, as stated by Cor Beekmans, Project Manager at RWS. The inclusion of increasing potential costs of damage caused by a higher river water level may be neglected, while the added value as a result of quality improvement of the surrounding wetlands is not appreciated by the Central Plan Bureau, part of the Ministry of Economic Affairs and Climate Policy of the Netherlands. A side effect however would be the reallocation of land, possibly with a different form of land use, such as agrarian businesses.

The budget for each city and the measures to be taken were defined by the amount of water level reduction, as estimated externally by Deltares and a quality team, led by Prof. Dirk Sijmons. For the purpose of this report, investment cost and their boundaries were approximated following this ratio.

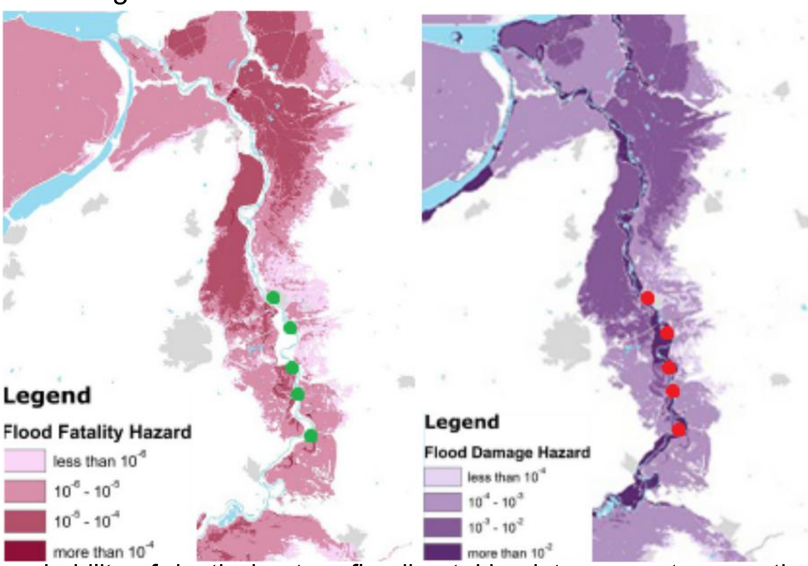

Figure 2. The probability of death due to a flooding taking into account evacuation possibilities in the Netherlands (left), and the expected annual fraction of the maximum damage of residences if they would be present at that location (right) (de Bruijn *et al.*, 2014)

This line of thought has been the reference point for matching a realistic approach to the expectations from the simulation modeling. As a result, an open exploration and sensitivity analysis would be essential to be conducted, in order to gain specific insight in the relations between objectives and measures and a better understanding of the IJssel Dike model.

In this step, the sensitivity analysis allows a multilateral understanding of the case study for identification of vulnerability in each location. The optimum policy, as extracted from the MORO analysis, will be compared to the 'No Policy' scenario for filtering the results.

Figure 3. Outcomes versus Uncertainty SA Matrix under No Policy

Figure 3, the heatmap matrix represents "vulnerability results in terms of outcome of interest versus uncertainties on the model. The value is based on total indices value from SOBOL sensitivity analysis. From the graph, the dike failure in location 1 and location 3 affects most of the outcomes. In this case, locations A1 and A3 are more vulnerable, thus dike heightening will be required as a countermeasure in these locations. This is also verified by de Bruijn et al. (2014), where flood hazard and damages around locations A1 and A3 are particularly high (See Figure 2).
The systematic sampling of the uncertainty space offers insight into the sensitivity of outcomes to the various levers. Under the "No Policy" scenario, Room for the River measures are primarily driven by Investment costs and in alignment with the estimation that river widening would be one and a half times more expensive than dike reinforcement. Dike heightening is in general more sensitive to changes of the number of deaths and evacuation costs, indicating that safety becomes a priority for RWS when it comes to dike strengthening.

Figure 4. Objectives versus levers SA Matrix under Reference Scenario Based on Research Paper

The potential loss of life after a dam failure is heavily dependent on the warning time available to evacuate the population at risk (Al Riffai, 2013), which is validated in Figure 4 under the measure of Early Evacuation. Additionally, a negative relationship for the "EWS_DaysToThreat" with the Number of deaths is also indicated by looking at the Figure 5 (d). Negative direction of impact can be also observed between Dike Increase in Location A3 and the total fatalities, which is a clear indication that reinforcing the dike would be imperative, given that pfail is impactful to the outcome under "No Policy".

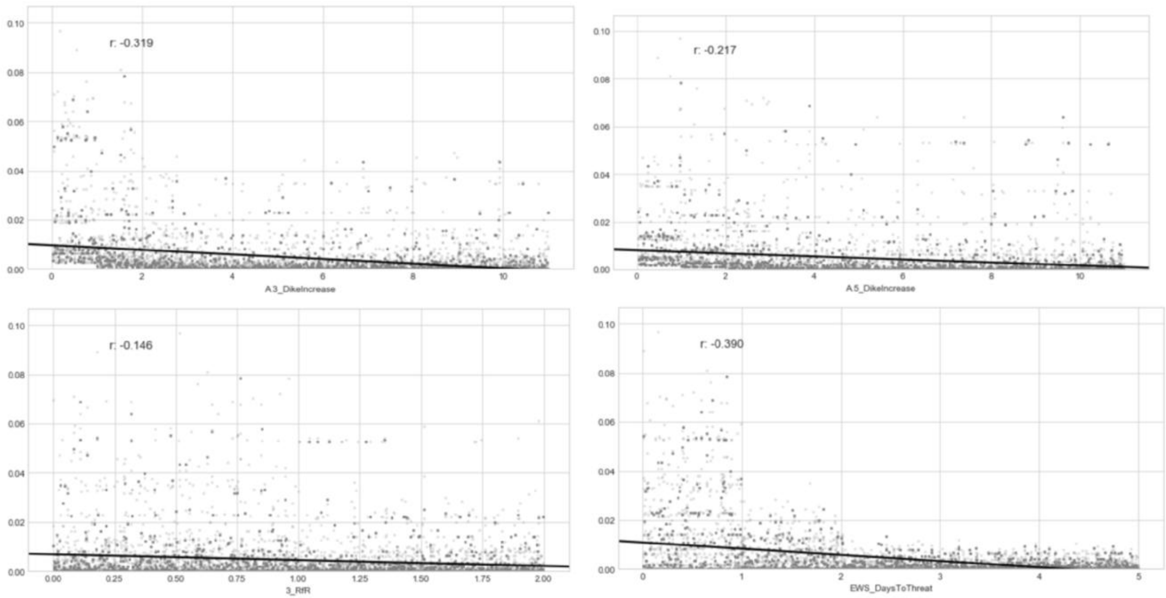

Figure 5. Regression Analyses of Room for the River and Dike increase at A3 and A5 to explain Number of deaths

However, bar chart plot will be required to see the difference between first-order (S1) and total (ST) Sobol indices in pfail of A1 and A3 to understand the impact of those particular variables as individual elements. If there are big differences between S1 and ST value, this means there are correlations with other variables as well. Figure XB below shows there is no major gap between S1 and ST value, and further investigation will not be required. Notably the pfail parameter has the highest ST index in both locations, as shown in Figure 6, indicating that it contributes over 30% and 70% of output variance, respectively, when accounting for interactions with other parameters.

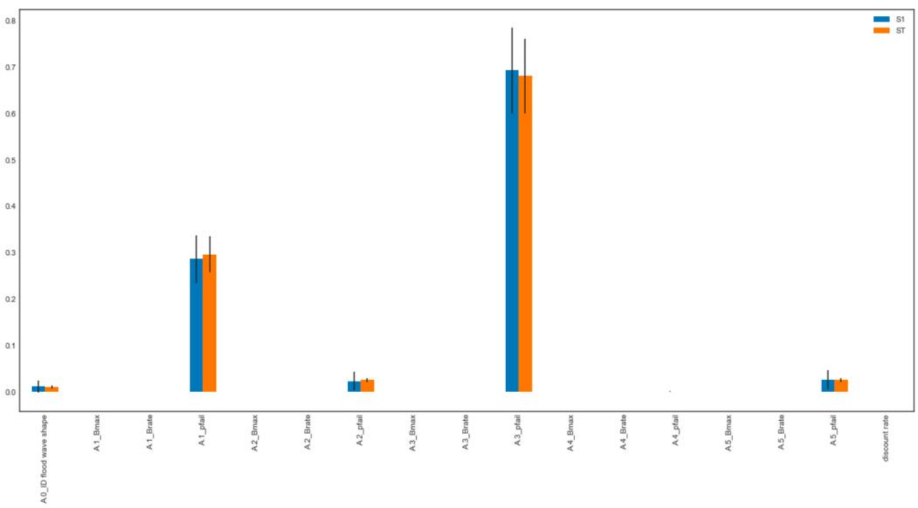

Figure 6. Uncertainty SA results with No Policy implementation

However, a sensitivity analysis of the levers needs to be performed. The following analysis investigates this sensitivity, having the following as a reference scenario: 'Bmax': 300, 'Brate': 1.5, 'Pfail': 0.7, 'Discount rate': 3.5, 'ID flood wave shape': 98. The confidence bounds are broad, indicating each input's individual contribution to variance (See Figure 7).

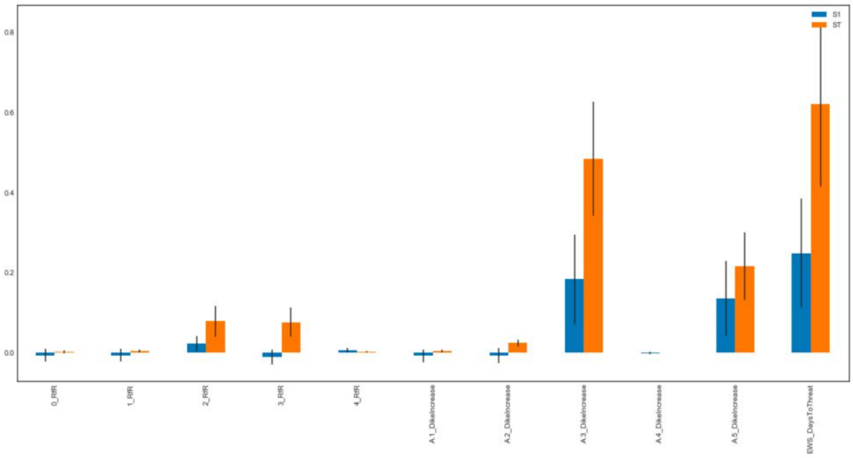

Figure 7. Levers SA result using Reference Policy based on research papers

By looking at Figure 7, and comparing the S1 with ST indices, the contribution to the output variance in the case of A3_DikeIncrease, A5_DikeIncrease and EWS_DaysToThreat does not occur by these single model inputs alone. This means that further investigation is necessary to conclude on the interrelation of the aforementioned measures or dependence to others. The confidence bounds are also broad, indicating each input's individual contribution to variance.

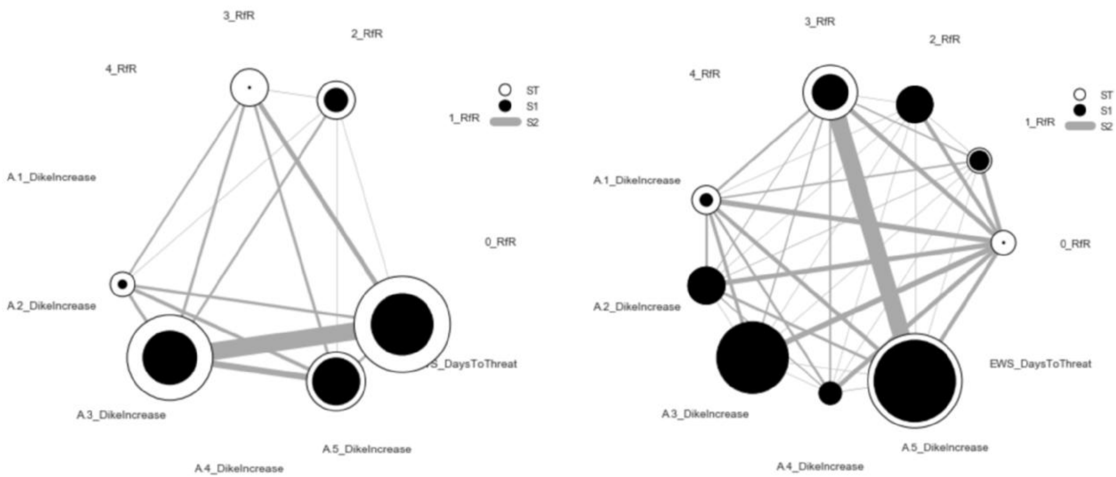

Figure 8. Policy Sensitivity Network Diagram for Number of Deaths (left) and Expected Damage (right) under No Policy scenario

The size of the ST and S1 circles correspond to the normalized variable importances as shown in Figures 7. Dike increase in location A3 is strongly correlated with the application of an early warning system in regards to the expected number of deaths, as shown in Figure 8. This correlation is proven negative, following Figure 5 (a), (d). Modifications of such nature in neighboring locations would also have an effect in A3, while RfR infrastructure in the river system would have a negligible effect on the casualties in location A3.

By contrast, the Expected Damage in upstream locations is interrelated but not strongly correlated with any other measures on other locations, with the exception of A5, where the widening of the river upstream in A3 would have a significant effect on the expected damages in location A5 under dike increase constructions. This is not verified by the above analysis, where it was argued that the combination of dike increase in downstream locations and river widening upstream would have more effective results in decreasing the expected damages.

Worst-Case scenario analysis

Worst-case scenario would be generated using MORDM (robust.optimize) algorithm by maximizing the direction of the outcomes in the first step instead of using minimize. MORDM would be used to find pareto-optimum solution by considering all of available objectives. In Figure 9 the parameters of the worst- case scenario can be found. These parameter values for the worst-case will be used in further analysis.

{'A.0_ID flood wave shape': 123,
'A.1_Bmax': 287.6677474388988,
'A.1_Brate': Category('1000', 1000),
'A.1_pfail': 0.17686240666354947,
'A.2_Bmax': 156.3217657959773,
'A.2_Brate': Category('1000', 1000),
'A.2_pfail': 0.015437698957163208,
'A.3_Bmax': 312.19873198634286,
'A.3_Brate': Category('0.9', 0.9),
'A.3_pfail': 0.1546762468272212,
'A.4_Bmax': 224.58961798234225,
'A.4_Brate': Category('0.9', 0.9),
'A.4_pfail': 0.037800279430313256,
'A.5_Bmax': 104.45131856082365,
'A.5_Brate': Category('1000', 1000),
'A.5_pfail': 0.008895839887874128,
'All Costs': 2790330198.6269255,
'Dike Investment Costs': 0.0,
'Expected Annual Damage': 2790330198.6269255,
'Expected Evacuation Costs': 0.0,
'RfR Total Costs': 0.0,
'Total Investment Costs': 0.0,
'Total Number of Deaths': 2.4904995505}

Figure 9. Worst-case scenario parameters.

Sensitivity Analysis under worst-case scenario

After the results are obtained from sensitivity analysis above, worst case scenario will be used as reference scenario to know the difference between previous sensitivity analysis and current sensitivity analysis by using worst case as reference scenario. From the observation, the sensitivity analysis by using worst case as reference scenario produced similar result like previous observation (see Figure 10). From Figure 10, dike increase in location 3 (Zutphen), dike increase in location 5 (Deventer), and EWS days to threat are the sensitive levers that affects the outcomes more compared to other levers in terms of number of death. The same thing for expected annual damage, the difference only the EWS is not effective to minimize expected annual damage as EWS is only beneficial for the people not to protect from damage. As in previous section, the graph below used ST value from SOBOL analysis to see the level of sensitivity of the outcomes to the changes in levers. However, further understanding will be required whether there is correlation between variables as will be showed on figure 11 and 12.

Figure 10. Outcomes versus Levers SA Matrix for worst-case scenario

In Figure 11, big differences between S1 value and ST value can be observed. S1 value explains about how sensitive a particular variable could affect the result of the outcomes while ST value explains about the total order of sensitivity. If there is major difference in terms of ST and S1 value, it means a particular variable has correlation with another variable as can be seen in Figure 12. In this Figure, dike increase in location 3 has strong correlation with EWS days to threat, it means the combination of those two policies could be an effective measure to reduce number of deaths (visualized by thick line between levers measures). The thick individual circle represents S1 value as explained previously. On the right of Figure 12, there are strong correlation between dike increase in location 1 and room for the river on location 1 as well as between dike increase in location 3 and room for the river on location 1. Additionally, moderate correlation exists between room for the river on location 1 and location 3 as well as between location 1 and location 4. From this, dike increase on location 1, dike increase on location 3, room for the river on location 1, 3, and 4 could be considered important levers to minimize number of deaths and expected annual damage. Since total-order indices are substantially larger than the first-order indices, then there is likely higher-order interactions occurring.

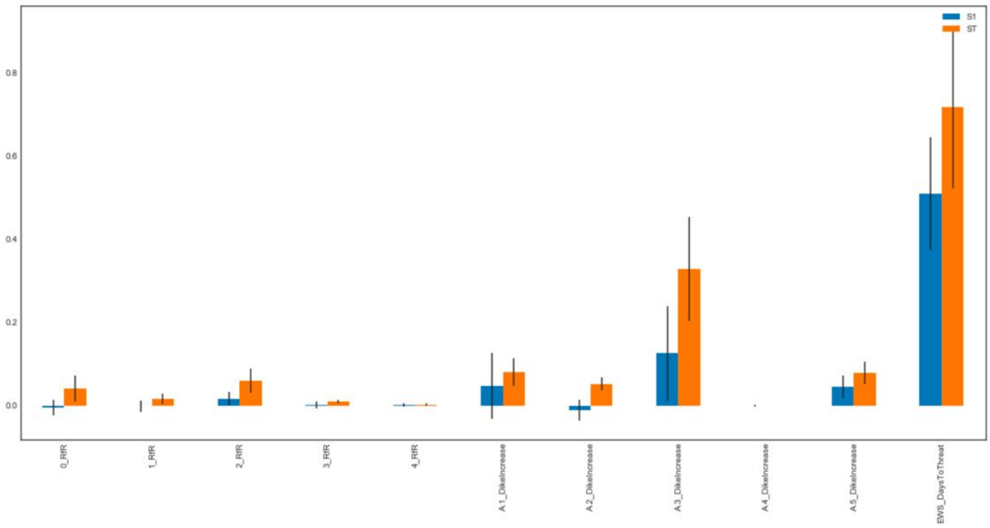

Figure 11. Levers SA result for worst-case scenario

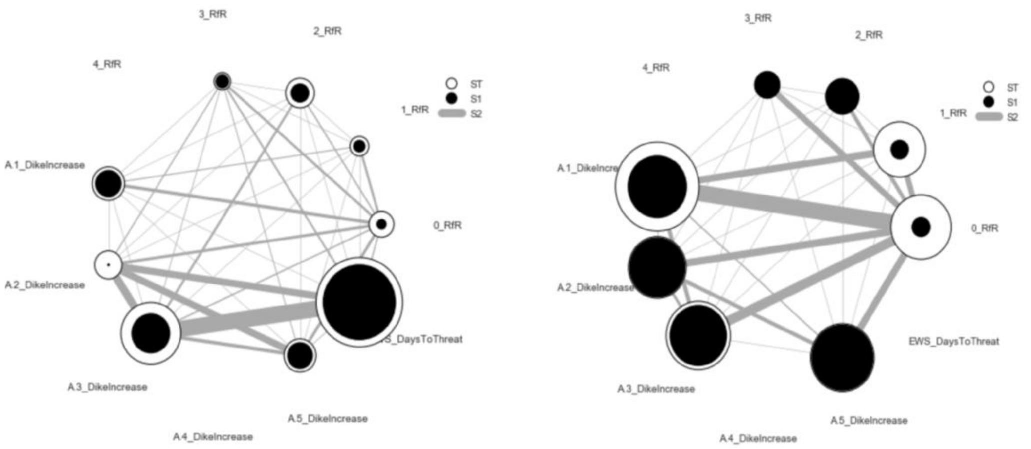

Figure 12. Policy Sensitivity Network Diagram for Number of Deaths (left) and Expected Damage (right) under worst-case scenario

Moreover, as a supporting analysis, regression graph is used to plot the value by how much the levers as individual element could reduce number of death in this context. Negative value that is provided by the graph shows that a particular lever will minimize the number of deaths as an outcome. Finally, dike increase on location 1, dike increase on location 3, room for the river on location 1, 3, and 4 will be used to filter optimisation policy recommendations in latter stages as can be concluded from this stage of analysis.

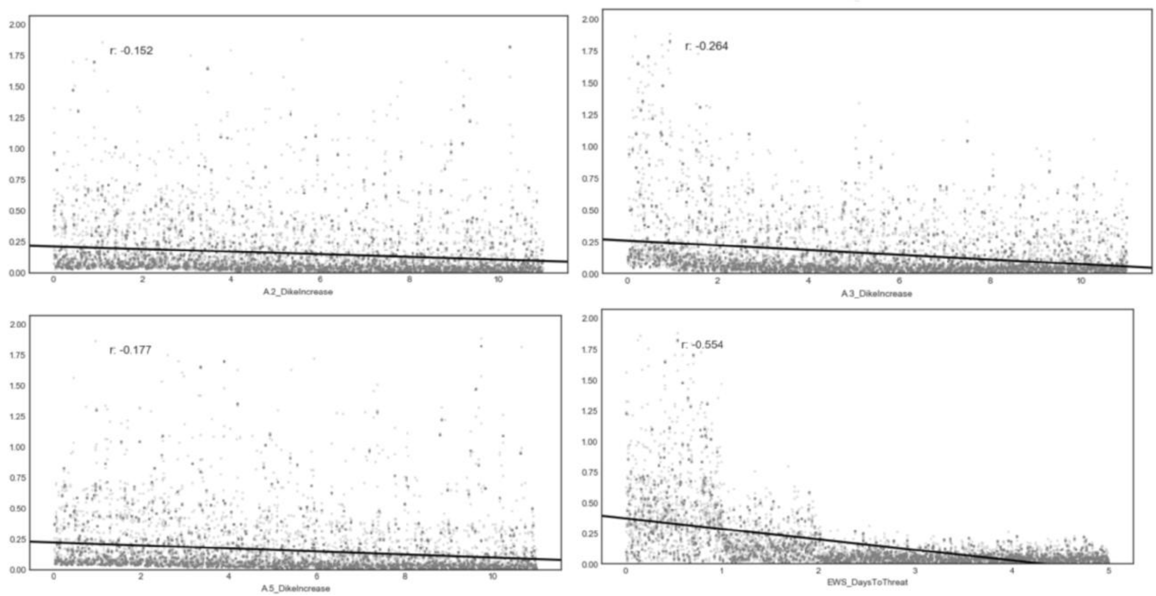

Figure 13. Regression of selected measures against the Number of Deaths under worst-case scenario

Many-Objective Robust Decision Making and boundary setting

MORDM optimisation is used to search over the levers to get the optimum policies and understand the variations on the outcome of interests' values (also use worst case scenario as reference scenario). The understanding on the variations on the outcome of interests would be useful to set boundary for next optimization which is (MORO). On this specific step, a single value as a boundary of top 10% percentile from experiments result will be used as a threshold for next stage of analysis. On the right are the values of threshold that will be used for MORO from the experiments.

```
print(death_optimize_constrain)
print(annualdamage_optimize_constrain)
print(totalinvestment_optimize_constrain)
print(allcosts_optimize_constrain)
print(dike_optimize_constrain)
print(rfr_optimize_constrain)
print(evacuation_optimize_constrain)
```

```
1.732866723414336
2440576466.547265
837147332.2237141
2760035153.520763
198745082.18579027
679700000.0
73323.4458008802
```

Multi-objective robust optimisation (MORO)

The results that would be produced by MORO are considered as a robust policies (considering regret value and do optimization iteratively inside the algorithm already). MORO is using the existing Worst Case scenario to find optimum policies during worst case scenario. Open exploration (experimentation, PRIM, and regret) will be used right afterwards for verification, in order to check policies' performance under several random scenarios. This is only done for the first set of promising alternatives. The results of the second set should be retrieved at a later date.

Policy	Measure	Locations					EWS_Days
		A1	A2	A3	A4	A5	
1	Dike Increase [dm]	10	9	8	7	2	1
	RfR [1: Yes, 0: No]	0	0	1	1	0	
2	Dike Increase [dm]	5	4	0	3	7	3
	RfR [1: Yes, 0: No]	1	1	1	1	1	
3	Dike Increase [dm]	3	1	0	4	5	0
	RfR [1: Yes, 0: No]	0	0	0	0	0	

Table 1. MORO optimisation results

The performance of those policies will be checked through open exploration methods as will be presented below. Best policy to be implemented will be argued and the rationality will be explained in the next section based on scenario discovery and performance test in open exploration.

Scenario Discovery

The scenario discovery was done twice, as the PRIM experiments were done for both sets of promising policies. The results from the PRIM experiments over the first set of promising policies are shown below (1000 random scenarios and 3 MORO policies). The PRIM result showed the main driver on top quartile in terms of total number of deaths (top 25% on total number of deaths). Total number of deaths is considered as an important variable because it represents "*safety*" which is the crucial mandate of **Rijkswaterstaat** (problem owner and client in this case). According to PRIM results, there is one important variable that determine deaths which is probability of dike failure in location 3. Based on this result, dike heightening results in location 3 will be necessary to prevent dike failure which cause more fatality. Hence, the selection of policy that involve dike heightening in location 3 will be necessary. According to MORO optimization result, there is one possible policy that is suitable to the requirement which is policy 1. However, performance checking as explained in next section will be required to compare different policies and to strengthen the argumentation of the selection.

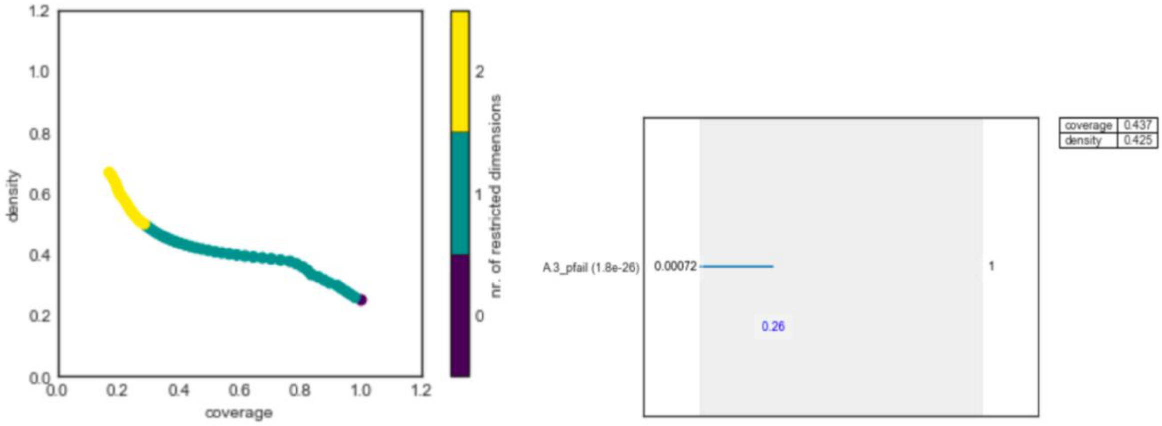

Figure 14. PRIM Results – Total Number of Deaths

To strengthen the argumentation, besides to ensure the safety of the citizens from water, one of the mandate of Rijkswaterstaat is also to minimize number of annual damage from flood. Hence, following PRIM result (Figure 14) would strengthen the argumentation (top 25% of expected annual damage). Figure 15 provides the same result as previous PRIM result. Both of those results were driven by probability of dike failure in location 3. Hence, dike heightening policy will be required in location 3.

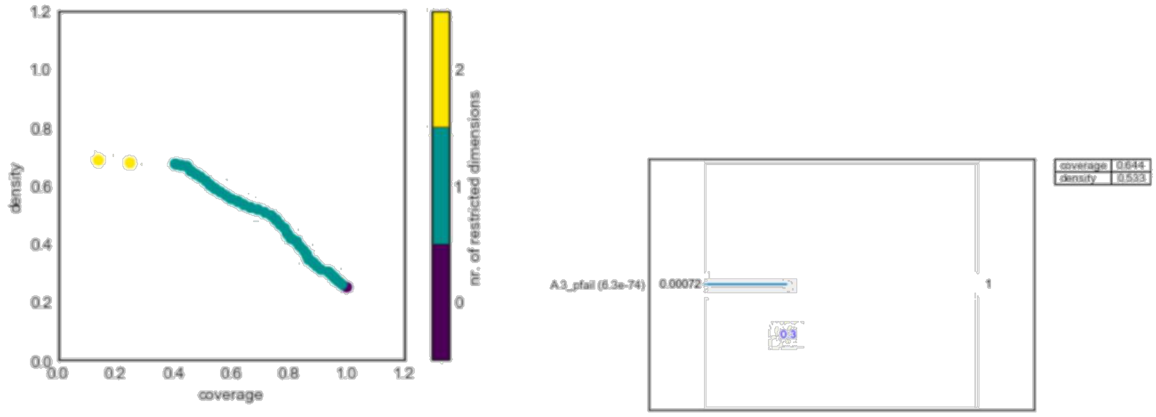

Figure 15. PRIM Results – Expected Annual Damage

The scenario discovery for the second set of promising policies utilizes 400 random scenarios and 5 policies. The outcomes of these PRIM experiments are shown below in Figure 14. Here it is again shown that the failure chance in dike ring three is the main driver on the top quartile. A large difference between this set of policies and the previously assessed set, is that no dike increase in the third location is proposed. It seems that the effects of policy in the previous locations are used to reduce damage in the third location.

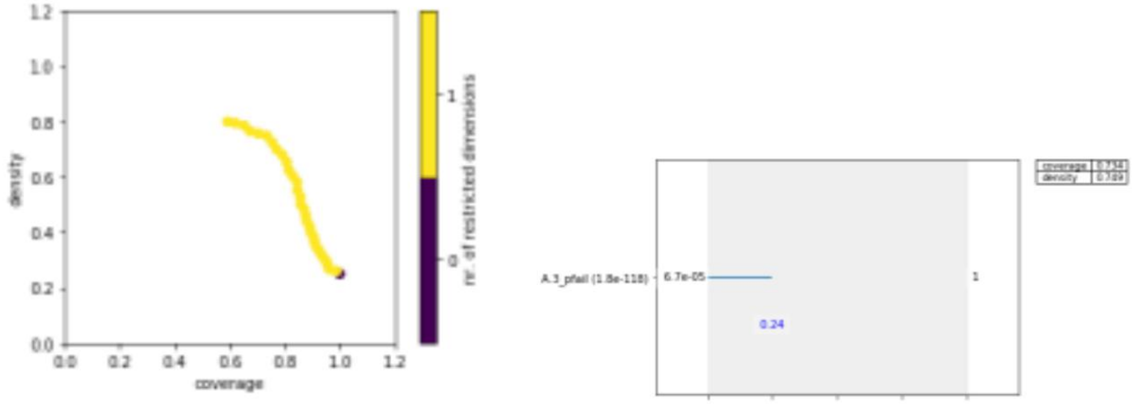

Figure 16. PRIM Results for the second set - Total Number of Deaths

Open Exploration for Performance Checking (Policy Effectiveness)

The first set of promising policies will again be addressed first, and the second set will later be introduced and explained how this section is important for implementing any of the more damage allocating policies.

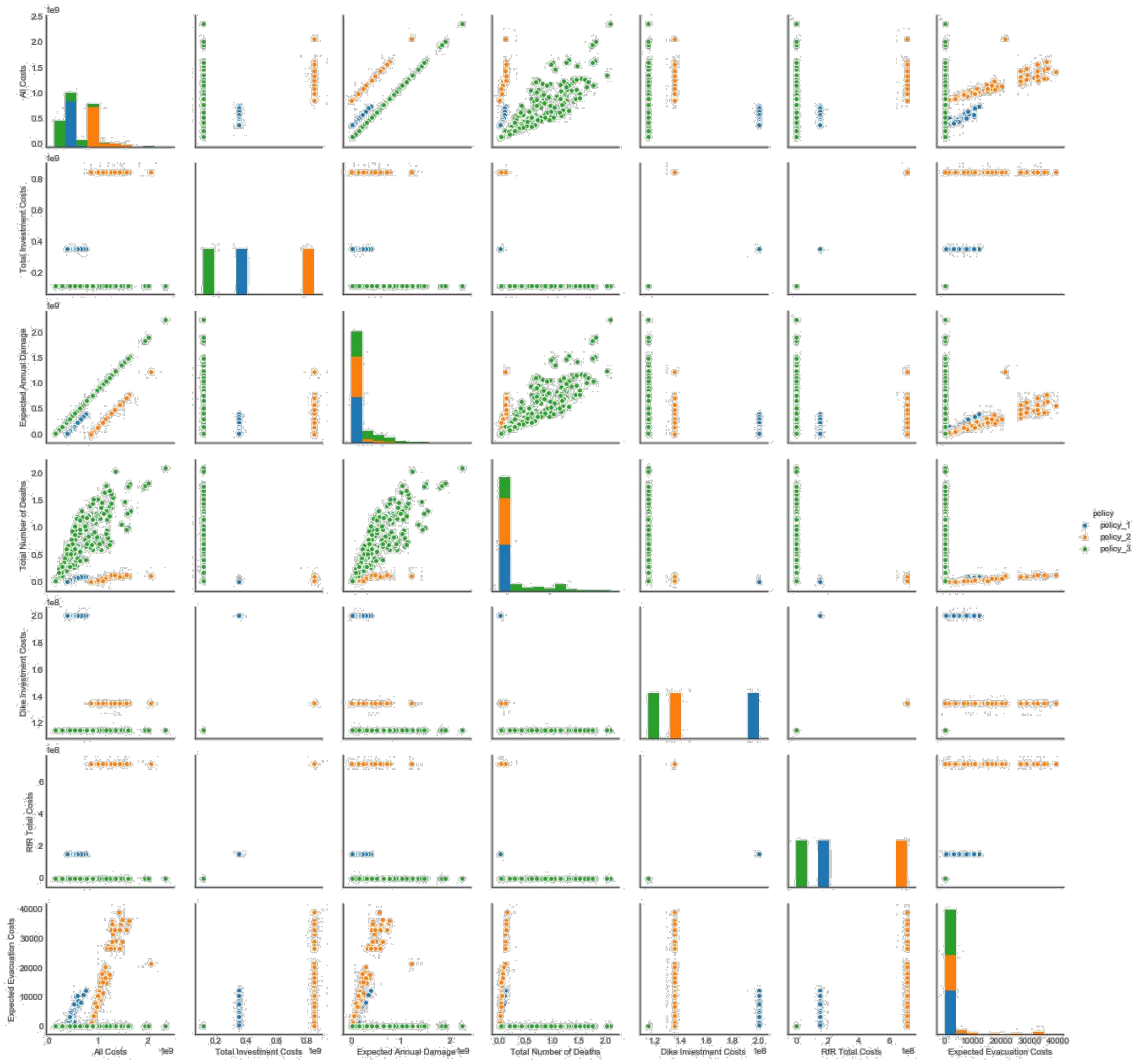

Figure 17. Performance of policies on different objectives

Figure 17 represents the correlation results from one outcome versus another. From the figure, on total number of deaths vs total investment costs, it can be understood that policy 1 is an effective policy to reduce the variance number of deaths greatly based on random scenario results. Compared to policy 3, policy 3 has large variance in terms of total number of deaths that can be seen from the graph due to the facts that policy 3 has no dike heightening in location 3 which is the driver on top quartile of total number of deaths. On the top of that, policy 2 is not preferred as well due to the facts it has the most expensive investment costs. Additionally, policy 2 has no dike heightening in location 3 as well. Those rationality explains the larger variance on total number of deaths compared with policy 1. From this, policy 1 can be concluded as the optimum policy in this case. The 3D graph below (Figure 18) may further strengthen the argumentation the selection of policy 1 as the optimum policy. The 3D graph shows total number of deaths vs total investment costs vs expected annual damage. From the graph, policy 1 presents less variance in 3 criteria which are deaths, investment costs, and expected annual damage. Policy 1 also has mediocre investment costs without sacrificing the safety criteria (small total number of deaths). Hence, policy 1 is the best policy to be implemented in this case.

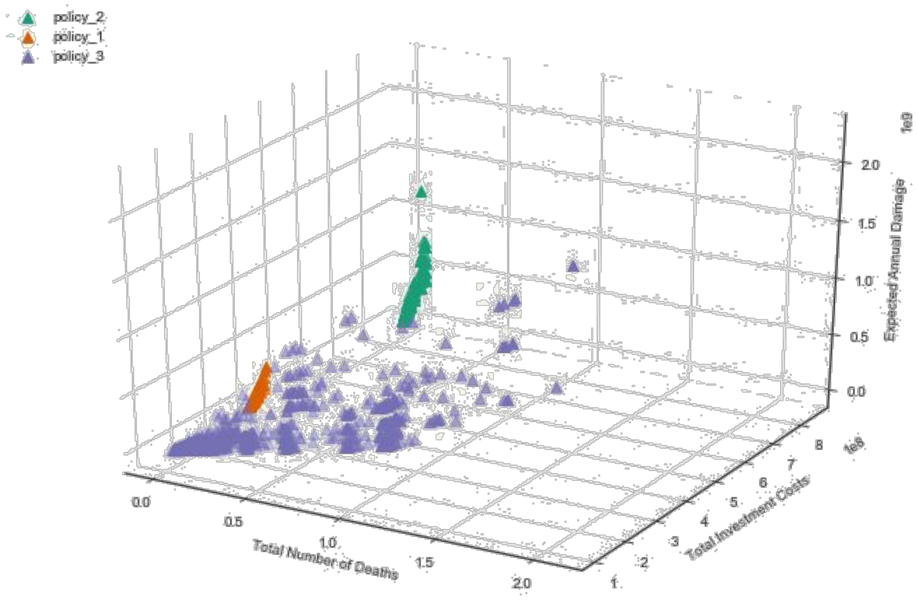

Figure 18. Policies performing on three dimension for the first set of objectives

The second set of promising policies performs well in terms of damage ranges in those cases were no significant changes are made to the dikes but dike increase in location five is of rather importance. The security of life however seems reliant on the increase in dike ring two. The addition of increase in dike ring one would be a robust implementation, to further create safety.

Still the outcomes seem at odds with the notion that dike ring three is the driver of the top quartile. To that end it is unsure how well the policy will hold if great changes occur and room for the river implementation upstream is highly recommendable to provide stress relieve on the Zutphen area.

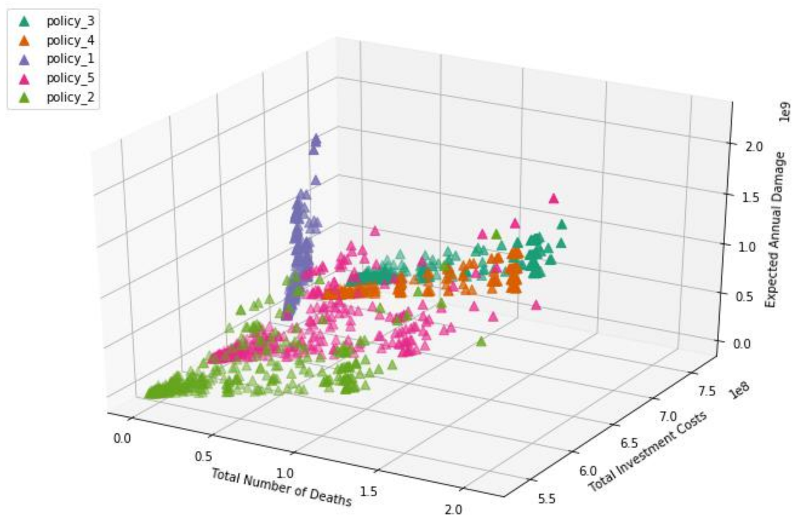

Figure 19. Policies performing on three dimension for the first set of objectives

Opportunities for Adaptive Policies and Trigger Identification

By referring to previous PRIM result, top 25% on total number of deaths and expected annual damage were driven by probability of dike failure in location 3. Hence, dike heightening in location 3 could be used as trigger policy for adaptive policy implementation. Once the number of deaths achieved the boundary of top quartile, the dike heightening in location 3 should be implemented. However, due to the limitation of the model, it is not possible to visualize the evolution of the case since there is no time frame included in the model. Therefore, evolution in total number of deaths time by time cannot be visualized and implementation of adaptive policy trigger could not be simulated.

Conclusion

Two experiments were conducted, with two differences among them. The first difference is the size of the area in which unwanted experiments fall, and the second being the number of function evaluations. To that end, two sets of promising policies were found. The first containing three policies, the second five.

The experiments were optimised over the worst-case scenario. This assures that the mandate of the RWS is followed, as safety is prioritised. The policies that MORO returned were retrieved using an epsilon value of 0.05 and Nfe number of 1000 and 3000 respectively. The first set of policies had combinations in line with what was expected, given the sensitivity analysis. The number of deaths and expected damages were minimised in case the third dike ring (Zutphen) was heightened significantly. In case the safety is seen as a very firmly constraining factor the most promising policy from this set would be recommended.

The policy proposes large increases in dike height working downstream, reducing the total increase the further the location is from the starting point. In the very prone area at Zutphen it would then be recommended to utilise a combination of RfR and dike increase. This should then also be done in the following area to ease the flow significantly enough to reduce the damage and mostly loss of life significantly. The cost of this policy is really low in comparison reaching just over 600 million, which provides plenty of room to negotiate compensation packages.

Funds for compensation will likely be needed as with such significant changes to the living environment, it is expected that the provinces and civilians near the dikes will protest. Therefore, this project is recommended to be done over a longer period of time with gradual improvements and with clear negotiation with the affected parties. Even though the policy implementation might be a necessity, implementation will not be easy.

The second set of five promising policies show a somewhat conflicting outcome with the sensitivity analysis, as dike ring three around Zutphen does not get an increase in height which seemed most sensitive. It does on the other hand focus more on policies upstream. This makes sense as it will reduce investment costs along the river.

Room for the river policies seems to be a mandatory part in maximizing output given the selected objectives: keeping people save, reducing costs and damage limitation. Especially in combination with the upstream implementation preference, RfR in the first location seems very promising.

Further downstream, the pressure and danger that has to be dealt with near Deventer comes with significant costs, if done insufficiently. As such RfR policy often in combination with dike increase is the most suitable combination given the worst-case scenario. This set of policies shows, given these RfR policy recommendations, a large change in the build environment.

Nonetheless, compared to the first analysed set of promising policies all five policies seem to allocate the change much more into specific areas. Besides, using RfR in areas 1 and 5, the dike increase will also be most useful in these areas with the addition of location 2. This means that those areas are facing dike increases of nearly a meter, but locations 3 and 4 are facing only small policy implementations. This will make compensation allocation to the affected areas a necessity.

Reflection

Three distinctly different policies which are thoroughly explained in the Discussion are provided by using MORO algorithm. It is important for the client to guarantee the mitigation of the potential damages and deaths, while keeping the costs to a minimum. As analysts, we also included a preference for Room for the River projects, given that it leaves open the possibility of additional measures. Apart from that, dike heightening creates a locked-in position which isn't flexible or adaptable (Radhakrishan, 2017), and can be considered a counter solution. If the dikes were to increase in many locations, this would greatly reduce the flexibility of future adaptability and implementation of other measures. This means that dike heightening creates a locked-in situation along the river which is not inline with adaptive planning. Therefore, "Room for the river" projects are preferred as they increase future flexibility and adaptability. However, based on the sensitivity analysis as well as regression analysis, "Room for the river" projects are not as effective in reducing the number of annual deaths and minising expected annual damages. Additionally, river widening requires high cost of implementation considering its effectiveness to reduce total number of death and minimize expected annual damage.

Then, in terms of simulation practice, there are several challenges concerning the simulation, the most important constraint is the limitation of time and computing power. Multi-Objective Robustness Optimisation (MORO) is computationally very expensive to run. Hence, in our simulation the number of NFE was reduced to have more time to perform other experiments following the optimisation step in order to verify the performance of the policy solutions found. However, reducing the number of NFE comes with a trade-off in the number of solutions found and convergence in hypervolume. It is very likely that by increasing the number of NFE better convergence in hypervolume is reached and more policy solutions are found.

As explained in the analysis chapter, open exploration and PRIM analysis were used to check the performance of policies. However, the Patient Rule Induction Method (PRIM) requires the analyst to choose one point by considering the density versus the coverage as a trade-off (Polonik & Wang, 2010). At that point in the analysis, human justification and selection bias may have been involved. As a result, the adaptive policy's trigger identification may not be entirely accurate. Once recommendations from the simulation are taken in real world context, it may or may not work due to a lot of factors that are not included in the model. Especially given that there are unidentified uncertainties in the real world. On top of that, the IJssel Dike Model lacks a time frame for policy implementation. Therefore, checking the performance of adaptive policies is not possible with the current version of the model.

Finally, considering the overall context of the IJssel Dike Model itself, the model is a simplification of real life as is any model (Bankes, 1993), which reduces the accuracy of the model compared the real world effects due to uncertainties involved. As analysts we believe that the effects of Room for the River projects are grossly undervalued and should have a higher impact on the objectives. Moreover, the Dutch Room for the River policy consisted of various measures such as: summerbed lowering, widening of the river, deepening of the river, dike relocation and creating of inundated areas. While the model reduces this to just one measure (*see Appendix I to see more detail explanation for policy reflection*).

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Appendix I: Reflection on tensions and challenges

The policy advice proposed by us, the analysts, for Rijkswaterstaat is a well-balanced policy in both costs, expected damages and total annual deaths. Most importantly it is a safe policy as the number of total deaths are estimated at an extremely low value. As a result of that Rijkswaterstaat, in terms of risk has very low exposure to risk of people dying due to floods meaning that the financial exposure, i.e. monetary value of the deaths, is almost negligible. In addition to low expected annual deaths the policy has relatively low expected annual damages in case of a flood. In case a flood occurs, the expected damages are around 270 million. While total investment costs are 352 million.

Given that Rijkswaterstaat's main concern is to minimise damages and probability of deaths this shouldn't give any challenges of conveying this to the Minister of Infrastructure and Internal Affairs that this policy achieves those goals. However, tensions may arise around the dike heightening as in all locations dikes are heightened.

Only in location A5, Deventer, dike increase is lower than 70 cm namely 20 cm. However, this will certainly lead to protests from citizens living in these areas as in Doesburg dikes are increasing by 1 meter, in Cortenover by 90 cm, in Zutphen by 80 cm and in Gorssel by 70 cm. Also, all these dike heightening measures create a locked-in situation along the IJssel river which reduces future adaptability and possible flood resilience. In in the future this policy measure proves to be insufficient only additional dike heightening is left as an option.

In addition to creating a locked-in situation dike heightening also does very little beneficial to the environment, whereas room for the river projects are highly beneficial for the environment. Although dike heightening does no harm to environment, interest groups or provincial or even municipal politicians might feel that if we spent a lot of money we should try to maximise the effects of the policy across multiple areas, not only focusing on safety.

Based on these challenges and tensions Rijkswaterstaat needs a clear strategy of communication and presentation of the policy as it will certainly be met with opposition. In order for Rijkswaterstaat to gain support across the board of all sorts of different interest groups as well as state actors Rijkswaterstaat may need to include some compensation. As previous projects have shown citizens and municipalities heavily oppose the heightening of dikes. Rijkswaterstaat should try as much to create awareness that dike heightening is a necessary evil, because otherwise it will result high probability of flooding resulting in enormous damages to citizens properties and probably loss of life. A easy way to create this understanding among citizens is by serious gaming. We propose creating sessions in all locations where dikes are heightened. The game would be based on the IJssel Dike Model but with an interactive environment, citizens can choose different policies for flood mitigation. From this game would flow that room for the river projects do not create enough flood resilience and citizens will understand why dikes need to be heightened.

To accommodate for the lack of environmental benefits as result of the policy Rijkswaterstaat could convince municipalities or even the province of Gelderland to create a new green multi-purpose area which increases the environmental value in the area and also has recreation purposes. So, the investment costs of the municipalities or province can be compensated by potential revenue from recreation area.

However, this strategy is not a guaranteed success there are some risks included in the execution of this strategy. Firstly, citizens might not understand or unwilling to accept the outcomes of the serious game. As citizens might be stubborn or even value the ecological historical lay-out of the area over their own safety. Also, citizens may create doubt about the validity of the model. Secondly, the effectiveness of the strategy relies on the quality of the serious game. If the serious game is not able to convey the message that room for the river projects have little effect on flood resilience the strategy proposed fails.

A final risk regarding this strategy is that municipalities and or the province refuse to accept the policy proposal as the feel they are not getting enough reward for their suffering, i.e. dike heightening.

Appendix II – Breach Morphology Evolution

The final dike collapse results from a sequence of failure modes, known as breach mechanisms. The most common dike failure mechanism, overtopping, is initiated by upstream flooding of the reservoir, due for instance to spillway damage or overflow, where the water level upstream of the dam rises higher than the dam crest and pours over the downstream slope (Al -Riffai, 2013). The underlying sand layer in the embanked area exerts more pressure on the covering clay layer (i.e. cohesive soil), which can cause the covering layer to burst open.

The breach erosion process starts by eroding soil away from the inner slope of the dike, followed by a combination of events, such as breach flow shear erosion, fluidization of the surface of the slope, and scour of the dike foundation (Zhu, 2006). The erosion along the dike crest lowers the height of the dike in the breach and increases the breach flow gradually. The acceleration of the rate of erosion enlarges the breach, accordingly also the breach flow rate. The dike body in the breach is washed away completely down to the dike foundation or to the toe protection on the dike outer slope, if any. The breach growth process terminates after a gradual decrease of the breach flow velocity due to the growing obstructive effect of the rising inner water level. The final width of a prototype dike breach (Bmax) has an order of magnitude of hundreds of meters.

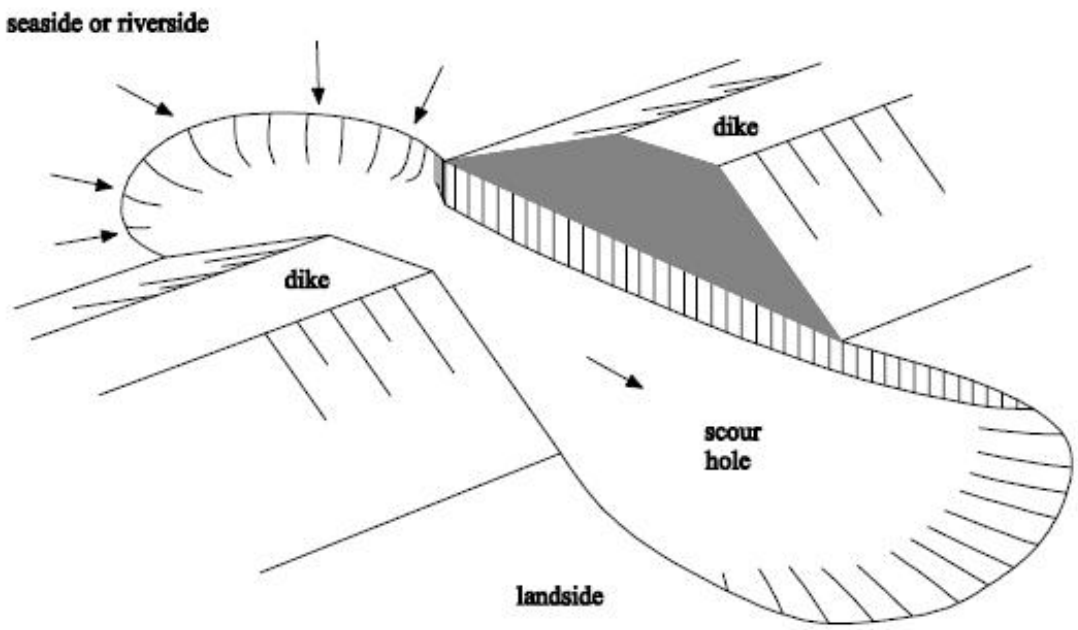

Figure 20. Breach erosion by final stages of the breach process (Zhu, 2006).

Appendix III – Uncertainty Variables

Overtopping is generally initiated by upstream flooding of the reservoir, due to for instance spillway damage or overflow, where the water level upstream of the dam rises higher than the dam crest and pours over the downstream slope (Al Riffai, 2013). With the assumption that a dam will breach under an overtopping condition, flow shear erosion occurs along the breach bottom as well as the breach side-slopes, when the initial breach in the dike crest is overflowed by the flooding water at t = t0 (see Figure 4.15a and 4.16 , Zhu, 2006).

Bmax (5, 400)[m]*:* Based on Vorogushyn (2010, see also Figure 6), where a hydrodynamic model was built and manually calibrated to constrain friction parameters within a feasible range, truncation was applied by skipping extreme values of breach width. In that case, calibration against distributed observations was chosen in order to fit to discharge series at the downstream gage, since precise water level predictions are crucial for dike breach modelling. Hence, we decided to extend the lower bound from 30 to 5 to include cases following the observations of the dike breaches in the flood events of 1995, 1998, 1999 and 2002. On top of that, an extension of the upper limit to 400 would include such occurrences of similar catastrophic events.

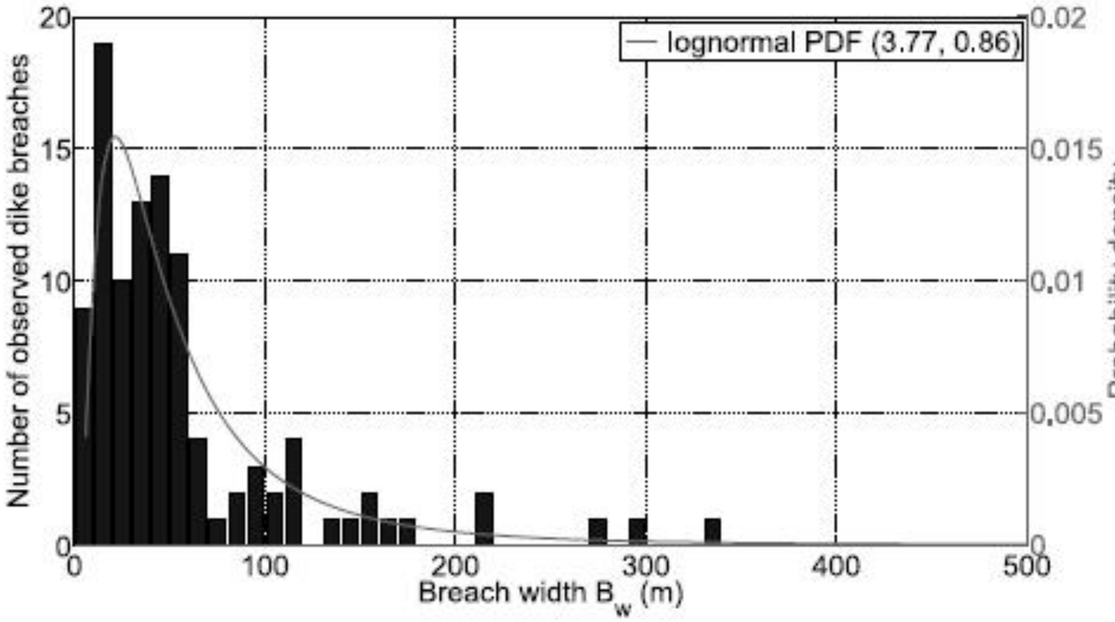

Figure 21. Empirical frequency distribution of breach width, as collected by dike failure statistics in Elbe catchment during the August 2002 flood, and fitted lognormal probability density function (Vorogushyn et al, 2010).

Brate {0.9, 1.5, 1000}[m/day]: The breach flow imposes shear stress on both the side-slopes and bottom of the breach, leading to steeper breach side-slopes due to the larger erosion rate at the lower parts than at the upper parts of the slopes (Vrijing, 2006). The growth rate of the breach width close to the dike foundation is larger than that on the upper part.

'Breach erosion growth rate' has units [meters/time]. 'Breach flow' has units [m^3 / time]. So, by "Brate", the assignment refers to the Breach erosion growth rate.

Discount rate {1.5, 2.5, 3.5, 4.5}: The discount rate largely determines the outcome of the analyses, if the benefits occur much later in time than the costs. In the Delta Programme, whereas it is particularly the long-term effects that play a major role, the costs and benefits occuring after a few decades barely count by using the discount rate (Delta Programme, 2015). A lower discount rate ensures that investments will be made sooner and in larger amounts than if the discount rate is high.

Pfail (0, 1): By this variable, the strength of the dykes is compared to the water level in order to evaluate dyke failure. By selecting a probability of failure at water level (yy' axis in Figure), the respective water level is extracted (xx' axis). Everything higher than a critical water level, defined as a threshold on the fragility curve, denotes the failure of the dyke.

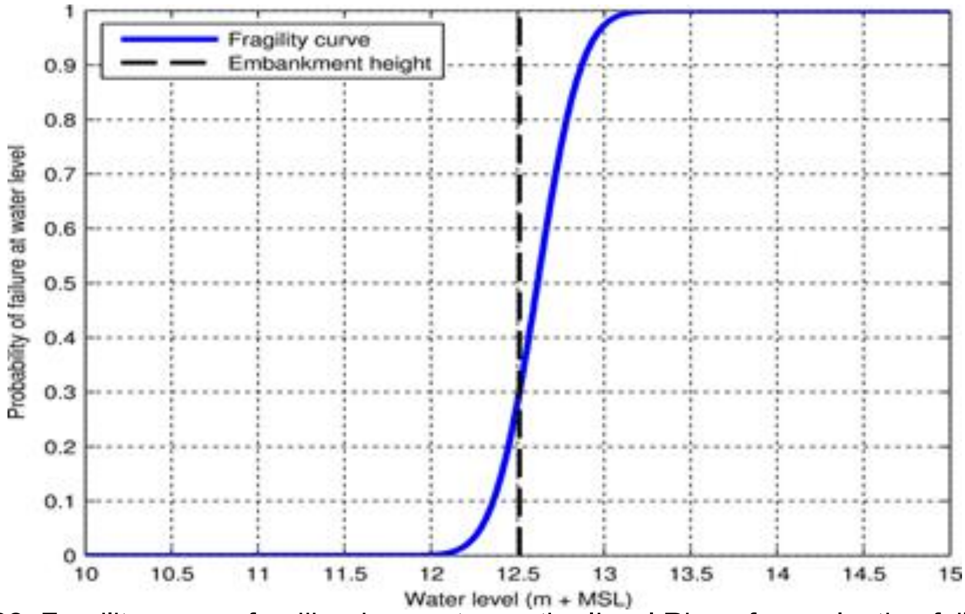

Figure 22. Fragility curve of a dike-ring upstream the Ijssel River, for evaluating failure over a critical water level (Mens et al., 2018)

ID Flood wave shape (0, 133): The generalized extreme value (GEV) distribution is used for modelling flood peaks, expressing the normalized water discharge for upstream high discharges. The statistic of high discharges upstream can be found in the python file funs_hydrostat.py.

APPENDIX IV - Outcomes of Interest

All costs
This objective refers to the total costs, as an aggregation of the “Expected Annual Damage” and the “Total Investment Costs”.

Expected Annual Damage
The expected economic losses caused by a flood include direct damage to capital goods such as homes, infrastructure and loss of business in the affected area, and indirect losses because economic activity outside the affected area also comes to a standstill. (Vergouwe et al., 2016)

Total Investment Costs
The objective consists of the sum of the “Dike Investments Costs”, “RfR Costs” and “Evacuation Costs”.

Dike Investments Costs
The investment costs in flood defence or reinforcement can include for example the construction costs of dikes and the maintenance costs. (Jonkman et al., 2004)**.**

RfR Costs
The creation of flood zone in a particular location is associated with less space or less opportunity for other functions, which are also societal appreciated (e.g. housings, business areas and other) (Warner et al, 2013).

Evacuation Costs
A set of costs is allocated for the preparation in threatened zones who are facing evacuation. Such costs can be transportation expenditures, use of generators, first aid etc.

Number of Deaths
”The number of fatalities caused by a flood is calculated on the basis of the number of people living in the area combined with the flood characteristics such as the velocity and rise rate of the water (Jonkman, 2007).