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Strategies in an uncertain world: A Systems Dynamics analysis of different flood protection strategies

Raphael Klein, Sjoerd Meeuwsen[*] and Jill Slinger

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Abstract

Flood defences are a key issue in low lying coastal areas. These defences can protect the economy of hinterland regions along with countless lives. A conceptually simple abstraction of the complexity of a flood defence system is formulated in system dynamics. This model is based on a ring dike concept as used in The Netherlands. The model is composed of three sub-models: the levee life cycle, the average height of the levees and the safety of the inhabitants. Floods are introduced as an external event. There are four key inputs which are meant to represent the diversity of policies that can be adapted in dealing with flooding with different countries. They are the investment level, the public perception of a government's action, the expertise of a certain country and the resource allocation. An exploratory study across different flood regimes displays expected results, with higher safety for higher investment, higher expertise and a higher level of public perception. A policy analysis study also details different policies for imaginary countries along with their associated results. The outcomes indicate that the model can be useful for policy selection and insight but should not be used to judge a specific country's policies.

Keywords: Floods, strategic flood defense planning, infrastructure, natural hazards, policy-making, public perception.

1 Introduction

Levees are a crucial part of the flood protection system in low lying plains around the world. In some countries, the amount of capital that is being protected from flooding by levees can be counted in billions of dollars, (Oost and Hoekstra, 2009). In others, countless lives of the people living in the middle of flood plains are at stake. The flood protection approaches taken in different countries

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can vary significantly, as was shown for the countries surrounding the North Sea by Van Raak (2004). This can be due to the different policies being adopted by different local governments, or because of socio-cultural differences in the relationship between citizens and their states as was shown in Slinger et al. (2008). Due to these different approaches, and the complexity of the system being considered, it can sometimes be difficult for policy-makers to oversee the full consequences of their decisions.

There have been many efforts at using large and detailed models to represent strategic planning for flood defences. However these models are very cumbersome and inconvenient for simple analyses (Lesser et al., 2004; Duong et al., 2015). Previous System Dynamics research has been performed in the field of natural hazard protection and flood protection. An example is provided by Deegan (2005, 2006), who simulated natural hazards, the reaction to these hazards, and the effects of different policies that can be used to be mitigate these hazards. The models presented are abstract and present a general approach to dealing with natural hazards. In Deegan (2005), this is applied to an example case of the New York basin flooding.

Following the model development and initial application, this paper presents a further exploration of the problem. The model presented is a simple abstract flood protection model that considers the life cycle of levees and the impact that the occurrence of floods have on these levees and the safety of concerned inhabitants. This model seeks to conceptualise of flood protection systems in such a way that the influence of different policies strategies can be explained.

This paper is structured in six main sections. In Section 2, the model is described first overall and then detailed in Section 3. Section 4 goes to on describe the results and analysis. This analysis is furthered for several case study in Section 5 by looking at different countries approaches and looking at the results of the policies from these countries. This paper is concluded by an overall discussion and conclusion provided in Section 6.

2 Model description

The model presented in this paper is a conceptually simple abstraction of the complexity of primary flood defences. The model is inspired by and based upon the case description and conceptualisation for the course Advanced System Dynamics (Slinger, 2015). This model is based on a ring dike or levee approach. The ring dike concept is applied in The Netherlands to protect a large part of its vulnerable territory from floods (Oost and Hoekstra, 2009). Figure 1 presents the ring dike concept. In this case, the ring protects a large part of the economic heartland of the Netherlands. This model simulates the life cycle of levees from construction through maintenance to breakage, and the effect of the occurrence of floods. Social aspects that can impact up on flood defence projects and policies are also included. This section explains the overall model through describing the boundaries, the country specific parameters and the conceptual model.

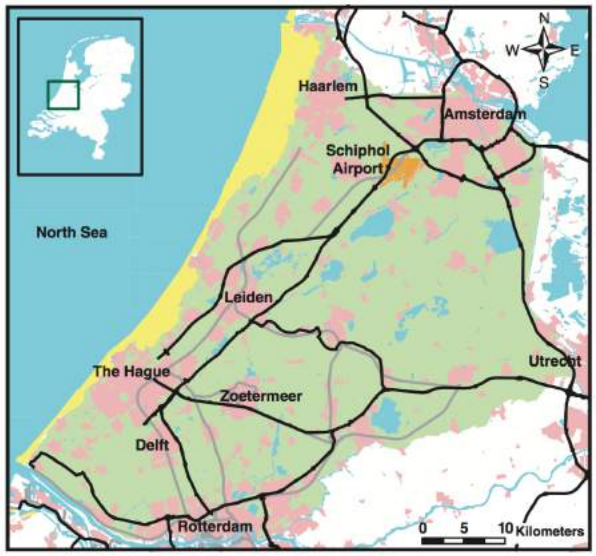

Figure 1: Dike ring area 14 in the Netherlands, reproduced from Oost and Hoekstra (2009).

2.1 System elements and system boundaries

Considering that this model is an abstract model, it is important to understand that it does not treat a specific case study. This has several repercussions on the modeling approach. The first is related to the level of details considered with respect to the levee failure modes. Levees can fail in any number of ways as shown in Allsop et al. (2007). However, to attain the requisite level of simplicity all failure modes of levees are not considered. Instead, a primary mode of failure is incorporated within the model, namely: failure through overtopping of the levee. Note that this does not mean that the levee is necessarily broken, only that overtopping and flooding of the hinterland occurs. A second failure mechanism is the breaking of a levee. This means that the levee will have to be replaced as it is not effective anymore in any condition.

This abstraction has a further impact on the model. The model considers the equivalent of a territory enclosed by levees. The interior of this territory is at the sea level height or lower meaning that if a levee breaches or the waves are higher than the levees, then floods are expected to occur throughout the territory. No elevated terrain is modelled within this system. This simplifies the analysis but prevents the modelling of evacuation as a method of flood risk management. It also means that human safety cannot be modelled and is considered beyond the scope of the model.

The boundaries are therefore set to exclude the study of human resilience in the face of floods, or different risk assessment methods that are being used in Germany as shown by Apel et al. (2004). The model built focuses on the extent of flooded area and the safety and perceived safety of inhabitants within the area. The recovery aspect is therefore also not considered.

2.2 The important model factors

The model focuses on the interaction between policies on flood defence public perception regarding safety and the construction and maintenance of levees. The main endogenous factors are represented in grey. These model the relation between the levee standards/norms and length, the safety of inhabitants in the face of floods, sea level rise over time. These are external factors (in green). The country specific parameters are then shown in magenta as inputs. They are presented in later sections.

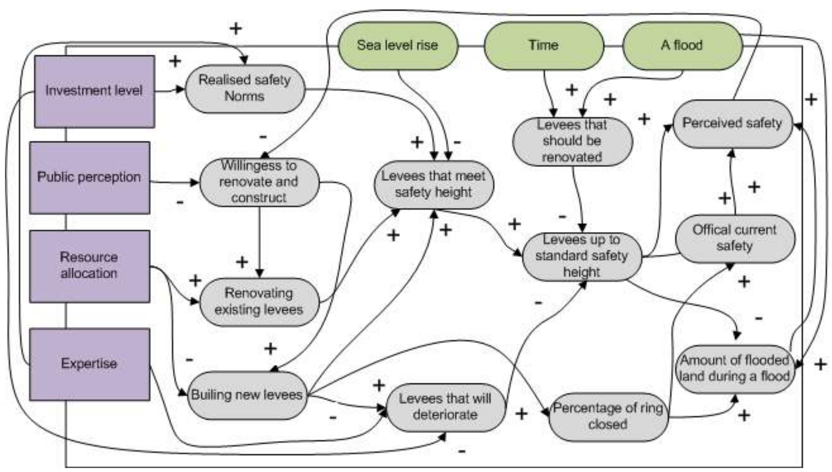

Figure 2: System diagram of the model delimiting the boundaries of the model with thee exogenous factors (in green), the endogenous factors (in grey) and the potential policy measures (in magenta).

The system diagram in Figure 2 shows the relation between the inputs ans the main factors considered within the model. In effect, larger investments and a larger expertise will lead to a higher amount of levees of a sufficient height. These levees are then able to prevent flooding that might occur from external events. The percentage of the ring closed also has a large impact on the amount of land that can be flooded as when the ring is not closed, the entire area can be flooded. The norms are set by policy makers and also affect the robustness of the model with respect to the incoming floods. Time has an impact on the entire system as the levees age and deteriorate or break with age.

2.3 The country specific parameters

The inputs in magenta (Figure 2) can be considered to be country specific parameters. Some of these parameters can be influenced by policy makers, while others are considered to be socio-culturally determined. Four of these parameters are used in the model.

2.3.1 Investment level

The first country specific parameter considered is the investment level. This corresponds to the level of investment that is attributed to flood defenses by the government. It is a policy driven parameter. This investment level contributes to the setting of the safety norms for which the levees are being built. It therefore affects the new levees but also the maintained levees (or standard levees as they are called within the model). It also has a small impact on the time it takes for levees to deteriorate. This parameter is graded on a scale from 0 to 10 where 0 signifies the lowest amount of investment and therefore the lowest safety norms. This will also mean that the levees will deteriorate slightly faster.

2.3.2 Public perception

The second country specific parameter is also the only socially driven parameter and is referred to as the public perception of the government's action. This parameter attempts to quantify the expectation that the public has of their government. In some countries, the public expects the government to protect them fully from any natural hazard (Van Raak, 2004) while in other countries, the public does not expect the government to play a large role in their safety. In the latter countries, the public takes an itself more individualistic and self-reliant stance. For this parameter, the willingness to build and maintain is affected by the perception of the public. A population that expects more governmental aid will be assigned a higher grade on a scale from 1 to 10 and have a larger willingness to build and maintain. The opposite is also true. This has an impact on the slope of the function that is used to represent this willingness to build. The plotted function is shown in Appendix B.

2.3.3 Resource allocation

The third country specific parameter is the government resource allocation priority. This parameter is influenced by policy makers and it represents the priority given to the construction of new levees rather than to the maintenance of existing levees. It is aimed at simulating the limited workforce capacity problem that is present in any country. There are only a number of workers that are qualified enough to work on a flood defense project. This parameter is graded from 0 to 10 where 0 means that the government is focusing all its resources, and therefore workforce, on the renovation of levees. Opposite to this, a grade of 10 means that the government places all of its resources on the building of new levees. A grade of 5 therefore means that the resources are split. Note that this parameter does not say anything about the level of investment committed by a government to flood defenses. The investment can be very low or very high, it has no impact on the priority of resource allocation.

2.3.4 Expertise

The fourth country specific parameter is the expertise. This parameter is meant to portray the knowledge that any government might have in levee construction and flood defense strategy. This parameter is tied to the time it takes for a levee to deteriorate or to break. Again, this parameter is estimated from 1 to 10. For a grade of 1, the expertise is considered low, the levees built are therefore of lower quality and will degrade or break faster. The opposite is true for a score of 10. The expertise also has a small impact on the norms set by the government. A high grade will mean higher norms. Note that this expertise is not only government based as it can be increased by government through the use of consultancies. It therefore does not only address the knowledge of a government but also its potential knowledge if there is a use of external expertise.

2.4 Conceptual model

Now that the model has been appropriately delimited and that the important inputs and factors have been described, it is interesting to examine the conceptual model. An aggregate causal loop diagram is used. It is presented in Figure 3.

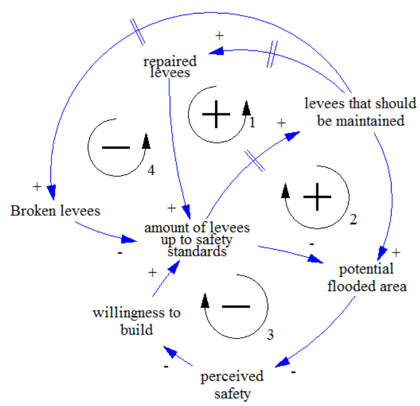

Figure 3: An aggregated Causal Loop Diagram (CLD) of the flood defence system

The causal loop diagram contains four main loops. The first loop (1) is the Maintenance Repair loop. This loop describe the relation between the amount of levees and the repaired levees. In effect, the more levees are present within the system, the more levees will ultimately deteriorate and the more levees there will need to be repaired. This is therefore a self reinforcing loop.

The second loop (2) and the third loop (3) are similar loops but act in opposite ways. The third loop or Sufficient Safety loop, is a feedback loop in which the increase of levees leads to an increase in perceived safety and therefore a lack of willingness to build more levees. The second loop acts with a delay and is opposite to this loop. This is because the larger the amount of levees, the larger number of levees to be repaired. This occurs with a certain deterioration delay. This in turn means that there will be more flooding, less perceived safety and an increasing willingness to build new levees.

The fourth and final loop (4) is the broken levee loop. This is a negative delayed loop where an increase in the levees that should be maintained leads, with a large delay, to an increase in broken levees. This in turns means that there are less levees that are up to standards and therefore less levees that should be maintained. This loops describes what happens to the levees that should be maintained, but that are not repaired in time and that fall in disrepair and are ultimately considered to be broken.

3 Detailed model

The model is split into three main parts: the levee life cycle sub-model, the levee height calculation sub-model and the perceived safety sub-model. These sub-models have different sizes and complexity. They are all detailed within this section.

3.1 Levee life cycle sub-model

The first and perhaps most important sub-model is the levee life cycle sub-model. This is the model that represents the construction, maintenance and destruction of all levees considered in the model. Its Vensim representation is shown in Figure 4. This sub-model can be further split into three main parts: the construction of levees (the left part of the figure), the maintenance of levees (the central part of the figure) and the destruction of levees (the central bottom part of the figure).

The construction of new levees is based on several parameters. It is related to the willingness to build, to the building capacity and to the total ring dike length. Considering the model assumes a levee ring around a specific land mass, the aim of the model is to close this ring so as to best protect the inhabitants within it. This is the driving factor for the construction of new levees. Once the ring has been closed, there is no need to build more levees. The building capacity is an arbitrary constant that can be affected by the resource allocation with respect to the construction of new levees. The construction of new levees is also performed to a certain standard or norm level which is affected by the investment level. The new levees have a certain design time and construction time, their construction is therefore not instantaneous, but delayed. After this delay, the levees appear within the 'new levee' stock. These new levees then take a certain time to deteriorate and flow to the 'levees that should be maintained' stock. This deterioration time is also a constant that is impacted by the expertise a certain country has and its investment level. A country with more knowledge

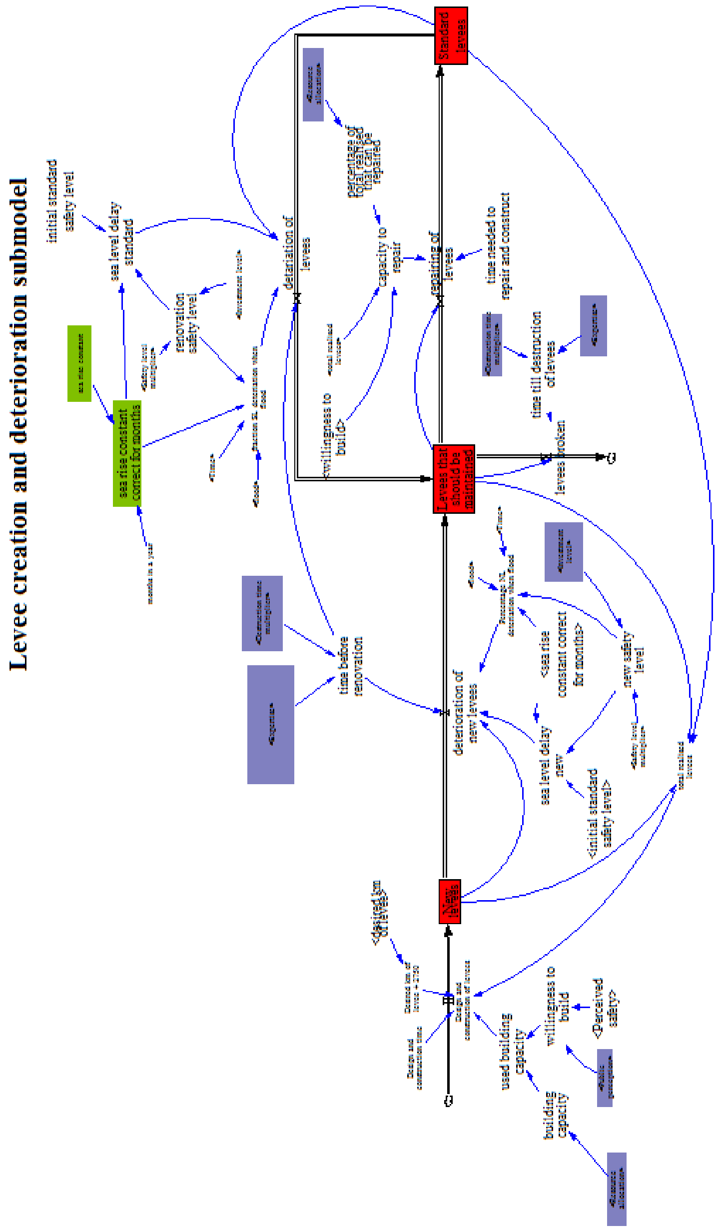

Figure 4: Sub-model showing the levee life cycle model.

and expertise or consultancy assistance on the construction of levees will see its deterioration time increase.

The second part of the sub-model consists of the maintenance of the levees. It therefore starts at the 'levees that should be maintained' stock placed centrally and in red in Figure 4. The levees that need maintenance are constantly being repaired. This rate of repair is dependent on the willingness to repair and also related to a certain percentage of levees that can be repaired at any time representing a limited workforce. This percentage can be impacted by the resource allocation. These repairs also take a certain time. They are not repaired at the same standard as the 'new levees' but are repaired to a slightly lower safety level. Once repaired, these levees are considered to be standard levees. These standard levees themselves then deteriorate after a certain amount of time dependent on the countries' expertise and investment level. This deterioration can be accelerated by floods. Once deteriorated, these levees flow back into the 'levees that should be maintained' and the cycle continues.

Finally, the third part of this sub-model reflects the destruction of levees. Once levees have to be maintained, some will fail and be destroyed. These are fully removed from the system and will need to be rebuilt. The time is takes for a levee to be destroyed or broken is a constant that can also be affected by the expertise which a country might have and its investment level.

3.2 Flood impact determination sub-model

A separate sub-model is used to show the impact that a flood has on the system. For a given height the percentage of the ring length that will be flooded is calculated. Considering that the height of every levee is not precisely tracked, a rough distinction and generalisation is made between levees. First, it is assumed that a levee that is in the 'levees that should be maintained stock will be flooded when there is a flood. This is because these levees are considered not to be up to the norms. Second, the height of the other levees which are located in the 'new levees' and 'standard levees' stocks is calculated. These calculations take into account the sea level rise and the different safety norms that apply for both stocks. If it is found that the flood will be higher than this calculated minimum levee height, all levees contained in these stocks are considered breached and the entire area will flood.

3.3 Official and perceived safety sub-model

The third sub-model is the official and perceived safety sub-model. This is an important part of the overall model as it is the main link between the floods and their impact with the levee life cycle sub-model. As hinted, this sub-model deals with two types of safety. The first one is the official safety. This safety parameter is a technical factor which is determined by two main conditions: the closed levee ring and the amount of levees which are up to standard. The first part of the safety is fully dependent on whether the levee ring has been fully closed or not. If the ring is not closed, then the official safety is considered to be zero. If it is closed, the official safety is allowed to climb above 0. The rest of the official safety is dependent on the overall average height of the levees. If all these levees are up to standards, that is either in the 'new levees' or the 'standard levees' stocks, then the official safety is 100%.

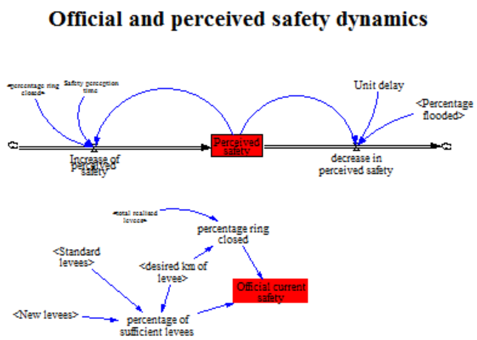

Figure 5: Submodel detailing the official and perceived safety models.

The second safety component is the perceived safety. This safety is psychologically and socially driven. It is constantly building up. As long as no flood occurs, the inhabitants feel confident and therefore feel safe. However, once a flood hits, and depending on its overall magnitude, the inhabitants are reminded of the flood threat and the perceived safety drops instantly. It then builds up gradually again as no floods lead to an increase of confidence.

This perceived safety represents a very important link to the construction and maintenance of levees. It directly affects the willingness to build and maintain. The higher the perceived safety, the lower the willingness of the inhabitants to build or renovate levees as they feel it is not important. However, after a flood, the perceived safety drops and the inhabitants are very willing to renovate and maintain their levees, as they are aware of the damages of the last flood. This link is an important one as it affects the model behaviour.

4 Results and analysis

Now that the model has been explained, it is possible to examine some of the results from the model. This section presents the reference case simulation to gain insight on the normal behaviour of the model. This is followed by a thorough uncertainty analysis to better study the overall impact of the different potential policies on the model outcomes.

4.1 Reference case

The reference case is simulated over a period of 1000 months. A flood of height 8.5 meters over a duration of one month occurs within the simulation at month

200. This is done to simulate the response of the model to a flood event. The results are provided in Figure 6 for the levee stocks and in Figure 7 for the safety related key performance indicators.

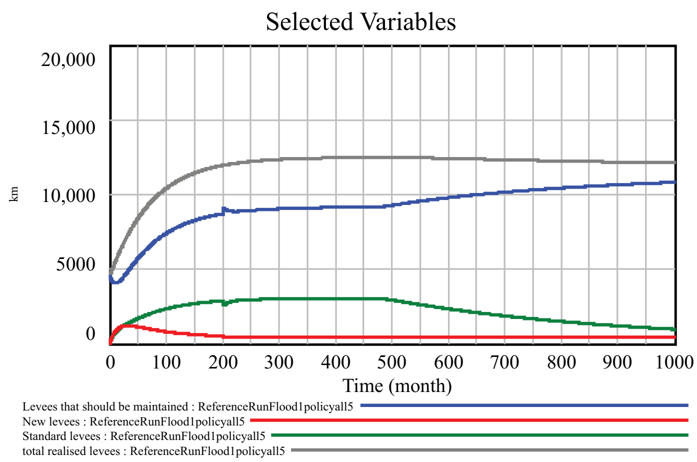

Figure 6: Results for the reference run displaying the total amount of levees (in grey), the standard levees (in green), the levees that should be maintained (in blue) and the new levees (in red).

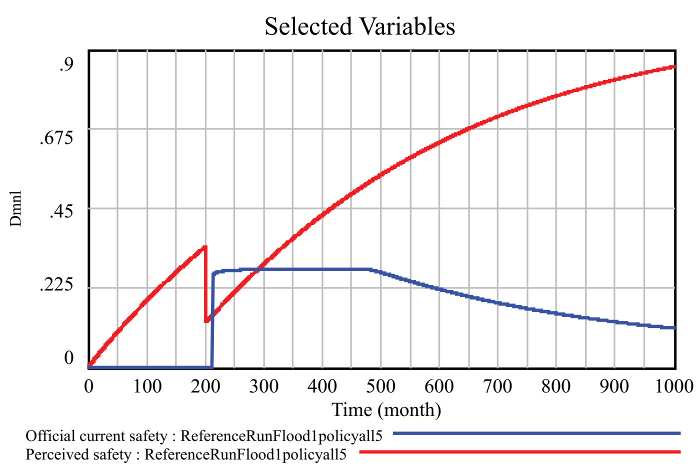

Figure 7: Results for the reference run displaying the official current safety (in blue) and the perceived safety (in red).

The flood has an impact on the levee stocks (Figure 6) as indicated by a slight increase in the 'levees that should be maintained' and a dented reduction of 'new levees'. The amount of 'standard levees' is also reduced by this flood. This is ascribed to the damages caused by the relatively small flood. The flood does not have an impact on the total amount of levees as the floods within the model do not destroy levees directly but instead damage them. The entire system recovers quickly after the flood.

The second behaviour that can be observed occurs throughout the model but is more evident after 500 months. This behaviour is related to the willingness to build and maintain, which decreases linearly after a flood has occurred and depends on the size of the flood as it is directly and linearly dependent on the perceived safety. The results for the perceived safety are shown in Figure 7. The flood has a small impact on the 'perceived safety' as can be seen within the figure. As the 'perceived safety' increases, the willingness to build decreases. This reflects clearly within the levee results where the amount of 'levees that should be maintained' quickly and steadily increases. Note the 'official safety' which jumps from 0 to a value of about 30% around time 200. This is not due to the flood, but instead due to the closing of the levee ring leading to a high official safety level. This official safety level is strongly influence hereafter by the levee figure and the redirection in the willingness to build and maintain at time 500. As less levees are being maintained and built, the overall height of the levees within the model decreases and this is illustrated by the slow reduction in official safety.

4.2 Uncertainty analysis

To analyse the different potential behaviours of the model, an uncertainty analysis is performed on the model. This analysis aims to randomly vary different parameters presented in model along with a possible range of sea level rise. The full range of variation covered in the multivariate sensitivity analysis is presented in Table 1. These are combined to form a large range of scenarios. The combinations are chosen using a latin hypercube sampling method (Stein, 1987). This ensures the entire constraint space is explored equally. Note that the public perception parameter is not present in Table 1. This is because this particular parameter affects the willingness to build which is a function. This function is presented in Appendix B.

For these scenarios, different flooding regimes are considered. They are presented within Figure 8. These flood regimes are considered to represent different approached to flood risk management that could occur in different countries around the world. Some countries are more likely to experience a large flood event every few decades while others are more likely to experience regular smaller floods. An exceptional scenario is also included in which two large floods occur within one decade so as to observe the resulting behaviour of the model.

Several key performance indicators (KPIs) are recorded for each run. Related to the amount of levees, the safety or the amount of land flooded, for conciseness, the results presented within this section only contain results for the standard levees KPI. The behaviour observed for the other KPIs is complementary. Within this section, the results for the first flood regime are presented, using an analysis of four different country specific parameters. For the three

Table 1: Range of the parameters that are varied for the uncertainty analysis.

Parameters	**Minimum**	**Reference**	**Maximum**
Yearly sea level rise	0.01	0.03	0.06
Investment level	0	5	10
Renovation safety level	0.01	0.06	0.11
Destruction levees time multiplier	0.50	1.00	1.50
New safety level	0.00	0.03	0.03
Resources allocation	0	5	10
Building capacity	10000	6000	2000
Renovation safety percentages	0.5	0.3	0.1
Expertise	0	5	10
Destruction levees time	15	30	45
New safety level multiplier	0.50	1	1.50
Time before renovation	5	15	25

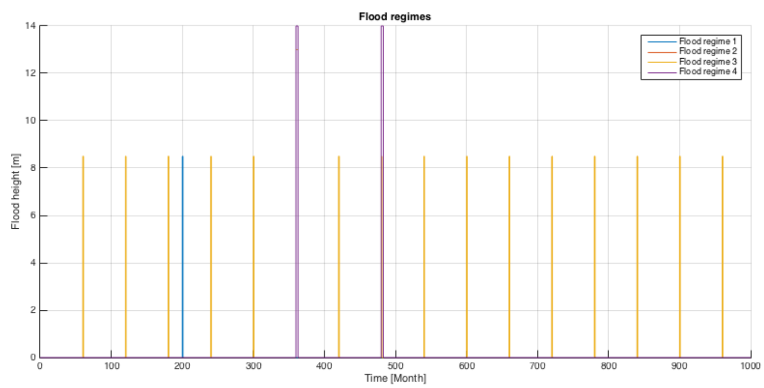

Figure 8: The different flood regimes being considered.

additional flood regimes, the results focus on the public perception parameter only.

The interpretation of the results is based on analysis of the graphical results in combination with insights derived from the model structure. The results of this uncertainty analysis for the first flood regime are presented in Figure 9, Figure 10, Figure 11 and Figure 12. The statistical analysis present on the left side of the figures are histogram representations of the results at the specified times.

The first figure, Figure 9, displays the results with post-processing filters applied on the resource allocation parameter which decides whether the government renovates or builds more levees. The results are split into three categories.

In red are the results corresponding to the tactic values which are above 7 on a scale from 0 to 10. The blue curves correspond to the tactic values between 4 and 7 while the green ones are for values below 4. On the right side of the figure, one can see the distribution of the results at the last time step (time step 1000 months).

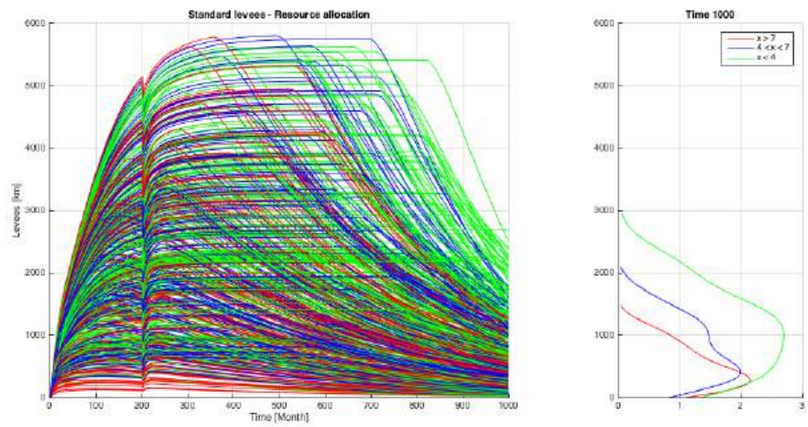

Figure 9: Standard levees - Resources allocation results - Flood 1.

Figure 10 is a similar figure but presents the results with a post-processing filter applied on the expertise. The results presented on the right of the figure are very different in this case. The results are shown at time 100 months and at the final time of 1000 months. One can see that the distribution changes over time with the majority of the low grade expertise scenarios accumulating at the bottom which means there are less standard levees in the system. This can be explained by the fact that levees deteriorate faster due to the lack of expertise. This behaviour is less present for the scenarios where the expertise is considered to be average. This is even less present for the scenarios with grades higher than 7 where the standard levee stocks start to decrease due to the decreasing willingness to build and not really due to the deterioration.

Figure 11 moves on to the public perception parameter. As in previous figures, the graphs on the right display the scenario distribution, but this time before and after the flood along with the final time. The results seem to indicate that this tactic has little impact on the results considering the model behaviour. One can observe a large reduction in standard levees when the public perception parameter is very low. Although this behaviour is already attributed partly to the expertise, it would also seem to be related to the public perception parameter particularly considering the large peak at time 1000. The public perception does have an impact on the willingness to build leading to a decrease in the willingness to build, which would explain the large decrease in standard levees quickly after the flood occurs at time 200.

Figure 12 displays the results regarding the investment level of the govern-

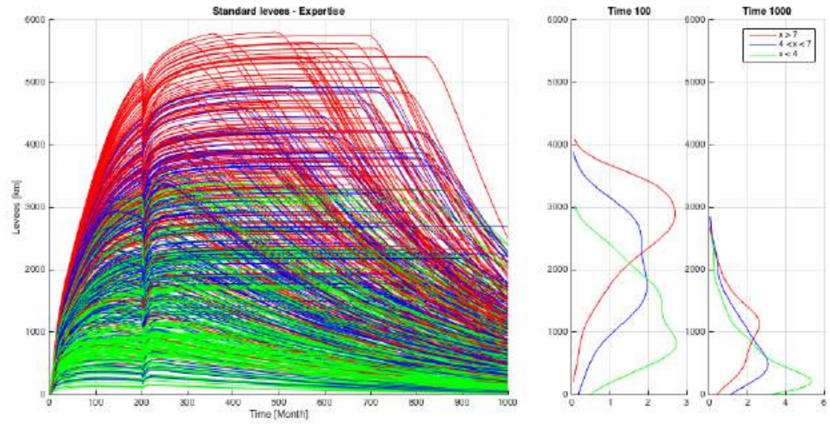

Figure 10: Standard levees - Expertise results - Flood 1.

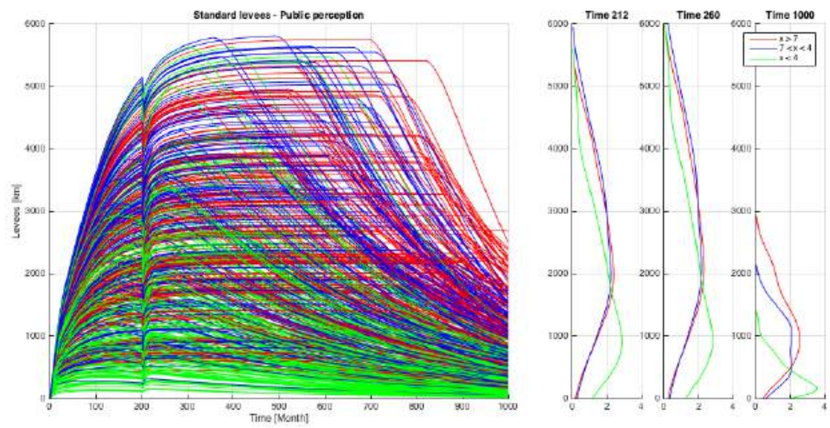

Figure 11: Standard levees - Public perception results - Flood 1.

ment. A government investing less, has a large number of scenarios with an almost depleted standard levee stock. This also results from the expertise and public perception as shown previously.

Figure 13 is the first of the figure that displays the response to a second flood. This flood regime comprises of a large flood event followed by a smaller one only a decade later. The results are processed for the public perception parameter. The distribution graphs are shown before the first flood in between the two floods, and at the final time. The results show a net difference from the previous results for the first flood regime. The willingness to build remains fairly high as the floods keep the perceived safety fairly low throughout the simulation.

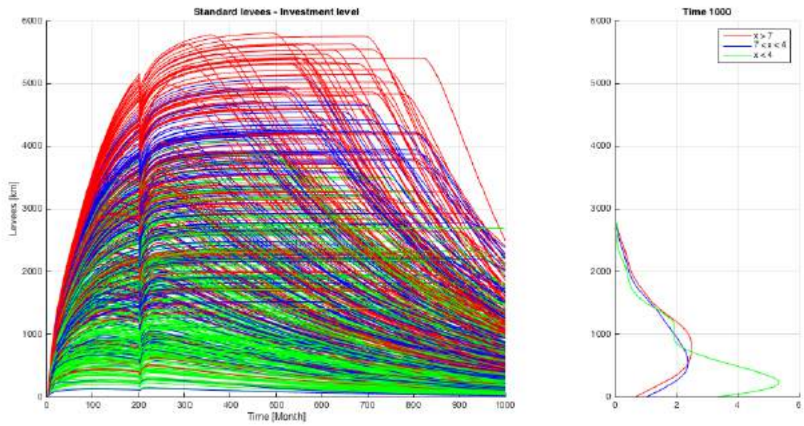

Figure 12: Standard levees - Investment level results - Flood 1.

Towards the end, there is still a net reduction in the standard levees for most of the scenarios. However, as shown for the previous flood regime, the lowest graded scenarios end up quickly at the bottom of the distribution graphs. This is the case throughout whether it be before, or after the floods. This shows that the public perception parameter has a large impact on the level of the levees and on the protection of the inhabitants. It is important to consider that, similarly to previous flood regimes, this is also impacted by the low priority and low investment grades.

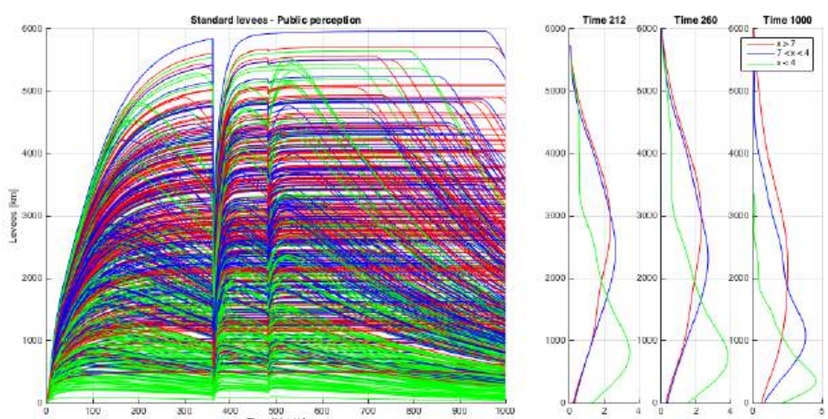

Figure 13: Standard levees - Public perception results - Flood 2.

Figure 14 presents the results for the third flood regime with recurrent small floods. The results clearly display the relentlessness of the floods which keep the perceived safety very low and hence the willingness to build very high. This translates to a public perception parameter in which most of the distributions are fairly similar due to this high perceived safety. This shows that regardless of the policy being applied, a constant low perceived safety will lead to a need to build more levees. A small impact of the policy can be observed for the distribution as the low graded curves are slightly lower, but this is almost negligible.

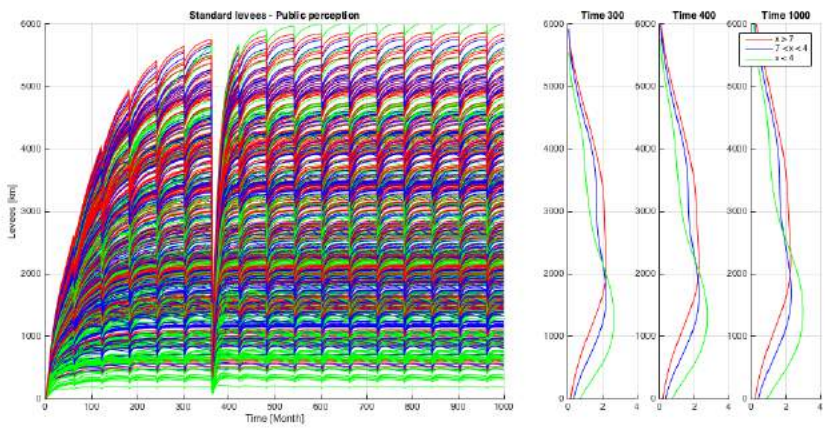

Figure 14: Standard levees - Public perception results - Flood 3.

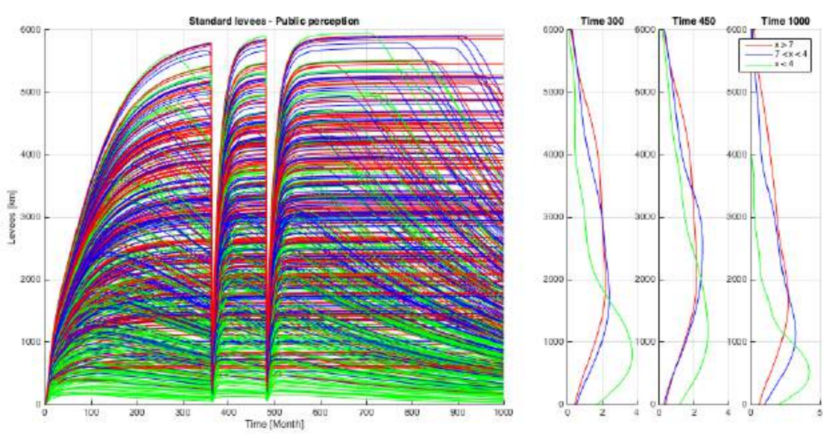

Figure 15: Standard levees - Public perception results - Flood 4.

Finally, Figure 15 displays the final flood regime which consists of two large floods happening within a decade. The results displayed here are similar to the results obtained for the third flood regime. The main difference relates to the magnitude of the results which are affected by the large second flood. This affects the distribution displayed on the right of the main figure. They remain similar except for the scenarios with low grades.

5 Policy analysis

After the uncertainty analysis was performed for a range of randomly selected scenarios, it is interesting to focus on more specific scenario that could represent real world countries and their internal policies.

To look at different scenarios, several stand-in countries are selected and their potential policies are mapped out as shown in Table 2. The values chosen represent coherent policies that could be followed by real life countries. The main aim from this analysis is to show the outcomes of policies on the state of the flood defense system within a certain country.

Table 2: Policy approaches considered for five imaginary countries.

Countries	**Expertise**	**Resources allocation**	**Public perception**	**Investment level**
A	10	4	10	10
B	7	10	2	3
C	7	5	3	2
D	7	4	8	4
E	8	4	8	5

The results of the policy analyses are shown through the main KPI used within this paper: the amount of standard levees. This is shown in Figure 16. Note that this analysis is only run for the first flood regime. This is done for conciseness. The results obtained can lead to some observation on the results obtained for the different policies. It is important to mention that the model used in this paper can in no way be used to judge the policies of different countries. This is because it only addresses investments and policies related to the construction and maintenance of new levees. It does not address additional aspects that need to be considered in the event of a flood such as evacuation or recovery.

According Figure 16, it is clear that country A is the country with the highest amount of standard levees. It could therefore be considered as the safest country from a flood defense perspective. The amount of levees is the highest and it is less affected by the flood than the other countries portrayed within the figure. However, the inevitable perceived safety leads to a reduction of the standard levees as there is no longer any experience of flooding. The investment level, along with the expertise and the public perception are fairly high. This leads to robust flood defenses.

The results obtained for the other countries are very different. There are

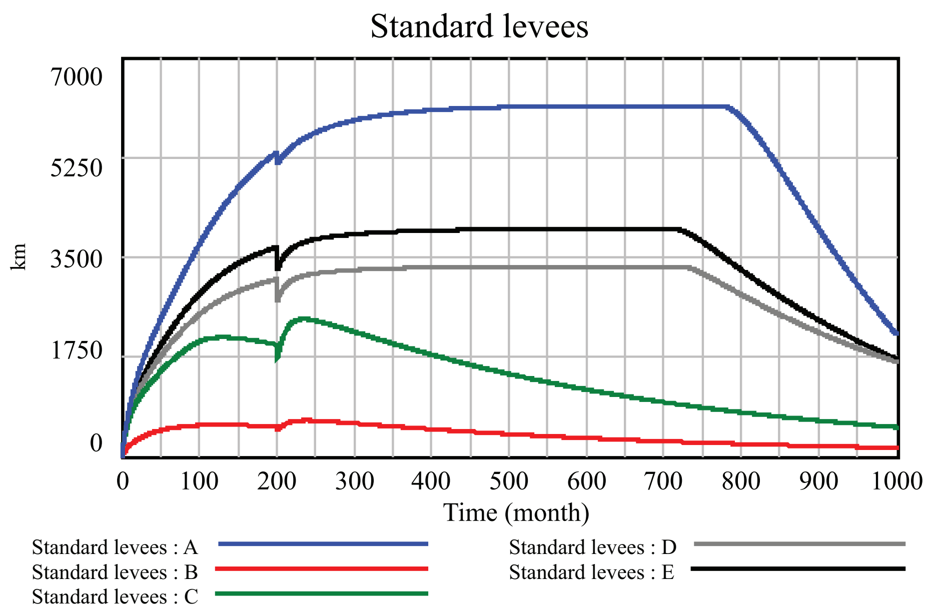

Figure 16: Policy analysis results plotted for the standard levee stock for first flood regime.

two main groups that can be considered. The first one is formed by country D and country E. For this group, the flood defenses appear fairly robust as the standard levee count is fairly high. This is due to a relatively high investment level overall and a high level of expertise. Note that the decrease due to a decreasing willingness to build also occurs late, as it did for country A. This is due to a predominantly high score for the public perception parameter.

The second group consists of countries B and C. These are the countries that exhibit the lowest amount of standard levees. This can also be explained by the policies that are adopted by policy makers as well as country specific attributes. Country B shows the poorest behaviour due in part to its very low public perception grade. This means that the country is less likely to finance flood protection and this is translated to a lower willingness to build in the model. The low amount of investment compared to the other countries is the main reason why the amount of standard levees is much lower. As a positive factor, the large amount of expertise does allow the amount of standard levees to not decrease at such a higher rate.

6 Discussion and conclusion

The model presented in this paper exhibits several behaviours of interest. These behaviours are closely related to the country specific parameters.

The first point of note is that the results obtained were, for the most part, very predictable. The model has however highlighted important points with respect to the willingness to build and the perceived safety. It has shown that after a number of years, the public will forget past floods and being to feel safe. This has been observed in real life too, where some countries will slowly lose the urgency to build or maintain levees when they do not experience a catastrophic flood in the recent past. Additionally, the model has shown that after a catastrophe there will be an urgency to build defences in a country. An example of such real life behaviour is the response to hurricane Katrina and the construction of one of the largest flood defence systems in the United States in New Orleans, (Jha et al., 2012). The model also highlighted a great deal of investment and expertise will lead to higher amount of levees which are also of higher quality.

This model does, however, have a number of limitations that should be emphasised. The policy analysis has suggested that the situation in certain countries might lie with the expertise, priorities on maintenance, the public perception and the level of investment. It would however be incorrect to provide advice based on the results obtained. This is because all significant differences between the countries are not represented in the model used within this report. For example, a country like The Netherlands will emphasise and invest in flood protection programs. This is justified by limited evacuation and recovery planning and the inability of inhabitants to flee to higher land in the case of a major flood. This justifies a very high level of investment. Other countries will have a much lower investment level, but this is not necessarily bad. Such countries may have higher land close to floodplains which would allow the evacuation of inhabitants and reduce the potential loss of life. These countries tend to also focus more on the recovery from flooding. These aspects are not presented within the model.

Another aspect that was mentioned within the policy analysis section is the relation between flood defenses and flood regimes. It is evident that different countries are likely to face different types of natural hazard. For example, the Gulf of Mexico region is more likely to face occasional flooding due to hurricanes while the North Sea region is more likely to be battered by more frequent but lower magnitude storms. This is not taken into account in the analysis presented. Based on the expected natural conditions, policy makers can choose on policies that are more adequate for their region. In this way, some flood defense protection will be designed to withstand regular low flooding events while other will be built to withstand larger storms that generally occur once a decade, or simply not be constructed in favor of evacuation plans.

To conclude, this model has enabled a comparison between high level flood risk policy making and its complications for system behaviour. The model should not be used to design such a system. It is merely intended to provide an elegant basis for indicating the complexity of flood risk management policy decision making.

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A Model equations

The following table presents the model equations that are used throughout the model. It presents the variables that are considered within the model along with their respective unites and formulas.

Variable	**Unit**	**Formula**
Average time that it will take a new levee to go to should be maintained	month	$\frac{1}{\frac{1}{\text{sea level delay new}} + \frac{1}{\text{time before renovation}}}$
Average time that it will take that a standard levee will go to maintained	month	$\frac{1}{\frac{1}{\text{time before renovation}} + \frac{1}{\text{sea level delay standard}}}$
Behaviour of first flood floodprofile2	Dmnl	PULSE(moment 1st floodprofile2, duration of flood 1 month)
Behaviour of first flood floodprofile3	Dmnl	PULSE TRAIN(60, 1, 60, 1000)-PULSE(360, 1)
Behaviour of floodprofile1	Dmnl	PULSE(moment 1st floodprofile1, duration of flood 1 month)
Behaviour of frist floodprofile4	Dmnl	PULSE(moment 1st floodprofile 4, duration of flood 3 month)
Behaviour of second flood floodprofile2	Dmnl	PULSE(moment 2nd floodprofile2, duration of flood 1 month)
Behaviour of second flood floodprofile3	Dmnl	PULSE("Moment 13 meter flood, flood profile 3", duration of flood 3 month)
Behaviour of second flood floodprofile4	Dmnl	PULSE(moment 2nd floodprofile 4, duration of flood 3 month)
Building capacity	km	(2000+800*Government allocation priority)
capacity to repair	km	total realised levees*percentage of total realised that can be repaired*willingness to build
decrease in perceived safety	1/month	(Perceived safety*Percentage flooded)/Unit delay
Design and construction of levees	km/month	MIN (max(("Desired km of levee + 2750"-total realised levees)/Design and construction tim, 0), used building capacity/Design and construction time)
Design and construction time	Month	90
desired km of levee	km/month	12000
Desired km of levee + 2750	km	desired km of levee + 2750
Destruction time multiplier	Dmnl	0.5+Governmental priority towards robust levees/10
deterioration of levees	km/month	MIN(Standard levees/time before renovation+Standard levees/sea level delay standar + fraction SL deterioration when flood *Standard levees,Standard levees)
deterioration of new levees	km/month	MIN((New levees/time before renovation)+(New levees/sea level delay new)Percentage NL deterioration when flooded *New levees, New levees)
duration of flood 1 month	Month	1
duration of flood 3 month	Month	3
extra height for flood of 1300 centimeter	m/km	13

flood	m/km	IF THEN ELSE(flood profile selector = 0, 0, IF THEN ELSE(flood profile select = 1, floodprofile1, IF THEN ELSE(flood profile selector = 3, floodprofile, IF THEN ELSE(flood profile selector = 4, floodprofile4, IF THEN ELSE(flood profile selector = 2, floodprofile2, 0)))))
Flood of 1400 centimeter	m/km	14
Flood of 800 centimeter	m/km	8
Flood of 850 centimeter	m/km	8.5
flood profile selector	Dmnl	0
flooded km of ring	Dmnl	IF THEN ELSE(flood >= 7, km of levee that are missing, 0)
floodprofile1	m/km	(Flood of 850 centimeter+sea rise constant correct for months*Time)*behaviour of floodprofile1
floodprofile2	m/km	(Flood of 1400 centimeter + sea rise constant correct for months*Time) * Behaviour of first flood floodprofile2 + (Flood of 800 centimeter +sea rise constant correct for months * Time) * Behaviour of second flood floodprofile2
floodprofile3	m/km	(Flood of 850 centimeter+sea rise constant correct for months*Time)*Behaviour of first flood floodprofile3+(extra height for flood of 1300 centimeter+sea rise constant correct for months*Time)*Behaviour of second flood floodprofile3
floodprofile4	m/km	(Flood of 1400 centimeter+sea rise constant correct for months*Time)*Behaviour of frist floodprofile4 + (Flood of 1400 centimeter+sea rise constant correct for months *Time)*behaviour of second flood floodprofile4
fraction SL deteriation when flood	Dmnl	max(0,MIN(1,(flood - ((1+renovation safety level)*7+sea rise constant correct for months*Time)) / ((1+renovation safety level)*7+sea rise constant correct for months*Time)))
Government allocation priority	Dmnl	5
Governmental priority towards robust levees	Dmnl	5
Individualism	Dmnl	5
initial standard safety level	m/km	7
km of levee that are missing	km	IF THEN ELSE(desired km of levee-total realised levees¡=0 , 0, desired km of levee-total realised levees)
km of new levee flooded	km	New levees*percentage of new levees flooded
km of standard levee flooded	km	Standard levees*percentage of standard levees flooded
km should be maintained levee flooded	km	Levees that should be maintained*percentage of maintained levees flooded
Levee construction expertise	Dmnl	5
levees broken	km/month	(Levees that should be maintained/time till destruction of levees)
Levees that should be maintained	km	Deterioration of levees+deterioration of new levees-levees broken-repairing of levees - Initial value: 4500
minimum height levee in stock new levee	m/km	safety height of a repaired levee*(1+new safety level)-safety height increase due to time for new levees
minimum height levee in stock standard levee	m/km	safety height of a repaired levee*(1+renovation safety level)-safety height increase due to time for standard levees
Moment 13 meter flood, flood profile 3	month	360
moment 1st floodprofile 4	month	360
moment 1st floodprofile1	month	200
moment 1st floodprofile2	month	360
moment 2nd floodprofile 4	month	480

moment 2nd floodprofile2	month	480
months in a year	month	12
New levee	km	Design and construction of levees-deterioration of new levees - Initial value: 0
new safety level	Dmnl	(0.01+Governmental priority towards robust levees*0.01)*Safety level multiplier
Official current safety	Dmnl	IF THEN ELSE(percentage ring closed¿=1, percentage of sufficient levees,0)
Perceived safety	Dmnl	total realised levees2-decrease in perceived safety,0)
Percentage flooded	Dmnl	total km of levees flooded/desired km of levee
Percentage NL deterioration when flood	Dmnl	max(0,MIN(1,(flood - ((1+new safety level)*7+sea rise constant correct for months*Time)) / ((1+new safety level)*7+sea rise constant correct for months*Time)))
Percentage of levees flooded	Dmnl	(km of new levee flooded+km of standard levee flooded+km should be maintained levee flooded)/total realised levees
percentage of maintained levees flooded	Dmnl	IF THEN ELSE(flood>=7, 1, 0)
percentage of new levees flooded	Dmnl	IF THEN ELSE(flood>=minimum height levee in stock new levee , IF THEN ELSE(flood<=(minimum height levee in stock new levee+safety height increase due to time for new levees), ((flood-minimum height levee in stock new levee)/safety height increase due to), 1), 0) time for new levees
percentage of standard levees flooded	Dmnl	IF THEN ELSE(flood<=(minimum height levee in stock standard levee+safety height increase due to time for standard levees), ((flood-minimum height levee in stock standard levee)/safety height increase due to time for standard levees), 1) , 0)
percentage of sufficient levees	Dmnl	(Standard levees+New levees)/desired km of levee
percentage of total realised that can be repaired	Dmnl	(0.5-Government allocation priority*0.04)
percentage ring closed	Dmnl	total realised levees/desired km of levee
renovation safety level	Dmnl	(0.01+(Governmental priority towards robust levees/100))*Safety level multiplier
repairing of levees	km/month	(MIN(Levees that should be maintained/time needed to repair and construct, capacity to repair/time needed to repair and construct))
safety height increase due to time for new levees	m/month	sea rise constant correct for months*average time that it will take a new levee to go to should be maintained
safety height increase due to time for standard levee	m/month	sea rise constant correct for months*average time that it will take that a standard levee will go to maintained
safety height of a repaired levee	m/month	sea rise constant correct for months*Time+initial standard safety level
Safety level multiplier	Dmnl	0.5+Levee construction expertise/10
Safety perception time	month	480
sea level delay new	month	initial standard safety level*new safety level/sea rise constant correct for months
sea level delay standard	month	initial standard safety level*renovation safety level/sea rise constant correct for months
sea rise constant	m/km/year	0.03
sea rise constant correct for months	m/km/month	(sea rise constant / months in a year)
Standard levees	km	repairing of levees-deterioration of levees
time before renovation	month	(5+2*Levee construction expertise)*Destruction time multiplier

time needed to repair and construct	month	42
time till destruction of levees	month	(15+3*Levee construction expertise)*Destruction time multiplier*12
total km of levees flooded	km	IF THEN ELSE((flooded km of ring+km of new levee flooded+km of standard levee flooded+km should be maintained levee flooded)>=12000, 12000, flooded km of ring+km of new levee flooded+km of standard levee flooded+km should be maintained levee flooded)
total realised levees	km	Levees that should be maintained+Standard levees+New levees
Increase of perceived safety	Dmnl/month	(max(1-Perceived safety,percentage ring closed-Perceived safety))/Safety perception time
Unit delay	month	1
used building capacity	km	building capacity*willingness to build
willingness to build	Dmnl	(1-Perceived safety)*(Individualism)

B Willingness to build lookup

The lookup function that is used for the calculation of the willingness to build is presented in Figure 17. As is shown in the figure, different grades for the public perception will lead to a different lookup representing a country where citizens feel like the government should take care of their protection or countries where citizens feel responsible for their own safety.

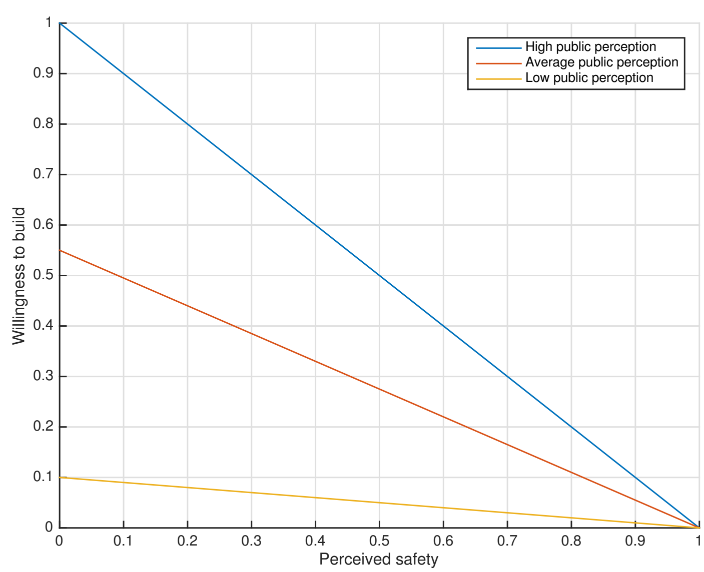

Figure 17: Public perception lookup function.