Systemic flood risk management
The challenge of accounting for hydraulic interactions

Ciullo, Alessio; De Bruijn, Karin M.; Kwakkel, Jan H.; Klijn, Frans

DOI
10.3390/w11122530

Publication date
2019

Document Version
Final published version

Published in
Water (Switzerland)

water

MDPI

Article

Systemic Flood Risk Management: The Challenge of Accounting for Hydraulic Interactions

Alessio Ciullo [1,2,*], Karin M. De Bruijn [1], Jan H. Kwakkel [2] and Frans Klijn [1,2]

[1] Department of Flood Risk Management, Deltares, 2600 MH Delft, The Netherlands
[2] Faculty of Technology, Policy and Management, Delft University of Technology, 2628 BX Delft, The Netherlands
* Correspondence: a.ciullo-1@tudelft.nl

Received: 14 October 2019; Accepted: 27 November 2019; Published: 29 November 2019

check for updates

Abstract: Rivers typically flow through multiple flood-protected areas which are clearly interconnected, as risk reduction measures taken at one area, e.g., heightening dikes or building flood storage areas, affect risk elsewhere. We call these interconnections 'hydraulic interactions'. The current approach to flood risk management, however, neglects hydraulic interactions for two reasons: They are uncertain and, furthermore, considering them would require the design of policies not only striving for risk reduction, but also accounting for risk transfers across flood-protected areas. In the present paper, we compare the performance of policies identified according to the current approach with those of two alternative formulations: One acknowledging hydraulic interactions and the other also including an additional decision criterion to account for equity in risk distribution across flood-protected areas. Optimal policies are first identified under deterministic hydraulic interactions, and, next, they are stress-tested under uncertainty. We found that the current approach leads to a false sense of equal risk distribution. It does, however, perform efficiently when a risk-averse approach towards uncertain hydraulic interactions is taken. Accounting for hydraulic interactions in the design of policies, instead, increases efficiency and both efficiency and equity when hydraulic interactions are considered deterministically and as uncertain, respectively.

Keywords: flood risk management; uncertain hydraulic interactions; equity

1. Introduction

It is well known that structural flood risk reduction measures alter a river's hydraulic regime, as demonstrated by, for example, increased downstream flood peaks due to upstream dike heightening [1] or downstream flood load reduction due to upstream flooding [2,3]. These phenomena are hereafter referred to as 'hydraulic interactions'.

Vorogushyn et al. [4] recently urged flood risk analysts, managers and policy makers to take full account of hydraulic interactions and adopt a system-wide perspective, in order to properly comply with the EU Flood Directive [5] which prescribes that flood risk management plans 'shall not include measures which, by their extent and impact, significantly increase flood risks upstream or downstream'. This, however, is not an easy task for two main reasons.

First, hydraulic interactions are uncertain. Structural measures, such as dams and dikes, are designed according to a certain load (i.e., the design event), such that they should ideally withstand every load of lower magnitude. However, the behavior of such infrastructures is hard to predict, and there have been cases of unexpected failures in the past [6]. Furthermore, besides the uncertainty on when and where dikes will fail, the way failure occurs, i.e., the breach growth rate and the final breach width, is also uncertain. Therefore, predictions of hydraulic interactions can be flawed and mistakes in such predictions can lead to undesired outcomes (e.g., flooding occurring where it was not predicted to occur or too much investments spent where it was not needed). To avoid this, policies should be stress-tested under uncertainties of hydraulic interactions and decisions made accordingly.

Second, even assuming hydraulic interactions can be accurately predicted, adopting a system-wide approach requires quantifying risk transfers across flood-prone areas within the system and to fully account for them in the design of risk management measures. However, current decision support methods in flood risk management, such as cost–benefit analysis, often fall short in considering risk transfers and accounting for risk distribution [7]. Previous flood risk management studies [8–10] based on cost–benefit analysis focused on optimizing for individual flood-prone areas independently and neglecting downstream risk changes, with the optimal risk management option being the one minimizing total costs (i.e., the sum of investment costs and the net present value of expected annual flood damage). This latter figure implies aggregating all local optimal risk reductions and investment costs. Minimizing this figure, however, does not imply that risk is reduced everywhere in the system. It may indeed be more efficient for the system as a whole that risk increases in some flood-protected areas, such that a larger risk decrease is achieved elsewhere [11].

Current practice in flood risk management seldomly addresses these two aspects, as hydraulic interactions and risk distribution are often neglected. Typically, flood risk management is conducted at the local level, e.g., the scale of a community, city, or small region, with system-wide plans, e.g., at the scale of large regions or countries, being the result of a mere combination of local plans. Ciullo et al. (2019) [12] demonstrated that policies following from such approach qualify as a 'better safe than sorry' policy which may be preferable when risk aversion is high. It is, however, unsure until what degree of risk aversion current practice remains desirable and, furthermore, how this compares with approaches that more appropriately address the aforementioned challenges of adopting a whole system approach.

This paper carries out a flood risk management study along the Lower Rhine River, including parts of Germany and the Netherlands. The study compares results between current practice and two alternative policy formulations in (1) designing flood risk management plans and (2) assessing the performance of these plans under uncertainty with respect to different risk aversion levels. Of the two alternative formulations, one formulation acknowledges only hydraulic interactions, while the other considers both hydraulic interactions and uses an additional decision criterion to account for equity in risk distribution across flood-protected areas.

The analysis is structured by following the Many-Objective Robust Decision Making approach [13]. First, for each problem formulation, optimal policies are identified under a deterministic scenario using a Many Objective Evolutionary Algorithm [14]. Second, these policies are stress-tested under uncertainties relative to hydraulic interactions. Finally, the performance of policies under uncertainties is evaluated under different levels of risk attitudes.

The paper is structured as follows. Section 2 introduces the case study. The simulation model is detailed in Section 3. Section 4 presents the method in more details. Section 5 reports results, with Section 5.1 introducing the optimal policies identified under the deterministic scenario and Section 5.2 reporting a stress-test analysis of these policies under uncertainty and on how results change under different assumptions regarding risk attitudes. Finally, conclusions are provided in Section 6.

2. Case Study

The Rhine River begins in the Alps and reaches the North Sea in the Netherlands after about 1320 km. From upstream to downstream, several sections can be identified [15]: The Upper Rhine (from Basel, Switzerland, to Bingen, Germany), the Middle Rhine (from Bingen to Bonn, Germany) and the Lower Rhine (from Bonn to the North Sea). The term Lower Rhine is, however, at times used to refer only to the German part, with the Dutch part being called Dutch Rhine [16]. We here follow this latter terminology. The Dutch Rhine can then be divided into a non-tidal zone, a transition zone and a tidal zone. In the non-tidal zone, water levels solely depend on river discharges and are not influenced by the sea level and tides.

The study area in the present study is the transboundary downstream part of the Lower Rhine, from Bislich (right bank) and Xanten (left bank) up to the end of the non-tidal zone of the Dutch Rhine (Figure 1). The Dutch Rhine bifurcates into the Waal River and the Pannerdensch-Kanaal, with the latter then bifurcating into the Lek to the west and the IJssel River to the north.

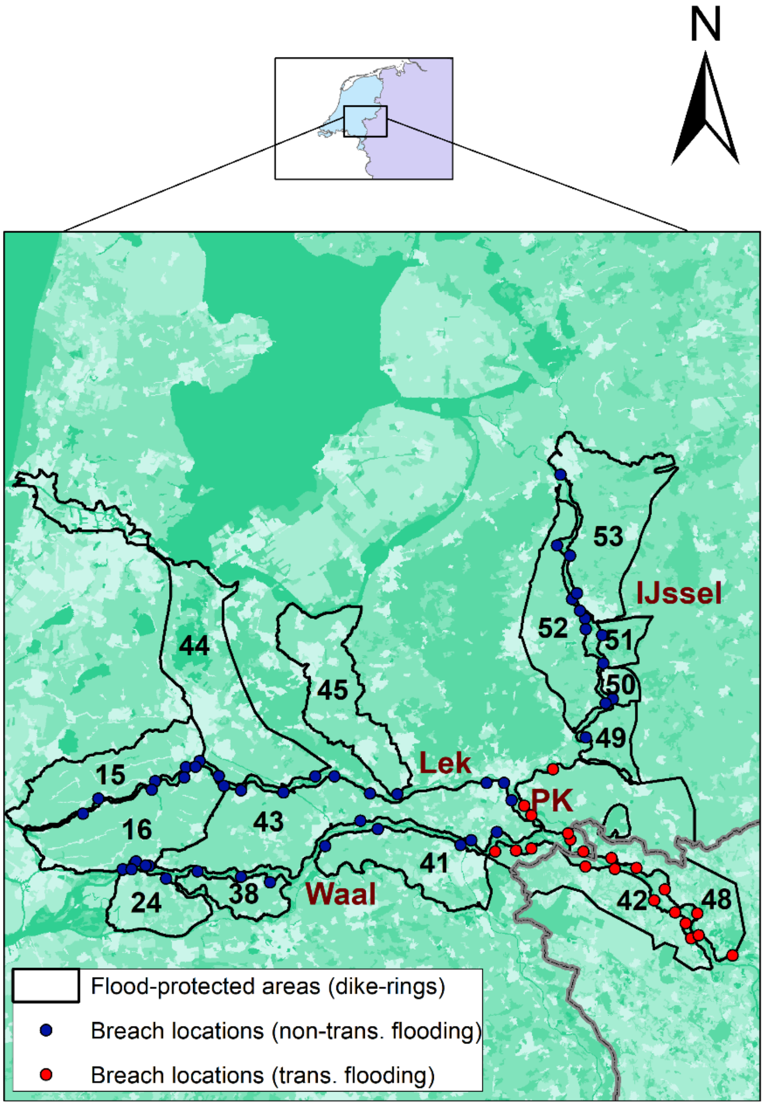

Figure 1. Transboundary case study area with the grey line representing the administrative border. Thick black lines represent dike-rings, i.e., dike-protected areas, with the code relative to each dike-ring reported within. Dots are breaching locations, with flooding at the red dots causing transboundary damage, i.e., damage in both countries. Beside the German Rhine, four branches are identified: Boven-Rijn (downstream the German Rhine, up to the bifurcation point), Waal, Pannerdensch-Kanaal (PK in the map), the Lek and the IJssel.

In Figure 1, the thick closed lines represent so-called 'dike-ring areas', alluvial plains that are protected from flooding by dikes. Seventy breach locations of interest (i.e., places where the protection might fail resulting in flooding) are recognized. Locations in red are located on transboundary dike rings, implying that flooding causes damage in both countries. All considered German breach locations result in transboundary flooding. In the Dutch Rhine, five main river stretches are identified: The Boven-Rijn, i.e., the Rhine River in the Netherlands up to the first bifurcation point; the Waal and the Pannerdensch-Kanaal, i.e., the left and right branches from the first bifurcation point, respectively; and the Lek and IJssel Rivers, i.e., the left and right branches from the second bifurcation point, respectively.

3. Simulation Model

The simulation model builds upon the model introduced in [12], which was developed for the IJssel River. The model is developed following the XLRM framework proposed in [17] but with slightly adapted terms. In the framework, *X* are the 'exogenous uncertainties', factors outside the control of the decision-maker; *L* (of lever) are 'policies', alternative strategies or interventions the decision-maker wants to explore; *M* (of measure) are 'outcomes of interest', the performance metrics used to rank the desirability of the different policies (L) in the face of the exogenous uncertainties (X); and, finally, R refer to 'relationships in the system', ways in which the exogenous uncertainties (X), policies (L) as well as outcomes (M) are tied together and relate to each other, namely the actual simulation model. The XLRM framework of the simulation model is reported in Figure 2 and described below.

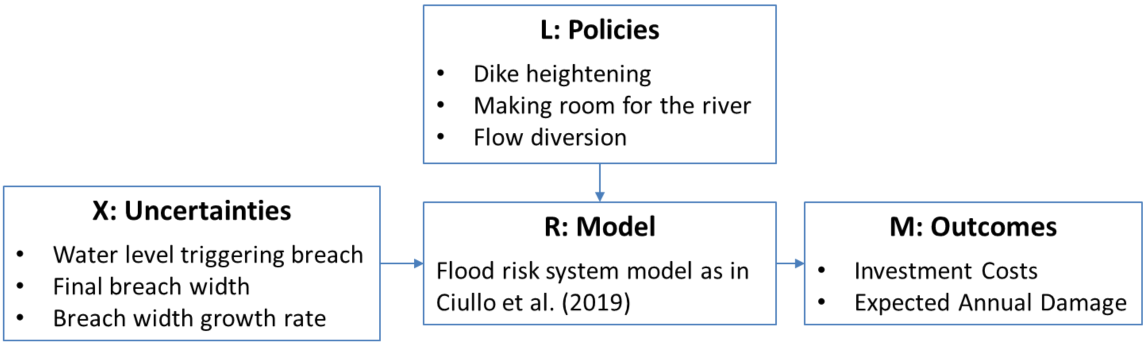

Figure 2. The XLRM framework of the simulation model used in this study.

3.1. *Policies (L)*

From a range of possible flood risk reduction measures and policy instruments [18], three major flood risk reduction measures are considered, viz.: dike heightening, making room for the river, and changing the discharge distribution at the bifurcation points. In the analysis, flood risk management policies result from the combination of these three types of measures.

As far as dike heightening is concerned, dikes can be raised at each location up to 1 m, with steps of 10 cm. As for making room for the river, an existing database [19] allows choosing from 156 individual Room for the River projects only along the Dutch Rhine. For our simulation, a project can simply be either implemented or not. Regarding making changes to the discharge distribution, there are two bifurcation points of interest, with the default flow distributions being the ones provided by a *SOBEK* model calibrated on the case study. At each bifurcation point, it is assumed that a distribution change of plus/minus 30% of the default distribution can be implemented.

3.2. *Model Uncertainties (X)*

Model uncertainties are summarized in Table 1. They relate to three main categories: Water levels triggering dike failure, breach width's growth rate and final breach width. Water levels triggering a breach are represented through fragility curves, i.e., a curve that indicates the dike's probability of failure given a water level. The lower the conditional failure probability, the higher the water level that would cause failure. The considered breach width growth rates are such that it takes either 1, 3, or 6 days to reach the final breach width, which can vary between 35 m and 350 m. As these uncertainties relate to all seventy potential breach locations in Figure 1, there are 210 uncertain factors.

Table 1. Description of the model uncertainties.

Uncertainty	Water Level Triggering Failure	Final Breach Width	Breach Growth Rate
Values	Given by fragility curves at each location	Between 35 and 350 m	The final breach width can be reached in 1, 3, or 6 days

3.3. Model Outcomes (M)

The model calculates the present value of expected annual damage, *EAD,* in each dike ring area and the investment costs, *I*, in Germany and the Netherlands.

The present value of expected annual damage is defined as follows:

$$EAD\ (T,\ r) = \sum_{t=1}^{T} \frac{\int_{H_{min}}^{+\infty} p(H)L(u,H)dH}{(1+r)^{t}} \quad (1)$$

where L is the flood damage (€); H is the water level in the river (m above mean sea level), with H_{min} being the lowest water level causing flood damage; u represents the effect of the chosen policy on the loss estimates; $p(H)$ is the exceedance probability of a given water level H; T is the planning period (i.e., 200 years), r the discount rate (3.5 percent per year).

Investment costs of dike raising are calculated as in [9]:

$$I\ = \begin{cases} 0 & if\ \overline{h} = 0 \\ (c+bu)e^{-\lambda(W+u)} & if\ \overline{h} > 0 \end{cases} \quad (2)$$

where $\overline{h}$ is the degree of dike heightening; parameters c and b are fixed and variable costs, respectively; λ is a scale parameter and W is the cumulative dike heightening over the entire planning period, establishing increasing investment costs per heightening unit as dikes become higher. As in the present work a single optimal dike height is identified, W is assumed to be equal to zero. Parameters c, b and λ are assigned per stretch of the dike system and their values are provided by [20]. As for making room for the river, costs of projects range from 50,000 euros for small-scale projects in the active floodplain to about 2 billion euros for large-scale dike relocations or bypasses in urban contexts. Regarding the changes to the discharge distribution, there are no associated costs as it is assumed this could be achieved by adjusting the hydraulic structures currently in place.

4. Method

Given the many-objective nature of large-scale flood risk management and the various uncertainties related to hydraulic system behavior, we follow a four-steps approach based on the Many Objective Robust Decision Making framework [13]. Essentially, optimal policies are first identified under a reference scenario (i.e., reference values for uncertain inputs) and, next, the performance of these policies is stress-tested under uncertainty. Finally, policies' robustness under uncertainty is assessed according to different of risk attitudes. The procedure is repeated for three different formulations of the policy problem, of increasing complexity:

1. Striving for overall risk reduction and neglecting hydraulic interactions,
2. ibid, but accounting for hydraulic interactions, and
3. also accounting for risk distribution.

The policy problem formulations are more formally introduced below.

4.1. Policy Problem Formulations

The first problem formulation resembles current practice. Policies are assessed based on total societal costs (i.e., sum of investment costs and expected annual damage) in Germany and the Netherlands and hydraulic interactions are neglected. The second problem formulation follows the first one in terms of decision criteria, but does consider hydraulic interactions, i.e., adopting a whole hydraulic system approach by recognizing effects of local measures on the discharges and flood levels in the rivers. These two formulations read as follow:

$$minimize \quad \sum_{i}(I_i + EAD_i) \;\; \forall\, i \,\epsilon\, I \tag{3}$$

$$\sum_{j}(I_j + EAD_j) \;\; \forall \;\; j \,\epsilon\, J \tag{4}$$

where I and J are respectively the set of dike rings in the Dutch and German area.

The last problem formulation acknowledges yet an additional complexity in decision-making, viz. accounting for the risk transfers among riverine areas. In particular, this formulation accounts for both hydraulic interactions and, in addition to minimizing total costs for the two countries, it minimizes uneven distributions of relative risk reductions (i.e., risk reduction $\Delta R = (EAD_0 - EAD)$ normalized by the initial risk level, $R_0 = EAD_0$). It thus involves quantifying and accounting for risk transfers such that a policy does not benefit some areas much more than others. This is achieved as illustrated in Figure 3.

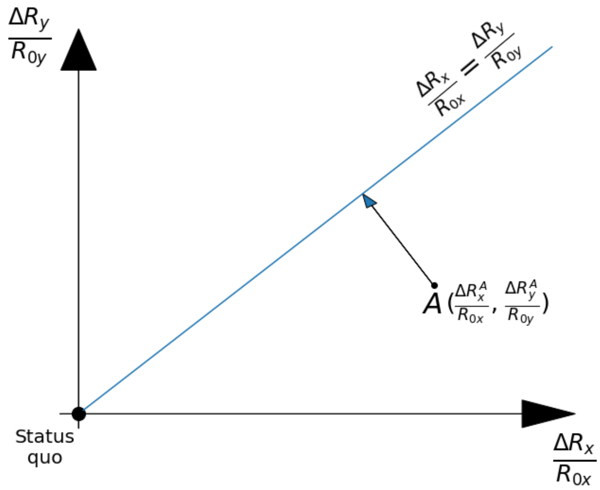

Figure 3. An example visualizing how relative risk reduction of two areas x and y following a policy A can be compared with respect to a situation of perfect equal distribution.

Imagine two areas, x and y, with their relative risk reduction being the axes of the first quadrant of a Cartesian diagram. The status quo (i.e., $\Delta R = 0$) is given by the point of origin. A policy A, would e.g., lead to a situation where $\frac{\Delta R_x^A}{R_{0x}} > \frac{\Delta R_y^A}{R_{0y}}$, in which area x has a greater relative risk reduction than area y, thus x benefits more from policy A than y does. The point of equal benefits is located on the bisector line, with the distance from point A to such line which is given by:

$$d = \frac{\left|\frac{\Delta R_x^A}{R_{0x}} - \frac{\Delta R_y^A}{R_{0y}}\right|}{\sqrt{2}} \tag{5}$$

Thus, minimizing this distance implies increasing equality in relative risk reduction distribution among areas x and y. Minimizing the distance implies, moreover, that if e.g., $R_{0x} > R_{0y}$, namely area x has a higher initial risk than area y, the former gets a higher risk reduction ΔR^A. Therefore, areas with a higher initial risk will benefit from larger risk reductions and, overall, the proposed decision criterion tends to level down differences in final risk levels across areas.

In the third and last problem formulation, the distance d between each pair of dike ring areas is calculated, and the maximum distance (i.e., most unequal comparison) is minimized. Additionally, no risk increase from the initial situation is permitted in any of the dike rings. This formulation thus reads as follows:

$$minimize \quad \sum_i (I_i + EAD_i) \;\; \forall\, i \,\epsilon\, I \tag{6}$$

$$\sum_j (I_j + EAD_j) \;\; \forall\, j \,\epsilon\, J \tag{7}$$

$$\max_{x,y} \frac{\left| \frac{\Delta R_x}{R_{x0}} - \frac{\Delta R_y}{R_{y0}} \right|}{\sqrt{2}} \;\; \forall\, x,\, y \,\epsilon\, I \,U\, J,\; x \neq y \tag{8}$$

$$with \quad EAD_{0,x} \geq EAD_x \;\; \forall \;\; x \,\epsilon\, I \,U\, J \tag{9}$$

where I and J are the set of dike rings in the Dutch and German area respectively.

4.2. Generating Alternatives

Optimal flood risk reduction policies are identified using Many Objective Evolutionary Algorithms (MOEAs) to find a Pareto-approximate set of solutions [14], namely solutions for which it is impossible to improve a single objective without deteriorating the performance of at least one other objective. In this study, the non-dominated sorting genetic algorithm ε-NSGAII search algorithm is used [21]. In a first step, Pareto-approximate solutions are established for a reference scenario defined by fixed values of the uncertain factors, as specified in Table 2.

Table 2. Values of uncertainties for the reference scenario under which many-objective optimization is carried out.

Water Level Triggering Failure	Final Breach Width	Breach Growth Dynamic
Water levels given by the fragility curves at a failure probability of 0.5	The final breach width reaches a maximum width of 150 m	The final breach width is reached in 3 days

The convergence of ε-NSGAII to the approximate Pareto front is measured through two performance metrics known as ε-progress [22] and hypervolume [23]. ε-Progress indicates whether a new solution is added at each iteration of the many-objectives search. The fewer new solutions are added, the closer to convergence. Hypervolume is the volume of objective space dominated by a given set of solutions at a given stage of the many-objective search. The fewer the increases in the hypervolume, the closer to convergence. ε-Progress and hypervolumes of each optimization are provided in the Supplementary Materials to this paper.

When using MOEAs, it is good practice to perform a seed analysis as the generated Pareto set relies on the random generation of an initial population. Thus, each problem formulation is solved five times. For each problem formulation, a final set of Pareto dominant solutions is identified across the five sets of generate Pareto sets. As in each formulation the simulation model is evaluated 100,000 times, generating alternatives for the three formulations required a total of 1.5 million of model evaluations.

4.3. Evaluate Alternatives Under Uncertainty

In a next step, the performance of the previously identified Pareto optimal solutions is stress-tested under uncertainty. The influence of the 210 uncertain input factors introduced in Section 4.2 and summarized in Table 1 is explored by conducting 10,000 simulations using a Latin Hypercube sampling technique. In particular, water levels triggering breaching are sampled based on fragility curves available for the case study area, all three breach growth models are uniformly sampled and, finally, a uniform distribution of the final breach widths is assumed. The convergence plot is shown in the Supplementary Materials.

4.4. Evaluating Robustness Under Different Attitudes Towards Risk

In policy analysis, robustness is defined as the capability of a policy to perform satisfactorily under uncertainty. The literature proposes several metrics to quantify robustness [24–26]. McPhail et al., [26] provides a classification of the existing robustness metrics according to their level of risk aversion. In this classification, the Maximin and Maximax metrics proposed by Wald [27] qualify as relatively pessimistic (highest risk aversion) and relatively optimistic (lowest risk aversion) metrics, respectively. This applies to a decision problem where decision criteria are to be maximized. In our case, however, all decision criteria introduced in Section 4.1. ought to be minimized. Thus, the Maximin and Maximax metrics, while retaining the same meaning in terms of risk aversion levels, become Minimax and Minimin, respectively.

Hurwicz [28] combined these two metrics in what is known as the optimism-pessimism rule, consisting of their weighted average:

$$Hurwicz\ Criterion = (1-\lambda)\min_{p}\max_{s} O_{p,s} + \lambda \min_{p}\min_{s} O_{p,s} \quad (10)$$

where λ is called 'coefficient of optimism' representing increasing levels of risk aversion for decreasing values; $O_{p,s}$ is the value of the decision objectives under policy p and scenario s.

In order to show what the above formula implies, we provide a simple example summarized in Table 3. Three policies are available, and their performance is shown in terms of residual flood damage in three different scenarios. By following a Minimin, optimistic, approach (i.e., *Hurwicz Criterion* with 'coefficient of optimism' λ equal to one), for example, the preferred policy is the one giving the lowest damage of the minimum damages (reported in the Minimin column) of each policy across scenarios. Instead, following the Minimax, pessimistic, approach (i.e., *Hurwicz Criterion* with λ equal to zero) one would select the policy with the lowest damage of the maximum damages of each policy across scenarios. Finally, the *Hurwicz Criterion* selects the policy with the lowest score of the weighted average of the two previous cases, and results for λ equal to 0.2 and 0.8 are provided.

Table 3. An example showing three fictitious risk reduction policies leading to uncertain residual damage (in Millions of euros) according to three different scenarios. The preferred policies according to the Minimax, Minimin, and two Hurwicz Criteria are underlined and highlighted in bold.

	First Scenario	Second Scenario	Third Scenario	Minimin (Hurwicz, λ = 1)	Hurwicz λ = 0.8	Hurwicz λ = 0.2	Minimax (Hurwicz, λ = 0)
Policy 1	3	5	3	3	3.4	**<u>4.6</u>**	**<u>5</u>**
Policy 2	9	2	6	2	3.4	7.6	9
Policy 3	7	1	11	**<u>1</u>**	**<u>3</u>**	9	11

As the level of risk aversion increases (i.e., decreasing λ), a shift in preference occurs between Policy 3 and Policy 1. Moreover, the higher the 'coefficient of optimism' λ, the lower the residual damage thus the better the expected performance from a policy, in a line with a more optimistic view.

5. Results

The analysis was carried out through the Exploratory Modelling and Analysis Workbench (EMA-Workbench) [29], an open source toolkit developed in the Python programming language.

Results are reported with the aim of exploring trade-offs between efficiency in the allocation of total costs (i.e., sum between expected annual damages and investment costs) in Germany and the Netherlands and between efficiency in the allocation of total costs and equity in the distribution of risk for the system as a whole. Related to the latter, equity is measured using the Gini index [30] of expected annual damages of all dike ring areas. The Gini index is used in welfare economics to measure inequality in the distribution of e.g., income or wealth. As such, it is a widely accepted measure of inequality which we here apply to the distribution of residual risks across flood-protected areas. The Gini index scores between 0 and 1, with increasing values for increasing inequality in the distribution. Therefore, in our case, if all dike rings have the same risk levels (i.e., perfectly equal risk distribution), then the Gini index is zero. Instead, if all risk is concentrated in one single flood-protected area, then the Gini index will be close to one.

Pareto optimal policies are first shown based on the reference scenario in Section 5.1 and, next, in terms of their robustness against uncertainties relative to hydraulic interactions under different risk attitudes in Section 5.2.

5.1. Generating Alternatives

Optimal policies for each of the three problem formulations given the reference scenario are shown in Figure 4. The left panel shows trade-offs between Germany and The Netherlands whereas the right panel shows trade-offs between the policies' overall efficiency and equity.

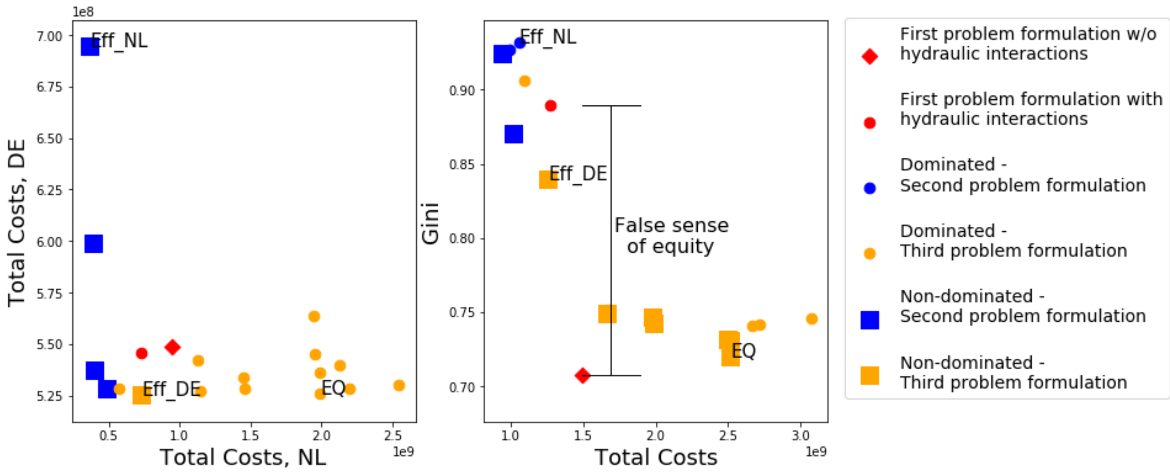

Figure 4. Results from the epsilon-NSGAII search under a reference scenario for the three problem formulations. By showing all policies from the three formulations together, a Pareto front across formulations can be identified (i.e., squares in both panels).

The performance of the policy resulting from the first problem formulation, i.e., neglecting hydraulic interactions, is shown based on its original values as well as by considering hydraulic interactions in order to make it comparable with those of policies identified by the other problem formulations. The original performance, i.e., neglecting hydraulic interactions, is shown red as a diamond, while the re-evaluation considering hydraulic interactions is shown in red as a dot. The performance of policies resulting from the second problem formulation, i.e., based on total costs and considering hydraulic interactions, are shown in blue. Policies from the third problem formulation, i.e., based on total costs and the risk transfer minimization criterion and considering hydraulic interactions, are shown in orange. By comparing policies across formulations, one can identify an overall Pareto front. Policies on this front are depicted as squares.

The comparison between the original (red diamond) and the re-evaluated (red dot) performance of the policy resulting from the first problem formulation reveals two interesting observations. First, in the left panel, we see that neglecting hydraulic interactions leads to an overestimation of total costs, especially in the Netherlands. This is due to an overestimation of the risk in the downstream Dutch dike ring areas when hydraulic interactions are neglected, as the potential flood attenuation effect of upstream breaches is neglected. In Germany, being it the upstream country, this effect is less evident than in the Netherlands, as the two total costs figures (red diamond and red dot) for Germany are very similar. Second, the right panel suggests that neglecting hydraulic interactions yields the lowest Gini index of final risk levels in comparison to all other policies (red diamond), i.e., the most equal distribution of risks. The same policy, however, leads to a much larger Gini index when hydraulic interactions are considered (red dot). This implies that neglecting hydraulic interactions, which is current practice, leads to a false sense of equity in risk distribution. This occurs because, when considering hydraulic interactions, downstream locations are found to be flooded less often than suggested by neglecting interactions, thus leading to a more uneven risk distribution between upstream and downstream locations, with the former experiencing more damages.

Unlike the first problem formulation, where only one optimal policy was identified, the second problem formulation, which considers hydraulic interactions within the optimization process, allowed identifying a set of Pareto optimal policies. This implies that an approach very similar to the current approach (first problem formulations) neglecting hydraulic interactions results in overlooking trade-offs in risk reduction and prevents the identification of alternative policies which better highlight conflicts among flood-protected areas. Furthermore, these policies Pareto dominate the one policy identified by the first problem formulation, which lies far from the Pareto front in both panels of Figure 4.

In terms of total costs in The Netherlands, all these policies do better than the one identified according to the first problem formulation. This results from the fact that lower risks levels are achieved and, yet, less is spent in investments. When hydraulic interactions are considered, indeed, downstream estimated risk is lower, thus less investments are required.

In terms of equity, no major differences in performance are registered as policies from both the first and second formulation are the worst performers. This is due to two issues common to both formulations. First, there is one area, namely the Dutch part (downstream part) of dike ring area 42, which, although it has its risk reduced, always gets a lower relative risk reduction than other dike ring areas, especially 43, 44, and 45. Second, two dike ring areas along the IJssel, namely 52 and 49 in Figure 1, have their risk increased with respect to the initial situation.

The policies identified with the third problem formulation, where risk increases are not allowed and a decision criterion is added to prevent uneven risk distributions, limit these two issues. These policies, thus, provide a significant improvement with respect to the Gini index. Interestingly, one of these policies is also located on the Pareto front in the left panel of Figure 4, namely as the best performing policy in terms of German total costs and the worst in terms of Dutch total costs. This results from two reasons, related to the two equity-related issues previously introduced. First, in order to increase the protection level of the Dutch part of dike ring area 42, a transboundary dike ring area subject to flooding from Germany, better protection is implemented along the German part of the river, which explains the good performance of these policies in Germany. In turn, this means that more water reaches more downstream Dutch dike ring areas, which increases their risk and thus total costs in the Netherlands. Second, for the sake of preventing any dike ring area in the Netherlands to have its risk increased, and as also shown in Figure 5, the leverage of changing the discharge distribution is used less, as this has a significant effect on shifting flood risk across branches. To compensate, flood protection in the Netherlands is achieved more through structural measures (i.e., dike heightening and Room for the River), which increases investment costs and thus total costs in the Netherlands.

From the analysis, four policies are identified as interesting for being explored further in terms of risk management measures. Figure 5 specifies the required dike heightening, water level lowering through making room for the river and changes to the discharge distribution by the four selected policies. These are: The policy resulting from the first problem formulation (red line); the most efficient policy for the Netherlands (*Eff_NL*, blue line) from the second problem formulation; the most efficient policy in Germany (*Eff_DE*, orange continuous line) from the third problem formulation; and the policy leading to the most equal risk distribution (*EQ*, orange dotted line), also from the third problem formulation.

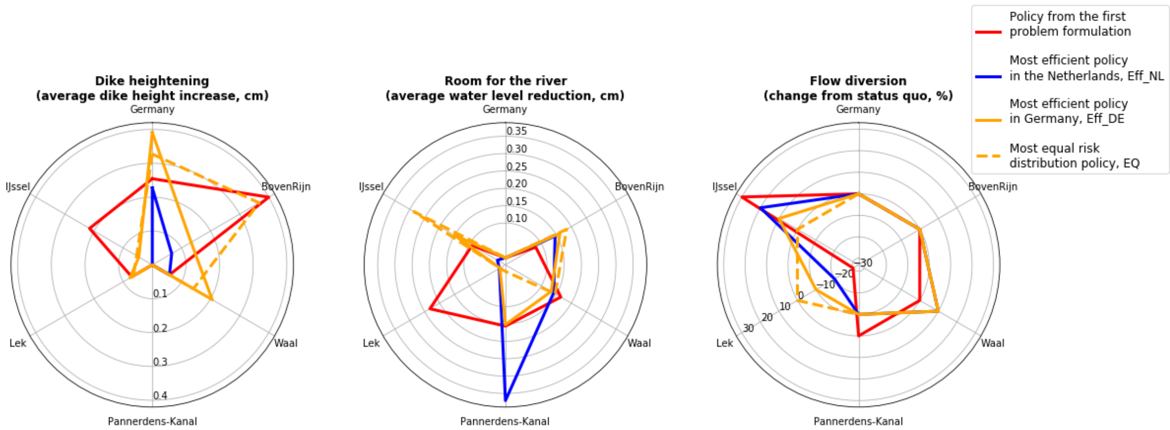

Figure 5. Spider diagram of the risk management measures of the four selected policies. Values refer to six areas: German territory and five major Dutch river branches, the Boven-Rijn, the Waal, the Pannerdensch-Kanaal, the Lek, and the IJssel. For each of these areas, dike heightening is expressed in terms of average increase in dike height, making room for the river as average water level reduction and flow diversion as change with respect to the initial diversion.

The policy resulting from the first problem formulation requires higher dikes than other policies do on the Boven-Rijn area, the most upstream Dutch area, and along the IJssel and the Lek branches, further downstream. In addition, it requires room for the river on all areas, with the Lek having the largest average water level reduction. The extensive structural measures required by this policy are explained by the fact that load reduction on the Boven-Rijn as a result of flooding in Germany is not considered in the design of this policy. Finally, as for the discharge distribution, +30% more water from the Pannerdensch-Kanaal is sent through the IJssel and, consequently, −30% through the Lek. This occurs because this policy was designed to minimize total costs in the Netherlands and Germany and changing the discharge distribution is then the most cost-effective measure (as this measure is assumed to be free of costs). This, as mentioned above, in fact implies increasing risk levels along the IJssel with respect to the initial situation.

A similar reasoning relative to the discharge distribution applies to *Eff_NL*, although here the change relates to both bifurcation points. At the first bifurcation, +10% more water is sent from the Boven-Rijn through the Waal and, consequently, −10% less through the Pannerdensch-Kanaal. At the second bifurcation, +20% is sent to the IJssel and −20% to the Lek. Structural measures, however, are much less adopted, especially in the Netherlands, as dike heightening is significantly less than in the other policies and no measures which make room for the river are applied along the IJssel or the Lek. This happens because hydraulic load reduction is considered, thus requiring less structural measures along downstream river stretches. The only exception is the Pannerdensch-Kanaal, where a larger water level reduction is achieved through making room for the river than in the other policies.

The most efficient policy for Germany, *Eff_DE*, requires the most dike heightening in the German areas from all policies, as dike heightening is the only available measure for the German areas.

The policy resulting in the most equal risk distribution, *EQ*, requires high dikes along all areas, whilst at the same time a large water level reduction is achieved through making room for the river along all river branches but the Lek and the Pannerdensch-Kanaal. This occurs in order to limit uneven risk distributions, as the Lek and Pannerdensch-Kanaal branches may cause flooding of dike ring areas 43, 44, and 45, earlier reported as the ones benefitting the largest risk reduction with respect to the Dutch part of dike ring area 42. Finally, *EQ* requires a slight change to the discharge distribution at the first bifurcation point, with +10% more water sent to the Waal and, consequently, −10% through the Pannerdensch-Kanaal and no change at the second discharge distribution. This latter result shows how much changing the discharge distribution may affect the risk distribution among dike ring areas, as this measure is barely used (i.e., only 10 percent change at one of the two bifurcation points) by the policies with the most equal risk distribution.

5.2. Evaluating Robustness Under Different Attitudes Towards Risk

Figure 6 shows policy robustness in terms of total costs for Germany and the Netherlands (left column) and the policies' total costs and Gini (right column) for different risk attitudes, i.e., different values of the 'coefficient of optimism' as introduced in Section 4.4. From bottom to top rows values of the 'coefficient of optimism' decrease (i.e., levels of risk aversion increase), with the bottom and top rows showing the best policies in the most optimistic (Minimin) and pessimistic (Minimax) cases, respectively. To facilitate comparison across panels, results in each column are shown within the same axes limits, and, in addition, an insert zooming on the policies is provided to better display the Pareto front. By comparing performances for increasing values of the 'coefficient of optimism', policies tend to move towards the bottom-left corner, i.e., towards a better performance, in line with the ever-increasing optimistic view.

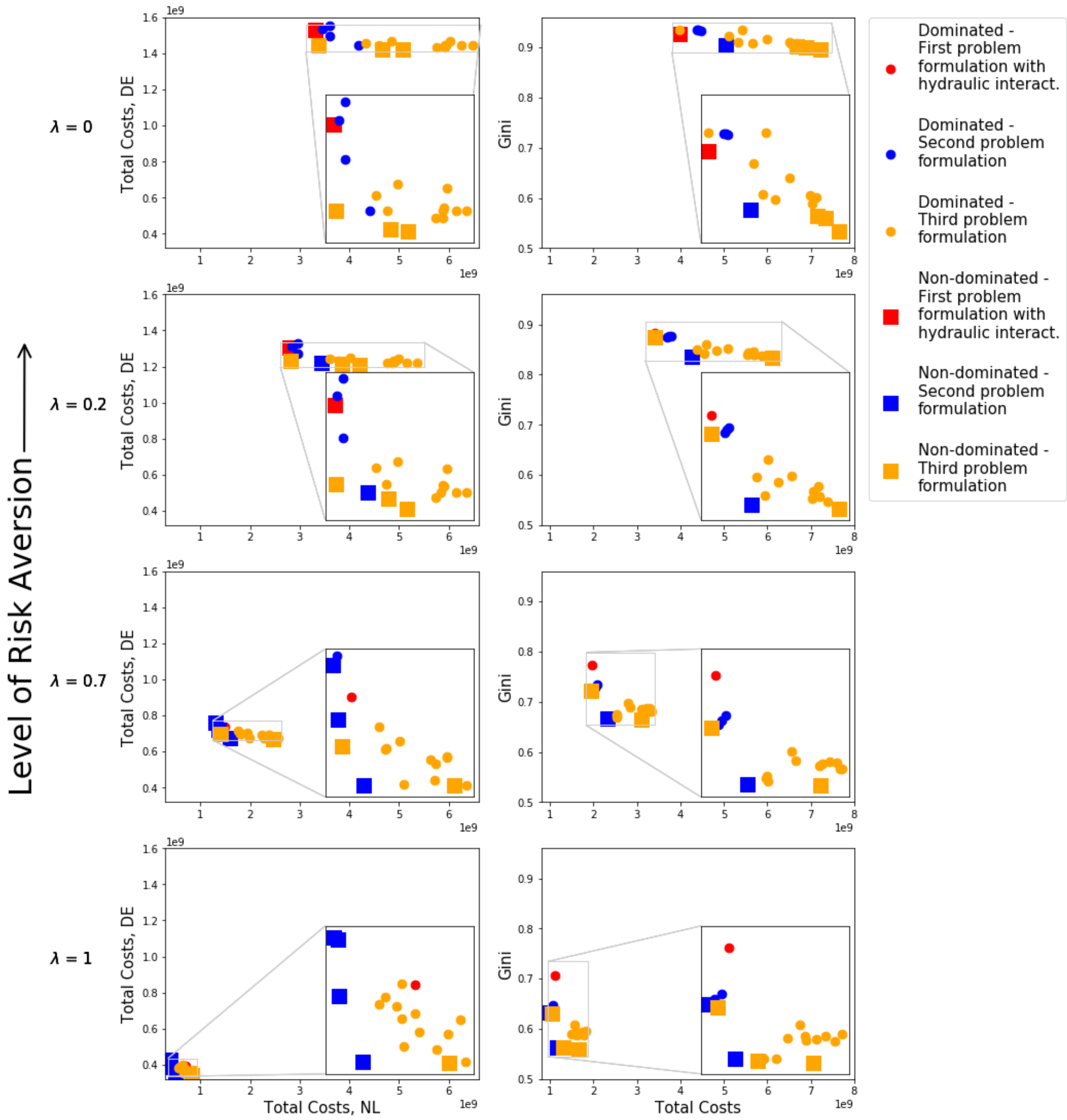

Figure 6. Evolution of the Pareto front across formulations for different risk attitudes (i.e., increasing risk aversion from bottom row to top row). Left: trade-offs between total costs in Germany and the Netherlands. Right: trade-off between efficiency and equity of the system.

The policy found for the first problem formulation lies on the Pareto front when risk aversion is high. It then qualifies as a policy performing, in terms of total costs, best in the Netherlands and worst in Germany. This can be explained from the fact that according to the first problem formulation measures are identified assuming that no breach would ever occur upstream. For the Netherlands, this means that breaches in Germany are not considered and dikes are overdesigned, which leads to policies that perform well when a pessimistic (or conservative) approach to risk management is taken. Moreover, when looking at the overall system performances (right column), this policy, which relies on total cost optimization only, shows the highest efficiency and lowest equity of the Pareto optimal policies.

The policies identified by the second problem formulation more and more locate on the Pareto front of total costs in the two countries as the risk aversion level decreases. These policies, indeed, perform well under uncertainties about hydraulic interactions as these interactions were duly accounted for in the optimization.

Policies identified by the third problem formulation, regardless the level of risk aversion, have a lower Gini index. However, the difference in terms of Gini index of these policies in comparison to some of those identified by the second problem formulation is insignificant. This implies that, unlike the reference scenario (i.e., Section 5.1) where low Gini were provided solely by policies from third problem formulation, under uncertainty policies from the second problem formulation can provide both efficiency and equity.

6. Discussion and Conclusions

In the present paper we compared the performance of an approach which resembles current approach to flood risk management, i.e., where hydraulic interactions are neglected and no quantification of the equality of distribution of risk levels across neighboring flood-protected areas is carried out, with the one of two alternative problem formulations. Of these latter two, one formulation acknowledges only hydraulic interactions (namely the second problem formulation), while the other (namely the third problem formulation) both considers hydraulic interactions and uses an additional decision criterion to account for equity in risk distribution across flood-protected areas. The aim of such a comparison is twofold. First, to understand differences in performances and design choices. Second, to explore the effect of different risk attitudes—or design conservatism—on the desirability of adopting one of the problem formulations. To do this we followed the Many-Objective Robust Decision Making approach [13]: First, a set of optimal policies is identified under a deterministic scenario and, then, the performance of the policies so identified is stress-tested under uncertainty.

We find that the economic optimization approach that neglects hydraulic interaction—i.e., similar to the current approach—neglects trade-offs and possible conflicts among geographical areas, as only one optimal policy is identified for the whole riverine system, which implies that the effects of changes in risk in one area along the river because of risk reduction actions elsewhere are consistently ignored. This, alone, would prevent an appropriate implementation of the EU Flood Directive, where instead conflicts should be made explicit and actions should be taken accordingly. Furthermore, this policy is also suboptimal in comparison to policies identified by alternative problem formulations under the reference scenario, and it is only robust with respect to uncertainties when risk aversion is high, thus qualifying as a 'better safe than sorry' policy. These findings are in line with what was previously found [12] in a smaller-scale case study.

Current approach moreover leads to a false sense of equity as neglecting hydraulic interactions leads to mistakenly equal final risk levels. When interactions are considered, however, the policy resulting from the same policy leads to an unequal distribution of risk across flood-protected areas, as in fact hydraulic interactions are such that flooding of upstream areas is more likely than flooding of those downstream. This indicates that a proper adoption of the solidarity principle, as prescribed by the EU Flood Directive, would be flawed if hydraulic interactions are not properly taken into account.

Overall, under a reference scenario, i.e., a deterministic case, there is a clear trade-off between the performance of the second problem formulation, which is very efficient in terms of costs but leads to an unequal distribution of risk among flood-protected areas, and the performance of the third, which instead enables to reach more equality in risk distribution, but at the cost of less efficiency. Under uncertainty, however, the second problem formulation performs well both in terms of efficiency and equity. Thus, it seems that, when stress-tested under uncertainty, accounting for hydraulic interactions is the most relevant improvement to the current approach in the endeavor to design plans where an equal risk distribution among flood-protected areas is to be achieved. The use of an additional criterion, which explicitly limits uneven risk distributions, is a useful but not essential improvement to the current approach. The above findings require crucial changes to the practice of flood risk management. First, effects of risk management measures which are local by their nature, i.e., dike heightening on a river stretch or making room for the river along a river branch, should not be solely evaluated in terms of benefits to the areas they are expected to protect. Rather, their effects of changing risk elsewhere in the system must also be accounted for. Second, measures which are less often considered and which by their nature change flood risk to several flood protected areas, i.e., regulating flows at bifurcation points as in the proposed case study, should be more often considered as it is shown that their role is indeed crucial in distributing flood risk. Third, adopting such a wider view to the problem of managing flood risk implies moving beyond the common idea of having a unique optimal risk management policy towards one of a Pareto-set of optimal policies which allow acknowledging and quantifying spatial trade-offs among flood-protected areas. In such a context, decisions on what policy to implement need to be based on a participatory approach which upstream and downstream communities take part of. Such a participatory approach needs to quantify (1) risk shifts across communities and (2) robustness of policies against uncertainties of hydraulic interactions. The former requirement would allow adequate compensation schemes to be put in place if required, while the latter would limit the occurrence of undesired surprises in the performance of the implemented policy.

Supplementary Materials: The following are available online at http://www.mdpi.com/2073-4441/11/12/2530/s1, Figure S1: Epsilon-progress and hypervolume of the five optimizations carried out for the first problem formulation, Figure S2: Epsilon-progress and hypervolume of the five optimizations carried out for the second problem formulation, Figure S3: Epsilon-progress and hypervolume of the five optimizations carried out for the third problem formulation, Figure S4: Hypervolume values of the final of Pareto policies (i.e., non-dominated policies across the five set of Pareto policies generated from the seed analysis) for each problem formulation, Figure S5: Convergence of the stress-test analysis of all policies.

Author Contributions: Conceptualization, A.C.; methodology, A.C. and J.H.K.; investigation, A.C.; writing—original draft preparation, A.C.; writing—review and editing, K.M.D.B., J.H.K. and F.K.; supervision, K.M.D.B., J.H.K. and F.K.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 676027.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Di Baldassarre, G.; Castellarin, A.; Brath, A. Analysis of the effects of levee heightening on flood propagation: Example of the River Po, Italy. *Hydrol. Sci. J.* **2009**, *54*, 1007–1017. [CrossRef]
2. Van Mierlo, M.C.L.; Vrouwenvelder, A.; Calle, E.O.F.; Vrijling, J.K.; Jonkman, S.N.; de Bruijn, K.M.; Weerts, A.H. Assessment of flood risk accounting for river system behaviour. *Int. J. River Basin Manag.* **2007**, *5*, 93–104. [CrossRef]
3. De Bruijn, K.M.; Diermanse, F.L.M.; Van Der Doef, M.; Klijn, F. Hydrodynamic system behaviour: Its analysis and implications for flood risk management. *E3S Web Conf.* **2016**, *7*, 11001. [CrossRef]
4. Vorogushyn, S.; Bates, P.D.; de Bruijn, K.; Castellarin, A.; Kreibich, H.; Priest, S.; Schröter, K.; Bagli, S.; Blöschl, G.; Domeneghetti, A. Evolutionary leap in large-scale flood risk assessment needed. *Wiley Interdiscip. Rev. Water* **2017**, *5*, 1–7. [CrossRef]

5. Directive 2007/60/EC of the European Parliament and of the council of October 23, 2007 on the assessment and management of flood risks. *Off. J. Eur. Union* **2007**, *L288*, 27–34.
6. Orlandini, S.; Moretti, G.; Albertson, J.D. Evidence of an emerging levee failure mechanism causing disastrous floods in Italy. *Water Resour. Res.* **2015**, *51*, 7995–8011. [CrossRef]
7. Hansson, S.O. Philosophical problems in cost-benefit analysis. *Econ. Philos.* **2007**, *23*, 163–183. [CrossRef]
8. Kind, J.M. Economically efficient flood protection standards for the Netherlands. *J. Flood Risk Manag.* **2014**, *7*, 103–117. [CrossRef]
9. Eijgenraam, C.; Brekelmans, R.; Hertog, D.D.E.N.; Roos, K. Optimal Strategies for Flood Prevention. *Manag. Sci.* **2017**, *63*, 1644–1656. [CrossRef]
10. Brekelmans, R.; Den Hertog, D. Safe Dike Heights at Minimal Costs: The Nonhomogeneous Case. *Oper. Res.* **2012**, *60*, 1342–1355. [CrossRef]
11. Hayenhjelm, M. What Is a Fair Distribution of Risk. In *Handbook of Risk Theory*; Roeser, S., Hillerbrand, R., Sandin, P., Peterson, M., Eds.; Springer: Berlin, Germany, 2012. [CrossRef]
12. Ciullo, A.; de Bruijn, K.M.; Kwakkel, J.H.; Klijn, F. Accounting for the uncertain effects of hydraulic interactions in optimising embankments heights: Proof of principle for the IJssel River. *J. Flood Risk Manag.* **2019**. [CrossRef]
13. Kasprzyk, J.R.; Nataraj, S.; Reed, P.M.; Lempert, R.J. Many objective robust decision making for complex environmental systems undergoing change. *Environ. Model. Softw.* **2013**, *42*, 55–71. [CrossRef]
14. Coello Coello, C.; Lamont, G.B.; Van Veldhuizen, D.A. *Evolutionary Algorithms for Solving Multiobjective Problems*; Springer: Raleigh, NC, USA, 2007. [CrossRef]
15. Silva, W.; Klijn, F.; Dijkman, J. *Room for the Rhine Branches in the Netherlands. What the Research Has Taught Us*; WL, Delft & RIZA: Arnhem, The Netherlands, 2001.
16. Lammersen, R.; Kroekenstoel, D. Transboundary effects of extreme floods along the Rhine in Northrhine-Westfalia (Germany) and Gelderland (The Netherlands). In *Floods, from Defence to Management*; van Alphen, J., van Beek, E., Taal, M., Eds.; Taylor & Francis Group: London, UK, 2005; pp. 531–536.
17. Lempert, R.J.; Popper, S.W.; Bankes, S.C. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*; MR-1626, RAND: Santa Monica, CA, USA, 2003.
18. FLOODsite. Flood Risk Assessment and Flood Risk Management. An Introduction and Guidance Based on Experiences and Findings of FLOODsite (an EU-funded Integrated Project). Deltares Delft Hydraul. Available online: floodsite.net/html/partner_area/project_docs/T29_09_01_Guidance_Screen_Version_D29_1_v2_0_P02.pdf140 (accessed on 29 November 2019).
19. Van Schijndel, S.A.H. The planning kit, a decision making tool for the Rhine branches. In Proceedings of the 3rd International Symposium Flood Defence, Nijmegen, The Netherlands, 25–27 May 2005.
20. De Grave, P.; Baarse, G. Kosten van Maatregelen: Informatie Ten Behoeve van Het Project Waterveiligheid 21e Eeuw (Deltares rep. 1204144-003). Available online: http://edepot.wur.nl/346748 (accessed on 29 November 2019).
21. Kollat, J.B.; Reed, P.M. The value of online adaptive search: A performance comparison of NSGA-II, -NSGAII, and MOEA. In *International Conference on Evolutionary Multi-Criterion Optimization (EMO 2005). Lecture Notes in Computer Science*; Coello Coello, C., Aguirre, A., Zitzler, E., Eds.; Springer: Berlin, Germany, 2005; pp. 389–398.
22. Hadka, D.; Reed, P. Borg: An Auto-Adaptive Many-Objective Evolutionary Computing Framework. *Evol. Comput.* **2013**, *21*, 231–259. [CrossRef] [PubMed]
23. Zitzler, E.; Thiele, L.; Laumanns, M.; Fonseca, C.M.; da Fonseca, V.G. Performance assessment of multiobjective optimizers: An analysis and review. *IEEE Trans. Evol. Comput.* **2003**, *7*, 117–132. [CrossRef]
24. Giuliani, M.; Castelletti, A. Is robustness really robust? How different definitions of robustness impact decision-making under climate change. *Clim. Chang.* **2016**, *135*, 409–424. [CrossRef]
25. Kwakkel, J.H.; Eker, S.; Pruyt, E. How Robust is a Robust Policy? Comparing Alternative Robustness Metrics for Robust Decision-Making. In *Robustness Analysis in Decision Aiding, Optimization, and Analytics*; Springer: Singapore, 2016; pp. 221–237.
26. McPhail, C.; Maier, H.R.; Kwakkel, J.H.; Giuliani, M.; Castelletti, A.; Westra, S. Robustness Metrics: How Are They Calculated, When Should They Be Used and Why Do They Give Different Results? *Earth's Futur.* **2018**, *6*, 169–191. [CrossRef]
27. Wald, A. *Statistical Decision Functions*; Chapman & Hall: London, UK; New York, NY, USA, 1950.

28. Hurwicz, L. An Optimality Criterion for Decisionmaking under Ignorance. In *Uncertain. Expect. Econ. Essays Honour GLS Shackle*; Augustus M. Kelley: New York, NY, USA, 1953.
29. Kwakkel, J.H. The Exploratory Modeling Workbench: An open source toolkit for exploratory modeling, scenario discovery, and (multi-objective) robust decision making. *Environ. Model. Softw.* **2017**, *96*, 239–250. [CrossRef]
30. Gini, C. Measurement of Inequality nd Incomes. *Econ. J.* **1921**, *31*, 124–126. [CrossRef]