Systemic Flood Risk Management Planning

A decision-support framework for large-scale flood risk management accounting for risk-distribution across flood-protected areas and deeply uncertain hydraulic interactions

Ciullo, Alessio

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by

Alessio CIULLO

Master of Science in Environmental Engineering,
University of Bologna, Italy
born in Tricase, Italy

This dissertation has been approved by the promotors.

Composition of the doctoral committee:

Rector Magnificus	Chairperson
Prof. dr. F. Klijn	Delft University of Technology, promotor
Dr. ir. J.H. Kwakkel	Delft University of Technology, promotor
Dr. K.M. de Bruijn	Deltares, copromotor

Independent members:

Prof. dr. B. Merz	GFZ German Research Centre for Geosciences
Prof. dr. ir. M. Kok	Delft University of Technology
Prof. dr. J.C.J. Kwadijk	Twente University
Prof. dr. ir. I.R. van de Poel	Delft University of Technology

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Preface and acknowledgements

This dissertation is the result of three years of research conducted as part of the Marie Skłodowska-Curie European Training Network SYSTEM-RISK. The work presented in this thesis aims at providing a decision-support framework for large-scale flood risk management. The research was conducted in the department of Flood Risk Management at Deltares and in the Policy Analysis section of the faculty of Technology, Policy and Management at TU Delft.

When I started this project, back in September 2016, I was full of enthusiasm, but did not quite know what to expect. What came after was three years of hard work, with alternate feelings of frustration and confidence. Luckily, the latter prevailed, certainly thanks to many people who supported me along the way and whom I would like to thank.

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My parents, my brother Gabriele and Moira, without whom I would certainly be a different person in a different place, and to whom a dedicate this thesis.

Alessio Ciullo
Bern, May 2020

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Summary

Problem statement

Floods are natural phenomena which have potentially catastrophic effects on societies and their economies. Flood losses have been increasing in the last years and they are expected to increase further in the future due to climatic and socio-economic changes. It is therefore paramount to design measures and plan strategies (i.e. combination of measures) to limit flood losses.

The current practice of designing flood risk management strategies adopts a risk-based approach, which recognizes that losses from floods cannot be reduced to zero but, at best, to a tolerable level against acceptable costs. Typically, a risk-based approach to flood risk management allows choosing measures by comparing them based on investment costs and effectiveness in reducing flood risk. A measure can e.g. be evaluated based on total societal costs, i.e. the sum of investment costs and the residual flood risk, with the most desirable measure being the one which minimizes total costs. In addition to minimizing total costs, objectives related to reducing individual risk or societal risk might also be applied.

Although the risk-based approach aims at wisely allocating economic resources while, at times, also guaranteeing basic individual safety as well as avoiding large societal flood losses, it often neglects that measures implemented at one location may affect flood risk elsewhere. Acknowledging this was a reason for scientists and policy makers to advocate a move towards a comprehensive system approach. Such approach supports system-wide flood risk management planning and fully accounts for *hydraulic interactions*, i.e. the effects on hydraulic loading at one area due to events, e.g. response of the embankment to hydraulic loading or implementation of measures, occurring elsewhere. Two challenges are identified as crucial in adopting such a comprehensive system approach while accounting for hydraulic interactions.

The first challenge is that designing flood risk management measures following a comprehensive system approach requires considering the interests of both on-site communities and those located elsewhere. This is seldomly done. It was, however, already stated in the EU Flood Directive in 2007: "*in the interests of solidarity, flood risk management plans established in one Member State shall not include measures which, by their extent and impact, significantly increase flood risks upstream or downstream of other countries in the same river basin or sub-basin*". A thorough implementation of the EU Flood Directive requires evaluating measures not solely based on their capability of providing risk-reduction, but also to consider equity in the distribution of flood risk across the entire flood risk system.

The second challenge is that quantifying hydraulic interactions requires dealing with several uncertainties, like the response of the embankment system (e.g. failure or not failure) to hydraulic loading. Typically, uncertainty in the response of embankment systems to hydraulic loading is assumed to be well-characterized. It is estimated based on so-called fragility curves which establish a relationship between the probability of failure of the embankment and hydraulic loads (e.g. water level, flow velocity, flood duration, etc.). The generation of these curves, however, requires extensive knowledge of the geotechnical properties of the embankment which, especially in case of large-scale systems, may not be available or sufficiently accurate for all locations of interest. In these cases, the computed fragility curves might not properly characterize uncertainties in embankment failure. Failing to properly quantify these uncertainties may lead to unexpected failures of the embankments and thus to flooding which take communities and authorities by surprise. In January 2014, an embankment failure occurred during a rather minor flood event along the Secchia River, Italy, due to animal burrows, the possibility of which had not been foreseen. In order to limit losses from such unexpected events, uncertainties in embankment stability could better be treated as *deep uncertainties*, i.e. uncertainties for which experts do not know or cannot agree on the probability distribution. Doing so requires to first select strategies based on their robustness, i.e. their capability to increase the possibility that the system remains functioning (in this context, that flood losses are limited) under all plausible scenarios (in this case, all plausible responses of the embankment to high water levels) and, after that, to explore how the performance of strategies changes under alternative beliefs or assumptions about the likelihood of scenarios (in this case, e.g. assumptions of how likely it is for the embankment to fail at a given value of high water level).

This thesis is dedicated to the development of a decision support framework which addresses the two challenges presented above and therefore enables a comprehensive system approach to flood risk management planning to be adopted.

A decision support framework for systemic flood risk management planning

This thesis aims at answering the following research question:

How to improve flood risk management planning in order to account for risk-distribution across flood-protected areas and deeply uncertain hydraulic interactions?

This question is addressed by proposing a decision support framework which comprises four steps: generate strategies, perform an uncertainty analysis, assess performance metrics and, finally, rank strategies. Each step is illustrated below where a comparison is drawn with the current approach, i.e. an approach where flood risk management strategies neglect interests of off-site communities and assume that uncertainties in hydraulic interactions are well-characterized.

Generate strategies

Traditionally, flood risk management strategies are developed with the aim of reducing risk locally. This is achieved by identifying strategies through an optimization procedure based on local risk-reduction objectives or based on expert elicitation. In this latter case, the analysis is usually followed by a cost-benefit analysis, cost-effectiveness analysis, loss-of-life risk analysis, or multi-criteria decision analysis.

In the proposed framework, the aim is to assess strategies for the system as a whole. Strategies are selected through either an iterative stress-testing and refining procedure, or from a system-wide optimization in order to account for the off-site effects of flood risk management strategies. Strategies are evaluated based on criteria that assess both efficiency in risk-reduction and equity in risk-distribution.

Perform an uncertainty analysis

Typically, uncertainty analysis in flood risk management is carried out through a Monte Carlo analysis assuming well-characterized probability distributions of the uncertain factors. This assumption, however, does not hold when hydraulic interactions are deeply uncertain.

The proposed framework makes use of space-filling experimental design approaches (like Latin Hypercube or quasi-Monte Carlo) in order to evenly explore the space of uncertain factors and test each combination of these factors regardless its probability of occurrence.

Assess performance metrics

Usually, the performance of flood risk management strategies is assessed through an expected value metric. This leads to selecting the flood risk management strategy that, on average, performs best. Expected values are, however, not meaningful under conditions of deep uncertainty, when experts do not know or cannot agree on how likely various possible states of the system are.

In the proposed framework, flood risk management strategies are assessed based on robustness metrics, which allow quantifying the capability of strategies to attain acceptable performance across all possible uncertain scenarios, regardless any specification on how likely these scenarios are.

Rank strategies

As typically the expected performance of flood risk management strategies is assessed focusing on local objectives under well-characterized uncertainty, an unambiguous preference ranking of alternative strategies is possible.

In the proposed framework, instead, not a single ranking of strategies is provided. Multiple rankings are explored each related to different preference orderings of the decision objectives and assumptions about the likelihood of deeply uncertain scenarios of hydraulic interactions.

Overall, the proposed approach aims at providing decision support to flood risk management planning by accounting for:

- *Diverging preferences across stakeholders*
- *Diverse objectives in the realm of risk management*
- *Uncertainty about the likelihood of scenarios of hydraulic interactions*

This allows policy making to shift from an approach where experts and analysts provide single-best solutions to a flood risk management problem, to one where many solutions are on the table. Defining the most preferable one is ultimately a policy decision, depending on which stakeholders are given more weight (e.g. whether upstream or downstream communities), which objectives are deemed more important (e.g. efficiency in risk reduction versus equity in risk distribution) and on whether strategies are deemed to perform satisfactorily under uncertain hydraulic interactions.

The benefits of adopting a system approach

Based on the analysis of three case studies, i.e. the IJssel River (the Netherlands), the Lower Rhine River (including Germany and the Netherlands) and the Po River (Italy), three major benefits of adopting a system-wide approach to flood risk management planning are identified. First, it increases efficiency by cost reduction; second, it more reliably quantifies equity in risk-distribution across flood-protected areas and, third, it widens the range of viable flood risk management measures.

When a comprehensive system approach is adopted, efficiency increases as downstream overspending in risk-reduction is avoided. Along the IJssel River, for example, the analysis revealed that lower embankments could be built downstream than when costs are optimized locally without taking into account hydraulic interactions, and yet the same risk-reduction is achieved.

Adopting a system approach also provides more reliable estimations of equity in the distribution of risk across flood-protected areas as found along the Lower Rhine. When identifying flood risk management strategies based on local objectives and thus neglecting hydraulic interactions, such strategies appear to equally distribute risk, while, in fact, they lead to some of the most unequal distributions when hydraulic interactions are taken into account. This occurs because, when adopting a site-specific approach while neglecting hydraulic interactions, downstream areas seem to be equally flood-prone as upstream ones. In fact, when a system approach is adopted and hydraulic interactions are taken into account, downstream areas prove to be flooded more rarely. This leads to an uneven risk distribution between upstream and downstream areas, with the upstream experiencing more frequent damages.

Adopting a system perspective also widens the range of flood risk management measures available, particularly regarding the adoption of measures like changing the discharge distribution at bifurcation points in the Rhine River and embankment strengthening, both of which are seldomly applied. For the Lower Rhine it is found that changing the discharge distribution at the point where the Lower Rhine bifurcates into the Nederrijn and the IJssel is paramount in balancing risk levels across the system. For the Po River it is found that embankment strengthening, typically regarded as a too expensive measure to consider for wide implementation, may be a lower regret measure than embankment heightening when either uncertainty about hydraulic interactions is large or expected investment costs of embankment strengthening are low.

Overall, it is found that taking a local approach to flood risk management planning and thus neglecting hydraulic interactions leads to “better safe than sorry” strategies, which i.e. provide risk reduction at the expense of high investment costs. It is shown, however, that such an approach is defendable only from an efficiency point of view and only under a very pessimistic assumption about how hydraulic interactions take place. Under all other conditions, a systemic approach to flood risk management planning which accounts for hydraulic interactions is preferable. Therefore, if flood risk analysts do not account for hydraulic interactions, they are inevitably constraining the analysis to a worst-case scenario with the identified flood risk management strategies only working well in terms of overall risk reduction. This is problematic as policy makers then take decisions based on assumptions by the analysts of which they are potentially unaware. Instead, for policy makers to properly make flood risk management decisions, it is crucial that hydraulic interactions are taken into account, trade-offs between the equity of the risk distribution across flood-protected areas and the overall risk reduction are quantified, and different attitudes (e.g. optimism or pessimism) towards uncertain outcomes are explored.

The research conducted in this thesis is a first step towards fully understanding the implications of adopting a comprehensive system approach to support flood risk management planning. It is established that a system approach results in fundamentally different choices about what flood risk management measures to implement, where to implement them and how much to invest in these measures. Thus, more research and attention from the scientific community should be devoted to this topic as this is expected to bring major benefits to communities living in large flood-prone areas.

Samenvatting

Probleemschets

Overstromingen zijn een natuurverschijnsel met potentieel catastrofale gevolgen voor samenlevingen en hun economie. De gevolgen van overstromingen nemen toe en zullen naar verwachting in de toekomst verder toenemen als gevolg van klimaatverandering en sociaaleconomische ontwikkelingen. Het is daarom van het grootste belang om maatregelen te bedenken en strategieën (combinaties van maatregelen) te ontwerpen om overstromingsrisico's te beheersen.

De huidige praktijk om strategieën te ontwerpen voor overstromingsrisicobeheersing is gebaseerd op een risicobenadering, waarbij wordt erkend dat overstromingsrisico's niet volledig kunnen worden weggenomen maar, op z'n best, kunnen worden gereduceerd tot een aanvaardbaar niveau tegen aanvaardbare kosten. Zo'n risicobenadering berust typisch op het selecteren en dimensioneren van maatregelen op basis van de investeringskosten en de bereikte risicoreductie. Zo kan een maatregel worden beoordeeld op bijv. de totale maatschappelijke kosten, d.w.z. de som van investeringskosten en het risico na implementatie van de maatregel, waarbij degene met de laagste totaalkosten het meest gewenst is. In aanvulling op zo'n economische optimalisatie kunnen nog doelstellingen betreffende individueel verdrinkingsrisico of groepsrisico van toepassing worden verklaard.

Alhoewel de risicobenadering beoogt financiële middelen doelmatig in te zetten en ervoor te zorgen dat de bereikte risicoreductie in termen van minder schade en slachtoffers opweegt tegen de kosten van het implementeren van een strategie, wordt in de praktijk zelden rekening gehouden met het feit dat maatregelen op één locatie de risico's elders kunnen vergroten; ten koste van doelmatigheid of efficiëntie. Deze vaststelling was reden voor wetenschappers en beleidmakers om te pleiten voor een alomvattende systeembenadering. Zo'n benadering ondersteunt besluitvorming over overstromingsrisicobeheersing op het niveau van gehele systemen, en houdt rekening met hydraulische interacties, d.w.z. hoe de hydraulische belasting op de ene plaats wordt beïnvloed door gebeurtenissen – zoals een dijkbreuk – of ingrepen – zoals een dijkversterking – elders. Een systeembenadering waarbij hydraulische systeemwerking volwaardig wordt meegenomen, kent twee grote uitdagingen.

De eerste uitdaging in een volledige systeembenadering is dat het ontwerpen van maatregelen die het risico verkleinen niet alleen lokale belangen dient te beschouwen, maar ook belangen van gemeenschappen elders. Dit gebeurt maar zelden. Terwijl de Europese Richtlijn Overstromingsrisico's (RoR) al stelt: "In het belang van de solidariteit mogen overstromingsrisicobeheerplannen die in een lidstaat worden opgesteld geen maatregelen omvatten die door hun omvang en gevolgen leiden tot een aanzienlijke toename van het overstromingsrisico in stroomopwaarts of stroomafwaarts gelegen andere landen in hetzelfde stroomgebied of deelstroomgebied". Een gedegen implementatie van de RoR vraagt dus om een beoordeling van maatregelen niet slechts naar hun effectiviteit in het verkleinen van de risico's in het algemeen, maar ook van de verdeling van de risico's over het gehele overstromingsrisicosysteem.

De tweede uitdaging is dat het kwantificeren van hydraulische interacties vereist dat met veel onzekerheden rekening wordt gehouden, zoals bijv. over het onzekere gedrag van het waterkeringssysteem (falen of niet falen) onder invloed van een onzekere hydraulische belasting. Meestal wordt aangenomen dat de onzekerheid van de faalkans van een dijk goed kan worden gekarakteriseerd. Dan wordt deze in zogeheten fragiliteitscurves (of breekbaarheidscurves) weergegeven, die de conditionele faalkans van een waterkering gegeven een bepaalde hydraulische belasting (meestal waterstand) weergegeven. Het maken van deze curves vraagt echter zeer veel kennis van de geotechnische eigenschappen van de dijk die, vooral in zeer uitgestrekte gebieden, niet altijd voorhanden is of onvoldoende goed bekend is voor alle relevante locaties. Dit kan betekenen dat de fragiliteitscurves een onvoldoende volledig beeld geven van de onzekerheid betreffende de faalkans. Als dat het geval is, kan onverwacht falen van dijken optreden en kunnen overstromingen de bewoners en de verantwoordelijke instanties verrassen. Zo brak in januari 2014, tijdens een niet zo erg hoog water in de rivier de Secchia in Italië, een dijk door waarin dieren holen hadden gegraven; een toen niet voorzien faalmechanisme. Om op dergelijke onvoorziene gebeurtenissen voorbereid te zijn lijkt het beter onzekerheden over de faalkans van waterkeringen als diepe, fundamentele onzekerheid (*deep uncertainty*) te beschouwen; diepe onzekerheden zijn onzekerheden waarvan de kansverdeling niet bekend is of waarover deskundigen van mening verschillen. Het omgaan met diepe onzekerheden vraagt om het selecteren van strategieën op basis van hun robuustheid, d.w.z. in hoeverre het systeem duurzaam kan blijven functioneren (in dit geval de gevolgen van overstroming beperkt en beheersbaar blijven) onder allerlei plausibele scenario's (in dit geval van hoe de dijken reageren op hoogwater); en daarna te verkennen hoe goed de strategieën het doen als de aannames over de waarschijnlijkheid van optreden van scenario's worden veranderd (in dit geval bijv. aannames over de faalkans van de waterkering in relatie tot hoogwaterstanden).

Dit proefschrift gaat over de ontwikkeling van een raamwerk ter ondersteuning van besluitvorming over overstromingsrisicobeheersing vanuit een alomvattende systeembenadering, die de twee bovengenoemde uitdagingen adresseert.

Een beslissingsondersteunend raamwerk voor planvorming van systemische overstromingsrisicobeheersing

Dit proefschrift beoogt het beantwoorden van de volgende onderzoeksvraag:

Hoe de planvorming inzake overstromingsrisicobeheersing te verbeteren waarbij rekening wordt gehouden met de diepe onzekerheden rond hydraulische systeemwerking en met het oog op de ruimtelijke verdeling van risico's over onderscheiden beschermde gebieden?

Deze vraag wordt in vier stappen geadresseerd en mondt uit in een voorstel voor een raamwerk voor ondersteuning van besluitvorming: 1) het genereren van strategieën, 2) het doen van een onzekerheidsanalyse, 3) het vaststellen hoe goed de strategieën het doen, en tenslotte 4) het bepalen van hun rangorde. Iedere stap wordt hieronder kort toegelicht in vergelijking met de huidige praktijk, d.w.z. een praktijk waarbij strategieën voor overstromingsrisicobeheersing de belangen van gemeenschappen elders langs de rivier meestal niet expliciet beschouwen en waarbij wordt verondersteld dat onzekerheden inzake hydraulische interacties goed kunnen worden gekarakteriseerd.

Genereren van strategieën

Vanouds worden strategieën voor overstromingsrisicobeheersing ontwikkeld met als doel het risico ter plaatse te reduceren. Dit wordt bereikt door strategieën te identificeren hetzij met behulp van optimalisatietechnieken die beogen lokaal de grootste risicoreductie te bereiken tegen de laagste kosten hetzij gebaseerd op het oordeel van meerdere deskundigen. In het laatste geval worden dan gewoonlijk ook nog een kosten-batenanalyse, een kosten-effectiviteitsanalyse, een aanvullende slachtofferrisicoanalyse of een multi-criteria-analyse uitgevoerd.

In het voorgestelde raamwerk is het doel echter de strategieën voor het gehele systeem te beoordelen. Daartoe worden de strategieën onderworpen aan een selectieproces met hetzij achtereenvolgens een iteratie van stresstests en aanpassingen, hetzij systeem-breed geoptimaliseerd om aldus de gevolgen van een strategie voor gebieden elders (overzijde van de rivier of stroomafwaarts) volwaardig mee te nemen.

Onzekerheidsanalyse

Meestal wordt voor onzekerheidsanalyses gebruik gemaakt van een soort Monte-Carloanalyse, waarbij kansverdelingen worden verondersteld betreffende de onzekere factoren. Die veronderstellingen houden echter geen stand als er sprake is van diepe, fundamentele onzekerheden over hydraulische interacties.

Het voorgestelde raamwerk gebruikt een experimentele ontwerpbenadering (met behulp van *Latin Hypercube sampling* of quasi-Monte Carlo) om een afgewogen en onbevooroordeelde verkenning van de invloed van verschillende onzekere factoren te kunnen maken, en om de uitwerking van mogelijke combinaties van deze factoren te toetsen onafhankelijk van hun kans van optreden.

Beoordeling

Gewoonlijk worden strategieën voor overstromingsrisicobeheersing beoordeeld aan de hand van verwachtingswaarden. Dat leidt tot een keuze voor die strategie die, gemiddeld genomen, het best uitpakt. Verwachtingswaarden zijn echter niet van de allergrootste betekenis als er sprake is van diepe, fundamentele onzekerheden, zoals wanneer deskundigen het systeem niet volledig goed kennen of van mening verschillen over de kans op falen van dijken bij verschillende omstandigheden.

In het voorgestelde raamwerk worden strategieën beoordeeld op robuustheid. Dat maakt het mogelijk te kwantificeren in hoeverre het systeem op aanvaardbare wijze blijft functioneren in alle plausibele scenario's, dus ongeacht welk scenario zich voordoet en ongeacht de kans van optreden van die scenario's.

Vaststellen van rangordes

Aangezien gewoonlijk verwachtingswaardes ten aanzien van het functioneren van strategieën van overstromingsrisicobeheersing worden gebruikt voor alleen het realiseren van lokale doelstellingen en onder de aanname dat onzekerheden goed gekwantificeerd kunnen worden, leidt de gebruikelijke benadering tot een eenduidige rangorde van de onderzochte alternatieve strategieën.

In het voorgestelde raamwerk wordt zo'n eenduidige rangorde echter niet vanzelf gegenereerd, maar kunnen daarentegen verschillende rangordes worden verkend in relatie tot verschillende voorkeuren betreffende beoordelingscriteria (weging) en onder verschillende aannames over de waarschijnlijkheid van optreden van verschillende scenario's van hydraulische wisselwerkingen.

Over het geheel genomen beoogt de voorgestelde aanpak ondersteuning te bieden aan planvorming voor overstromingsrisicobeheersing door rekening te houden met:

- Uiteenlopende voorkeuren tussen belanghebbenden
- Verschillende doelstellingen op het gebied van risicobeheersing
- Onzekerheid over de waarschijnlijkheid van verschillende scenario's betreffende hydraulische systeemwerking

Op deze wijze kan beleid een overstap maken van een benadering waarbij deskundigen en analisten één beste oplossing van een overstromingsrisicobeheersingsprobleem leveren, naar een benadering waarbij meerdere goede oplossingen ter tafel komen en waarin de keuze van wat dan de meest gewenste is uiteindelijk aan het beleid is; afhankelijk van aan welke belangen het grootste gewicht wordt toegekend (bijv. de bovenliggers (bovenstrooms) die het eerst/vaakst getroffen worden of juist de onderliggers (stroomafwaarts), afhankelijk van welke doelstellingen het belangrijkst worden gevonden (bijv. economische efficiëntie versus gelijkheid), en afhankelijk van de vraag of men streeft naar overwegend bevredigend functioneren gegeven de nu eenmaal onzekere hydraulische wisselwerking of liever het zekere voor het onzekere wil nemen tegen hogere kosten.

De voordelen van een dergelijke systeembenadering

Op basis van een analyse van drie gevalstudies, namelijk van de IJssel (Nederland), van de Duitse Niederrhein en het Nederlandse Rijntakkengebied, en van de Po (Italië), kunnen drie belangrijke voordelen worden genoemd van een systeembrede benadering van het planvormingsvraagstuk inzake overstromingsrisicobeheersing.

Met een alomvattende systeembenadering kan een efficiënter alternatief worden gevonden, waarbij overinvestering stroomafwaarts kan worden voorkomen. Zo is uit de analyse gebleken dat bijvoorbeeld langs de IJssel de meest stroomafwaarts gelegen dijken lager zouden kunnen dan wanneer slechts lokaal wordt geoptimaliseerd zonder rekening te houden met systeemwerking en dat toch dezelfde mate van risicoreductie wordt bereikt.

Een systeembenadering maakt ook een betrouwbaarder inzicht mogelijk over in hoeverre overstromingsrisico’s gelijk verdeeld zijn over de verschillende beschermde gebieden zoals die voorkomen langs de Niederrhein en in het Rijntakkengebied. Als strategieën voor overstromingsrisicobeheersing worden gebaseerd op locatiespecifieke doelstellingen en zonder rekening te houden met systeemwerking, dan lijken die strategieën de risico’s eerlijk te verdelen, maar blijken ze in werkelijkheid te leiden tot een zeer ongelijke verdeling van de overstromingsrisico’s indien hydraulische wisselwerkingen wel in de analyses worden betrokken. Dit is het gevolg van het feit dat het risico in stroomafwaartse gebieden even groot lijkt als dat in meer stroomopwaarts gelegen gebieden. Maar als wel rekening wordt gehouden met hydraulische wisselwerkingen die leiden tot ontlasting door overstromingen meer stroomopwaarts blijken stroomafwaarts gelegen gebieden veel minder vaak te overstromen. Het gevolg is dat de verdeling van risico's ongelijk is tussen bovenstroomse en benedenstroomse gebieden, waarbij de bovenstroomse gebieden veel frequenter schade ondervinden.

Een alomvattende systeembenadering maakt het ook mogelijk meer verschillende maatregelen ter verkleining van de overstromingsrisico's in beschouwing te nemen in relatie tot elkaar, waaronder wijziging van de afvoerverdeling over de Rijntakken of het uitsluitend versterken van de dijken zonder verhoging; twee maatregelen die zelden worden overwogen. Voor de Rijn blijkt de afvoerverdeling over Nederrijn en IJssel cruciaal voor een uitgebalanceerde verdeling van overstromingsrisico's over het gehele systeem. Voor de Po is gevonden dat versterking van de dijken, iets wat over het algemeen als een te dure maatregel wordt beschouwd voor grootschalige toepassing, minder spijt zou kunnen opleveren dan verhoging van de dijken zolang er hetzij grote onzekerheid is over de hydraulische wisselwerkingen hetzij de kosten van versterking relatief overzienbaar zijn.

Over het geheel genomen is vastgesteld dat een aanpak op basis van een locatie-specifieke risicoanalyse zonder rekening te houden met systeemwerking uitmondt in een strategie die kan worden aangeduid als "*better safe than sorry*", en die robuust is door extra risicoreductie ten koste van een grotere investering. Het blijkt echter dat zo'n benadering alleen verdedigbaar is vanuit een oogpunt van efficiëntie en onder een pessimistische aanname over hoe het systeem hydraulisch werkt (nl. met weinig tot geen ontlasting). Dat leidt tot de conclusie dat planvorming voor overstromingsrisicobeheersing gebaseerd op een alomvattende systeembenadering waarin rekening wordt gehouden met hydraulische interacties in gevallen die lijken op de onderzochte casussen altijd de voorkeur heeft. Ofwel, als in risicoanalyses geen rekening wordt gehouden met hydraulische systeemwerking houdt dat onvermijdelijk een *worst-case*benadering in, hetgeen resulteert in strategieën voor overstromingsrisicobeheersing die alleen goed scoren qua totale risicoreductie. Dat is in zoverre problematisch dat beleidsmakers dan beslissingen nemen die berusten op aannames door de onderzoekers waar die beleidsmakers zich mogelijk niet van bewust zijn. Voor een zuivere besluitvorming over overstromingsrisicobeheersing is het daarentegen cruciaal dat hydraulische interacties worden beschouwd, dat uitruil tussen gelijkheid van verdeling van risico's en totale risicoreductie in beeld wordt gebracht, en dat verschillende grondhoudingen (bijv. optimistisch of pessimistisch) tegenover onzekere resultaten worden verkend.

Het in dit proefschrift beschreven onderzoek is een eerste stap in de richting van een volledig doorgronden van de implicaties van het gebruik van een alomvattende systeembenadering ter ondersteuning van planvorming voor overstromingsrisicobeheersing. Het is vastgesteld dat zo'n systeembenadering resulteert in fundamenteel andere keuzes over welke maatregelen waar te implementeren, en dat doelmatiger kan worden geïnvesteerd. Daarom moet de wetenschappelijke gemeenschap meer aandacht en onderzoek aan dit onderwerp wijden aangezien te verwachten valt dat dit belangrijke voordelen biedt aan gemeenschappen in grote overstroombare gebieden.

1 Introduction

1.1 Background

Floods have catastrophic effects on societies and their economies. Flood consequences have been increasing in the last decades (Neumayer and Barthel, 2011) and are expected to keep increasing in the future. In England and Wales, for example, a 20-fold increase in economic flood risk is expected by 2080, if risk management measures are not implemented (Hall et al., 2005). It is therefore paramount to develop plans and design policies to cope with this threat.

The principles and methodological approaches for planning measures and strategies (i.e. combinations of measures) to manage flood risk have evolved over time in response to the recognition of the multi-disciplinary nature of flood risk management (Sayers et al., 2013). In the last two decades, there has been a shift from a primarily flood control approach, which seeks to reduce flood probability and prevent flood events of a certain magnitude, to a risk-based approach which focuses on the whole risk figure (Samuels et al., 2006) and recognizes that flood risk cannot be reduced to zero but, at best, to a tolerable level against acceptable costs (FLOODsite, 2009).

More recently, a further re-orientation in flood risk management is called for by scientists and practitioners (Klijn et al., 2012; Mens et al., 2015; Olson and Morton, 2012; Vis et al., 2003; Vorogushyn et al., 2017). The risk-based approach, typically applied for reducing flood risk locally, needs to widen its scope and move towards a comprehensive system approach which supports system-wide flood risk management planning. This thesis is dedicated to the development of a decision support framework to enable such a system approach to flood risk management.

1.1.1 The current risk-based approach to flood risk management

In risk-based flood risk management, flood risk is typically modelled as the interplay between three main factors: *hazard*, i.e. the probabilities of floods of different magnitude, *vulnerability*, i.e. the degree to which sensitive objects may be affected by flooding, and *exposure*, i.e. the sensitive objects exposed to flooding. Following Merz et al. (2010), flood risk R can be calculated as follows:

$$R(t) = \int_{h_{D(t)}}^{\infty} f_h\,(h,t) D(h,t) dh \qquad (1)$$

where $h_{D(t)}$ is the water level above which flood damage occurs; $f_h\,(h,t)$ is the probability density function of flood water levels h (i.e. *hazard*); and D is the estimated damage for the given h (i.e. consequence as function of *exposure* and *vulnerability*).

Flood risk can be limited by e.g. reducing flood probabilities, influencing flood patterns, or reducing flood impacts by structural or non-structural measures (Klijn et al., 2015). Structural measures are e.g. building dams, levees, and making room for the river; while non-structural measures refer to e.g. flood-proofing buildings, implementing early warning systems, and raising people's awareness to risk. Typically, in order to choose from the various risk management measures, these are compared based on their performance in terms of effectiveness to reduce risk and investment costs.

For example, a measure can be evaluated based on total societal costs, i.e. the sum of investment costs and the residual flood risk after implementing the measure, and the most desirable measures can be identified as those minimizing total costs (Brekelmans and Den Hertog, 2012; Eijgenraam et al., 2017; Kind 2014). In so doing, investment costs are outweighed by the risk reduction achieved, with the clear advantage of not solely aiming at protecting against one design flood but considering the full risk figure as defined by all possible floods. In addition to economic optimization, objectives related to reducing individual risk or societal risk might also be applied (Jonkman et al., 2011).

On the one hand, this approach guarantees that no investments are made unwisely and that acceptable levels of individual and societal risk are not exceeded. On the other hand, this approach has often been applied considering flood-protected areas along one and the same river as being independent from one another. Flood protection measures upstream are thus often designed based on the risk-reduction achieved locally, on-site, without considering possible risk-changes in other areas.

In a stylized flood risk system such as the one illustrated in Figure 1.1, the risk-based approach would typically support the identification of the height of the right embankment solely based on hydraulic loads at area B without accounting for what may happen at area A. However, hydraulic loads at area B may depend on the way the left embankment responds to hydraulic loads which, in turn, may change based on what measures are implemented at area A. Therefore, flood risk of the entire system (i.e. including both areas A and B) may differ from the mere sum of flood risk at area A and area B when these are assessed independently. Consequently, the best strategy for the system may hence also differ from the simple combination of the best strategy for area A and the best strategy for area B: while for A raising the embankment may be cost-effective, this may not be the case for the system as a whole. In other words, there are *hydraulic interactions* within the flood risk system which may be fundamental for determining flood risk of the entire system and for flood risk management planning. These hydraulic interactions are typically neglected in current risk-based flood risk management (De Bruijn et al., 2016).

As previous flood risk analyses have shown, neglecting hydraulic interactions may lead to inaccurate risk estimates as these interactions affect estimations of the flood frequency curve (Apel et al., 2009), the number of expected embankment failures (De Bruijn et al., 2016) and the estimated economic damage and casualties (De Bruijn et al., 2014; Courage et al., 2013). Therefore, a due consideration of hydraulic interactions in flood risk management planning is needed to assess whether and to what extent this in fact matters and, if it does, what changes to the current approach would be required.

When dealing with embanked flood risk systems, the way hydraulic interactions take place ultimately depends on the response of the embankment to hydraulic loading. The same flood wave may lead to significantly different risk patterns depending on if, where, and how embankments fail. Assessing this, however, is not a trivial task as embankment failure is a highly uncertain phenomenon. Planning flood risk management strategies accounting for hydraulic interaction should therefore take such uncertainty into full account, and the implemented strategies should then be able to minimize the impact of rare, unexpected, failures of embankments.

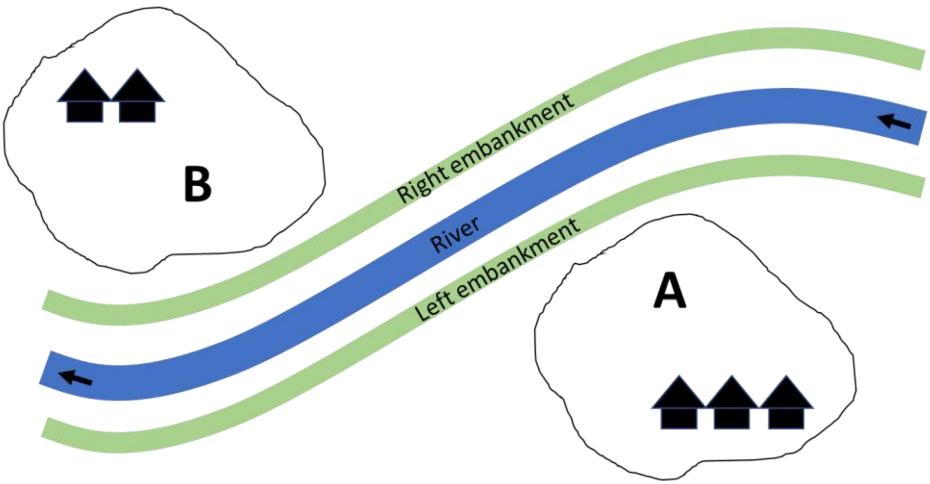

Figure 1.1 *Stylized representation of a flood risk system.*

1.1.2 A system approach to flood risk management

As previous research in flood risk management has shown (Klijn et al., 2012; Mens et al., 2015; Olson and Morton, 2012; Vis et al., 2003) and as recently pointed out by e.g. Vorogushyn et al. (2017) and De Bruijn et al. (2017), advancing the understanding of the effects of hydraulic interactions on flood risk management requires advancing the current risk-based approach by adopting a system-wide perspective, in which effects of local events (e.g. response to hydraulic loads, implementation of measures) on the system as a whole are taken into account. Adopting a comprehensive system approach brings two main challenges (De Bruijn et al., 2016): (1) risk-distribution across flood-protected areas must be taken into account, and (2) uncertainties about embankment failure might better be treated as deep uncertainties, i.e. uncertainties for which experts do not know or cannot agree on the probability distribution (Walker et al., 2013). Both challenges are explained in detail in the next two sections.

Considering risk-distribution across flood-protected areas

The first challenge of adopting a system approach relates to the fact that it further complicates the decision-making process (Van Mierlo et al., 2007). Deciding about flood risk management measures at one location will require decision makers to consider the interests of communities downstream of that location and, eventually, may require taking additional measures downstream and/or considering an alternative measure upstream.

Doorn (2015) argues that risk management for natural hazards is not just a risk-reduction problem, but also a risk-distribution problem, as risk can be reduced but also transferred, e.g. to other flood-protected areas. This is why the EU directive 2007/60/EC on flood risk management states that *"measures to reduce these risk should, as far as possible, be coordinated throughout a river basin"* and invoke the solidarity principle as a key principle of flood risk management: "*in the interests of solidarity, flood risk* *management plans established in one Member State shall not include measures which, by their extent and impact, significantly increase flood risks upstream or downstream of other countries in the same river basin or sub-basin, unless these measures have been coordinated and an agreed solution has been found among the Member States*". The solidarity principle of the EU Flood Directive is motivated by the will to avoid risk shifts like the one that resulted from implementing a flood protection measure along the Elbe River, Germany.

In 2002, the Elbe River catchment was hit by a severe flood and the federal states of Saxony (upstream) and Saxony-Anhalt (downstream) incurred losses. In response, Saxony invested in flood protection measures. A decade later, another flood event occurred but, this time, the reinforced embankments of Saxony withstood the hydraulic load (Vorogushyn et al., 2017). Losses to Saxony-Anhalt, however, were larger than in 2002, which raised public concern on whether newly built upstream flood protection measures caused higher losses downstream during the 2013 flood (Thieken et al., 2016). After the 2002 flood event, a system approach would have required to quantify the risk-distribution in the entire system composed of both Saxony and Saxony-Anhalt, and, based on that, to decide on whether to implement the proposed measures. To support such an analysis, new methods are needed for large-scale flood risk management.

Treating embankment failure uncertainties as deep uncertainties

The second challenge of adopting a system approach relates to the fact that it requires dealing with several uncertain factors, such as e.g. the breach locations ('which embankment will fail first, which other embankments will also fail, and in what order'?), the moment of breaching and the final breach width ('how large will the breach and the associated unloading effect be?').

Typically, embankment failure probabilities are estimated based on the so-called fragility curves, i.e. the probability of failure as a function of hydraulic loads (e.g. water level, flow velocity, flood duration, etc.). The generation of site-specific fragility curves, however, requires extensive knowledge of the geotechnical properties of the embankment which, especially in case of large-scale systems, may not be available or sufficiently accurate for all locations of interest.

A poor representation of uncertainty about embankment stability may lead to unexpected failures. In January 2014, for example, an embankment failure occurred during a minor flood event along the Secchia River, Italy. The failure was not due to any of the mechanisms typically covered by fragility curves, i.e. overtopping, piping and macro-instability (D'Alpos et al. 2014). Instead, embankment stability was compromised by animal burrows (Orlandini et al., 2015; D'Alpos et al. 2014) and the possibility of this had not been foreseen.

In a context of insufficient availability of geotechnical data or poor knowledge about all relevant failure mechanisms, embankment failure uncertainties might better be treated as *deep uncertainties*, i.e. uncertainties for which experts do not know or cannot agree on the probability distribution (Walker et al., 2013). Under deep uncertainty, strategies should preferably be first selected based on their *robustness*, i.e. their capability to increase chances that the system remains functioning under unexpected circumstances (Lempert et al. 2006; Lempert et al. 2003), and, successively, on how the performance of strategies changes under alternative beliefs or assumptions about how the embankments may respond to hydraulic loading. For such an analysis, new methods are needed to support decision making in large-scale flood risk management.

1.2 Problem statement and research objectives

This research is motivated by previous research in the field of flood risk management (Klijn et al., 2012; Mens et al., 2015; Olson and Morton, 2012; Vis et al., 2003) as well as more recent calls from the scientific community (Vorogushyn et al., 2017; De Bruijn et al., 2017) to adopt a system-wide perspective in flood risk management, as current approaches fail to do so. To summarize, adopting a comprehensive system perspective brings two main challenges:

1. The consideration of risk-distribution between flood protected areas located along the same river.
2. The treatment of embankment failure uncertainties as deep uncertainties.

With the aim of supporting decision-making in large-scale flood risk management planning while adopting a system approach and addressing the two related challenges, this research will focus on the following research question:

How to improve flood risk management planning in order to account for risk-distribution across flood-protected areas and the deeply uncertain hydraulic interactions?

Answering this question, requires answering four sub-questions:

1. *To what extent does taking into account the uncertain effects of hydraulic interactions influence the choice of flood risk management strategies?*

This question aims at assessing whether differences emerge in terms of the identified flood risk management strategies between the risk-based approach and one which adopts a system-wide perspective. Answering this question requires comparing strategies found by using a standard risk-based approach, i.e. neglecting hydraulic interactions, with those found when hydraulic interactions are being taken into account.

2. *What is the influence of adopting different ethical principles about the distribution of benefits across flood-protected areas on the identification of flood risk management strategies?*

This question addresses the first challenge of adopting a system perspective in flood risk management: the consideration of risk-distribution across flood-protected areas located within the same flood risk system. This question will be addressed by comparing outcomes of the same flood risk management problem between approaches that solely strive for the maximization of benefits of risk management strategies and approaches which also strive for their equal distribution.

3. *How can different assumptions on the deep uncertainties associated with embankment failure be taken into account in evaluating the performance of flood risk management strategies?*

This question addresses the second challenge of adopting a system perspective in flood risk management: treating embankment failure uncertainties as deep uncertainties. This requires defining a framework that supports the design of flood risk management strategies based on their robustness and to explore how robustness changes under alternative assumptions about embankment stability.

4. *How does a system approach which addresses the challenges of accounting for hydraulic interactions improve flood risk management planning?*

This question resembles question 1 in that it involves assessing whether and to what extent alternative approaches are preferable to current practice. Unlike question 1, however, where the aim is to conduct a proof of principle study to investigate whether adopting a system approach would at all matter for flood risk management, this question aims at assessing current practice in a way that the two challenges of adopting a system perspective are both addressed.

1.3 Research approach

To answer the research questions, the present research applies a modelling approach known as Exploratory Modelling and Analysis (EMA) (Bankes, 1993). EMA allows performing computational experiments by exploring (1) a wide variety of strategies, (2) alternative model structures and (3) alternative parameterizations of that structure. It serves as a basic tool for developing plans under uncertainty and supports multiple decision-analytic robustness frameworks such as Robust Decision Making (RDM) (Lempert et al., 2006) and Many-Objective Robust Decision Making (MORDM) (Kasprzyk et al., 2013).

Robust Decision Making is an iterative model-based decision support method that allows identifying robust strategies, i.e. strategies which increase chances that the system remains functioning under unexpected circumstances (Lempert et al., 2006; Lempert et al., 2003). A robust strategy is not expected to perform as the best performing strategy, but, instead, as the one performing satisfactorily no matter how uncertain circumstances unfold. In the context of flood risk management, a robust strategy would not provide the lowest costs, but it would e.g. limit the adverse consequences of an unexpected breach such as the one which took place along the Secchia River in 2014 (see section 1.1.2). Robust Decision Making allows finding robust strategies by following iterative steps:

- *Specify the policy problem*. This step requires determining which system elements and decision objectives are important and should be included in the simulation model.
- *Perform uncertainty analysis.* In this step, a Quasi-Monte Carlo analysis is carried out in order to evaluate the model performance under alternative assumptions related to e.g. parameter values, model structure and problem formulation.

- *Assess vulnerabilities.* In this step, statistical clustering techniques are applied to the large dataset of model output generated in the previous step. The aim is to identify what combinations of input values lead the system of interest to vulnerable states, i.e. undesired performances.
- *Propose strategies:* Once vulnerabilities are identified, this step aims at defining strategies in order to reduce such vulnerabilities, thus increasing the capability of the system to remain functioning under a broader range of uncertain external circumstances.

Many-Objective Robust Decision Making strongly relies on Robust Decision Making, but it is better suited for problems with multiple, potentially conflicting, decision objectives. In Many-Objective Robust Decision Making, after specifying the policy problem (i.e. first step of Robust Decision Making) Pareto optimal strategies are first identified for a reference scenario. These strategies are found through Many-Objective Evolutionary Algorithms (MOEAs) (Coello Coello et al., 2007), which allow displaying critical trade-offs emerging from alternative strategies without *a priori* attributing preferences (or weights) to any of the decision objectives. As in Robust Decision Making, a subsequent uncertainty analysis of these strategies is carried out and vulnerabilities are identified. Finally, in light of the identified vulnerabilities, the Pareto optimal strategies are ameliorated in a way to limit such vulnerabilities.

A crucial aspect of (MO)RDM is that the uncertainty analysis step is carried out by using statistical sampling techniques, e.g. Latin hypercube (McKay et al., 1979) or low discrepancy sampling series (Sobol, 1967), such that the input space is explored homogeneously and each possible combination of input factors is tested. The aim is to conduct a stress-test of the system under study and to identify critical combinations of input factors leading to system failures (i.e. undesired performances).

Most importantly, whether a combination of input factors is identified as causing system failure is *independent* from its likelihood of occurrence. In other words, identifying critical combinations of input factors is about studying intrinsic vulnerabilities of the system, which, by definition, do not depend on assumptions about the likelihood of the combinations of factors driving such vulnerabilities.

On the one hand, (MO)RDM improves the performance of the system by reducing its intrinsic vulnerabilities, and, thus, allows identifying robust strategies with respect to uncertainties. On the other hand, (MO)RDM does not typically allow considering that, even in a context of deep uncertainties, decision makers may believe certain values being more probable than others (Shortridge and Zaitchik, 2018). When providing decision support following (MO)RDM, it is thus important to explore the performance of strategies under alternative assumptions about deep uncertainties by exploring e.g. alternative probability distributions of deep uncertainties or alternative risk-attitudes towards such uncertainties. In this thesis, the former is accomplished by the use of importance sampling (Diermanse et al., 2014) while the latter by the use of the decision criterion proposed by Hurwicz (1953).

The frameworks introduced above contribute to answering each research question. To answer the first question (namely: *To what extent does taking into account the uncertain effects of system behaviour influence the choice of flood risk management strategies?)* the Many-Objective Robust Decision-Making framework is adopted to identify and compare optimal embankment heights in a case study of the IJssel River in the Netherlands when either considering or neglecting hydraulic interactions.

The second research question (namely: *What is the influence of adopting different ethical principles about the distribution of benefits across flood-protected areas on the identification of flood risk management strategies?)* is addressed by investigating the effect of four alternative formulations of the same flood risk management problem following four alternative ethical principles which either strive for maximizing benefits only, or also maximize equity in distributing these benefits. To address formulations which also include this latter objective, a novel decision criterion is proposed. The analysis focuses on a case-study along the lower Rhine River, including parts of Germany and the Netherlands and applies Many Objective Evolutionary algorithms (MOEAS) (Coello Coello et al., 2007) to assess changes in Pareto optimal policies across the four formulations.

The third research question (namely: *How can different assumptions about the deep uncertainties associated with embankment failure be taken into account in evaluating the performance of flood risk management strategies?*) is addressed by applying a combination of Robust Decision Making and importance sampling to identify robust structural interventions in a case study of the lower Po River in Italy.

The last research question (namely*: How does a system approach which addresses the challenges of accounting for hydraulic interactions improve flood risk management planning?)* is addressed by focusing on the case of the lower Rhine River again, including parts of Germany and the Netherland. In the analysis, the Many-Objective Robust Decision-Making framework is adopted to solve a flood risk management problem following current practice as well as by alternative problem formulations which account for hydraulic interactions and/or risk distribution. The analysis is carried out by exploring the effects of various risk-attitudes toward uncertain hydraulic interactions on the performance of strategies using the decision criterion proposed by Hurwicz (1953).

1.4 Structure of the dissertation

The four sub-questions presented in the previous section are addressed in dedicated scientific papers, which form the different chapters of this thesis. Figure 1.2 reports the core structure of the thesis. After a proof of concept study to address the first research question in Chapter 2, the two challenges of adopting a system approach are individually addressed to answer the second and third research question in Chapter 3 and Chapter 4, respectively. After that, both challenges are addressed in combination to answer the last research question in Chapter 5.

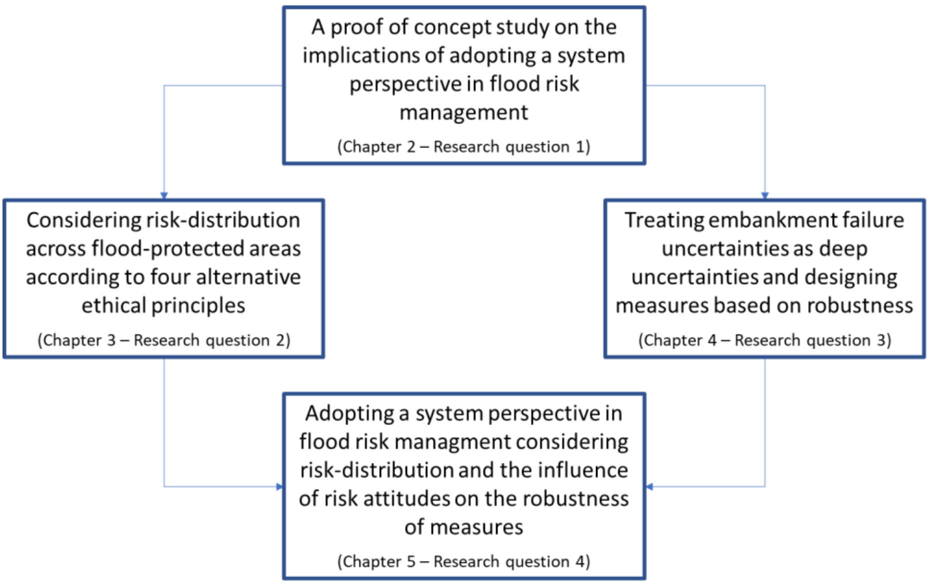

Figure 1.2 *Structure of the thesis. First, a proof of concept study is carried to understand the implications of accounting for hydraulic interactions in Chapter 2. Then, each of the two challenges of accounting interactions are tackled individually in Chapter 3 and 4. Finally, the current risk-based approach is compared with alternative formulations that address both challenges in Chapter 5*.

2 Accounting for the uncertain effects of hydraulic interactions in optimizing embankments heights: proof of principle for the IJssel River[1]

Abstract

Most alluvial plains in the world are protected by flood defences, e.g. embankments, whose primary aim is to reduce the probability of flooding of the protected areas. At the same time, however, the presence of embankments at one area influences hydraulic conditions of downstream areas located on the same river. These hydraulic interactions are often neglected in current flood risk management. The aim of this study is to explicitly acknowledge hydraulic interactions and investigate their impact on establishing optimal embankment heights along a stretch of the IJssel River. We find that the current approach leads to a single solution, while taking into account hydraulic interactions substantially expands the number of promising solutions. Furthermore, under a reference scenario, the current approach is in fact suboptimal with respect to both downstream locations and the system as a whole. Under uncertainty, it performs adequately from a system viewpoint, but poorly for individual locations, mostly due to risk overestimation downstream. Overall, the current approach proves to be too short-sighted, because spatial trade-offs among locations are neglected and alternative solutions remain hidden. Acknowledging the effect of hydraulic interactions provides policy makers with a broader and more comprehensive spectrum of flood risk management strategies.

[1] This chapter was published as: 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). doi:10.1111/jfr3.12532

2.1 Introduction

The alluvial plains along most large lowland rivers around the world (e.g. the Rhine, the Po and the Elbe River) are protected against flooding by embankments or other flood defences. Embankments have the primary aim of reducing the probability of flooding of the protected area and they have historically been the most commonly adopted flood risk reduction measure. Embankments sometimes substantially influence the way the protected alluvial plains develop, both economically and demographically (White, 1945). The Netherlands represents an emblematic case: structural defences such as embankments, floodwalls and dams have been built over the years and they currently amount to a total length of about 3500 kilometres, only accounting for the so-called primary defences (Kind, 2014).

Although embankments represent a successful flood risk management measure, their adoption is recognized to alter the hydrological regime of rivers. For example, Di Baldassarre et al. (2009) demonstrate the increase in the flood peaks experienced at a downstream location of the Po River as a consequence of the progressive enhancement of flood defences over time. Conversely, Van Mierlo et al. (2007) illustrate how potential breaches upstream lead to a reduction of flood load downstream. These examples illustrate the existence of complex, and yet understudied, hydraulic interconnections between planned interventions (e.g. raising embankment height) upstream and the associated unintended consequences (e.g. higher water levels or increased flood damage) downstream. This highlights the importance of considering what in the present thesis is referred to as 'hydraulic system behaviour', i.e. the change in hydraulic loads at one location as a consequence of the state of the embankment system at other locations (Van Mierlo et al., 2007; Vorogushyn et al., 2012).

Several studies investigated the effect of hydraulic system behaviour on flood hazard and risk. For instance, Apel et al. (2009) built a dynamic-probabilistic model to assess the effect of hydraulic system behaviour on flood frequency in contrast to traditional flood frequency analysis. They found that their model was able to provide a much more realistic flood frequency curve for downstream locations, especially for high discharge events, where embankment breaching mechanisms become relevant. Courage et al. (2013) performed a flood risk analysis by comparing results with and without considering hydraulic system behaviour. They found that hydraulic system behaviour leads to different individual as well as economic risks. De Bruijn et al. (2014) came to similar conclusions. They investigated the effect of hydraulic system behaviour on societal flood risk in the Netherlands and found that the number of fatalities *N* occurring with a given frequency *F(N)* is significantly lower when hydraulic system behaviour is considered. This applies especially to extreme flood events, which are those of more concern from a societal viewpoint. These studies show the relevance of taking into account the effects of hydraulic system behaviour in flood risk analysis and suggest that its inclusion may lead to different decisions and alternative investment schemes. However, a due consideration of hydraulic system behaviour in the design and planning of flood risk management measures is still lacking: current plans are usually based on flood risk analyses which assume hydraulic loads at each embankment as being independent from those nearby or upstream (De Bruijn et al., 2016; Vorogushyn et al., 2017). For instance, flood protection standards in the Netherland are based on a well-known and successfully applied embankment height optimization model which was first introduced by van Dantzig (1956) and then developed further by e.g. Brekelmans et al. (2012) and Eijgenraam et al. (2017). Although the value of these models is undeniable, flood probabilities of the protected areas are considered to be independent of one another. They thus ignore the change in the hydraulic load along the river stretch as a consequence of the state (e.g. failure, increase in safety) of embankments elsewhere.

The neglect of hydraulic system behaviour in flood risk management is due to two main reasons (De Bruijn et al., 2016). Firstly, considering hydraulic system behaviour requires dealing with multiple uncertainties such as the location of breaching ('which embankments will fail and in what order'?), the moment of breaching, the breach growth rate and the final breach width

(Vorogushyn et al., 2010). Secondly, considering hydraulic system behaviour would further complicate the decision-making process in flood risk management (De Bruijn et al., 2016; Van Mierlo et al., 2007). Deciding upon flood risk management measures at one location would require taking into account the interests of communities elsewhere, both upstream and downstream of that location. In fact, the European Flood Directive (Directive 2007/60/EC, 2007) prescribes that this should be done, but it is seldom applied in practice.

The aim of this study is to investigate what taking into account hydraulic system behaviour might mean for the choice of optimal embankment heights along a stretch of the IJssel River in the Netherlands. The analysis is carried out applying the Many Objective Robust Decision Making (MORDM) framework (Kasprzyk et al., 2013).

The chapter is structured as follows: we (1) introduce the case study and the optimization problem, explain (2) the Many Objective Robust Decision-Making framework and (3) the simulation model, (4) discuss the results and (5) provide conclusions and recommendations for further research.

2.2 The case study and the optimization problem

The IJssel River is a branch of the Rhine River in the Netherlands flowing north for about 125 km before discharging into the IJsselmeer. The present work focuses on a stretch of this river between the cities of Doesburg and Deventer (see Figure 2.1). Five locations of interest are identified, each representative of a different embankment stretch.

Typically, the problem of finding optimal embankment heights for each stretch is approached by searching for the least total costs solution (Kind, 2014). In other words, the optimal embankment height is considered the one for which the sum of embankment raising costs and expected annual damage is the lowest.

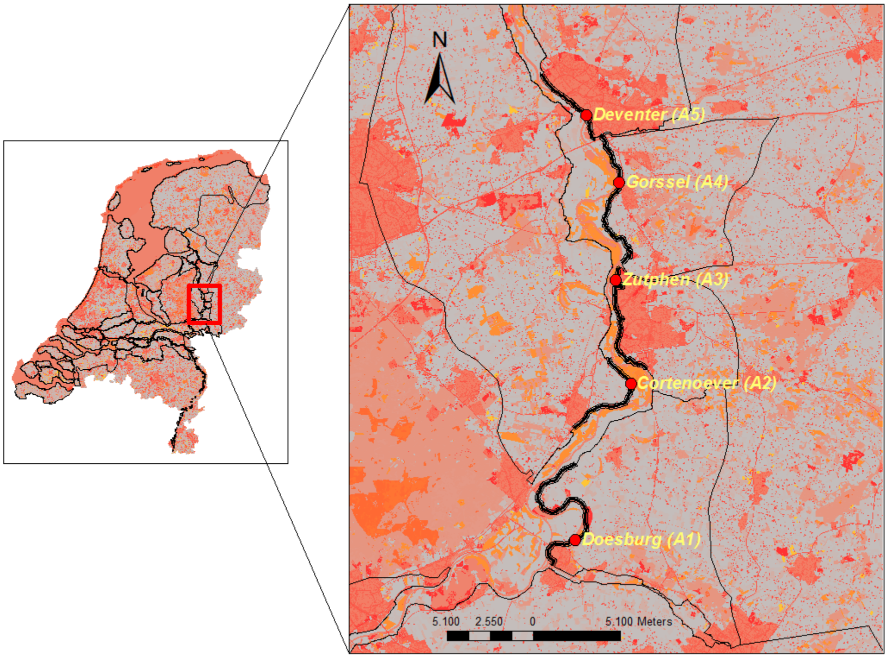

Figure 2.1 *The study area. The IJssel River flows from south to north. Red dots indicate locations of interest, each representative of a given stretch (thick black lines). Each stretch is part of a larger embankment system (in Dutch called 'Dijkring').*

Embankment raising costs are simulated as in Eijgenraam et al. (2017):

$$I(W,u) = \begin{cases} 0 & \text{if } u = 0 \\ (c + bu)e^{-\lambda(W+u)} & \text{if } u > 0 \end{cases} \qquad 2.1$$

where u is the degree of embankment heightening; parameters c and b are fixed and variable costs, respectively, λ is a scale parameter and W is the cumulative embankment heightening over the entire planning period.

Parameters c, b and λ are assigned per stretch of the embankment system. However, some of the stretches considered in the present study are only a portion of those for which cost functions are defined. New cost functions are estimated by multiplying the original cost functions by the ratio of the lengths of the original embankment stretch and the one considered in the present study. Values of parameters *c, b* and *λ* and the lengths of each stretch are shown in Table 2.1. The cost function is meant to apply to a sequence of optimal embankment height decisions over time. Therefore, *W* represents the increase in embankment heightening costs as a consequence of previous heightening. However, the scope of the present work is to find a single optimal embankment height and to study how the consideration of hydraulic system behaviour affects this choice. Thus, W is assumed to be equal to zero.

Table 2.1 *Cost function's parameters for each location as in de Grave and Baarse (2011).*

	***c* (M€)**	***b* (M€/cm)**	***λ* (1/cm)**	***Length of the original stretch (Km)***	***Length of the considered stretch (Km)***
Doesburg (A.1)	28.57	0.2	0.00336	19.38	12.40
Cortenoever (A.2)	124.2	0.61	0.00336	61.31	6.74
Zutphen (A.3)	18.58	0.04	0.00336	8.45	8.45
Gorssel (A.4)	5.41	0.05	0.00336	9.78	9.78
Deventer (A.5)	18.7	0.07	0.00336	4.43	4.43

The expected annual damage (EAD) is computed per location as:

$$EAD(H,\ u) = \int_0^1 L(p)dp = \int_{H_{min}}^{H_{max}} p(H)L(u,\ H)dH \qquad 2.2$$

where L is the flood damage (€); H is the water level in the river (m + m.s.l.), with H_{min} being the lowest water level causing flood damage and H_{max} the water level corresponding to the 12500-year return period event (maximum conceivable event in this study); u is the embankment height; p(H) is the probability density function of a given water level H. The EAD represents the average annual flood damages that communities would expect over the entire planning period. However, not all the expected damages have to be valued equally. Typically, the farther in the future losses are, the less important they are considered by policy makers. For this reason, EAD is discounted as follows:

$$EADd\ (H, u, t, r)\ = \sum_{t=1}^{T} \frac{EAD(H,u)}{(1+r)^t} \qquad 2.3$$

where EAD_d is the discounted EAD over the planning period T and r is the discount rate. Typically, cost-benefit analysis studies in The Netherlands apply a discount rate of 4.5%. However, our analysis neglects the effect of future economic growth on damage development and, as a consequence, a lower discount rate is needed in order to make investments in the increase of embankments height a viable solution. We thus assume a fixed discount rate equal to 1.5% over a planning period of 50 years.

Finally, the optimization problem can be formulated as follows:

$$\textit{minimize} \qquad I\,(W=0, u) + EAD_d\,(H, u, t, r) \qquad \forall \text{ location} \qquad 2.4$$

where u is the decision variable, i.e. increase in the embankment height, which can take values ranging from 0 to 1 meter with an interval of 10 centimetres. Equation 2.4 introduces an optimization problem where total costs at each location have to be minimized. If, as in current practice, hydraulic system behaviour is not considered, this optimization problem can be solved for each location separately. However, accounting for hydraulic system behaviour requires solving equation 2.4 as a many-objective optimization problem. This is due to two main reasons. Firstly, when acknowledging hydraulic system behaviour, a given set of optimal solutions no longer depends on the single decision objective of many locations, but rather on the many decision objectives of the entire embankment system. In such a system, flood risk reduction at a given location does not solely depend on measures implemented at that location, but it may also be accomplished by acting elsewhere. Secondly, the European Flood Directive (Directive 2007/60/EC, 2007) prescribes, founded on the solidarity principle, that flood risk management plans "*shall not include measures which, by their extent and impact, significantly increase* *flood risks upstream or downstream"*. This can only be achieved if trade-offs among locations are explicitly taken into account. Finally, a many-objective optimization approach allows *a posteriori* decision support, the aim of which is not to dictate the adoption of a given solution, which may be biased by upfront specified preferences of decision objectives or from their premature aggregation, but rather to support discussion and provide policy makers with a set of reasonable choices. In this way, a policy maker having a certain preference about the decision objectives (e.g. by assuming each location as equally important and thus looking for a least system-wide total costs solution), can still aggregate them accordingly.

2.3 Many objective robust decision making

Given the inherent uncertainties related to hydraulic system behaviour and the many-objective nature of flood risk management planning aiming to properly account for it, we solve the problem in equation 2.4 by applying the Many-Objective Robust Decision Making (MORDM) framework. The MORDM framework has been introduced by Kasprzyk et al. (2013) and comprises four steps:

1. *Policy problem formulation*. This step requires determining which system elements and decision objectives are important and should be included in the simulation model.

2. *Generating alternatives*. This step employs Many Objective Evolutionary Algorithms (MOEAs) to find a Pareto-approximate set of solutions, namely solutions for which it is impossible to improve a single objective without deteriorating the performance of at least one other objective, relative to a reference situation. Thus, by providing the best approximate set of Pareto optimal solutions, MOEAs allow displaying critical trade-offs emerging from alternative policies without *a priori* attributing preferences (or weights) to *any* of the decision objectives. The success of any MOEA in finding an approximation of the Pareto front is measured according to the convergence (the evolution of the Pareto

front) and diversity (degree of distribution of the solutions over the entire Pareto front) of the solutions. In this study, the ε-NSGAII search algorithm is used (Kollat & Reed, 2005), which exploits adaptive population sizing to provide more diverse solutions during the search.

3. *Uncertainty analysis.* In this step, the previously found Pareto optimal solutions are stress-tested under uncertainty in order to evaluate performance across a wide range of scenarios. Ideally, in this step all previous assumptions related to e.g. parameter values, model structure and problem formulation are relaxed

4. *Scenario Discovery.* In this step, statistical clustering techniques are applied to the large dataset of model output generated in step 3. Scenario Discovery (Bryant and Lempert, 2010; Kwakkel and Jaxa-Rozen, 2016), uses the Patient Rule Induction Method (PRIM) (Friedman and Fisher, 1999) to find orthogonal subspaces in the model input space (i.e., the space spanned by the uncertain factors) for which the resulting output is substantially different from the typical model output. A subspace is described by subintervals for one or more uncertain factors. PRIM returns a series of increasingly smaller subspaces. This series presents a trade-off between coverage (percentage of the cases of interest captured by a given box) and density (number of cases of interest over the total number of cases of a given box). Users can select their preferred subspace based on this trade-off.

The analysis is carried out through the Exploratory Modelling and Analysis Workbench (EMA-Workbench) (Kwakkel, 2017), an open source toolkit developed in the Python programming language.

2.4 Uncertainties and the simulation model

Three are the uncertain factors considered, they relate to (see Figure 2.2):

1. *Embankment strength*. This is represented by the conditional failure probability sampled from the fragility curve, i.e. a curve that indicates the embankment's probability of failure given a water level. The lower the sampled conditional failure probability, the higher the water level that would cause failure (i.e. critical water level), the stronger the embankment; This study makes use of fragility curves used in policy support flood risk management studies in the Netherlands.

2. *Breach growth*. Growth is assumed to follow an exponential model; however, the considered growth rate changes substantially. Three models are possible, i.e. where the maximum breach width is reached after 1, 3 or 6 days.

3. *Maximum breach width, B_{max}*. Final breach widths can assume values between 30 and 350 meters.

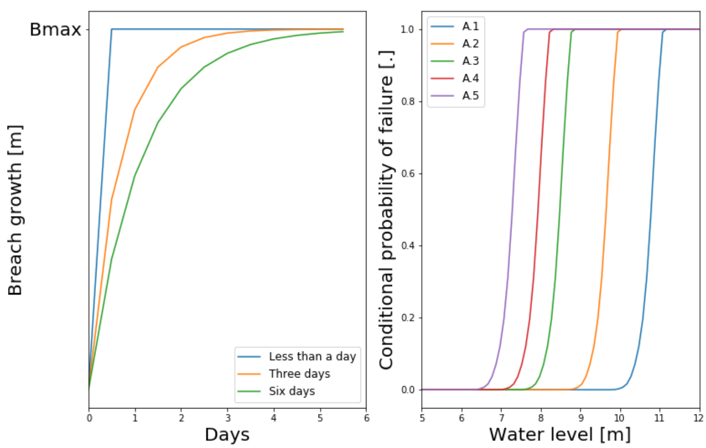

***Figure 2.2** Left: Breach growth models. Right: Adjusted fragility curves per location.*

The above uncertainties apply to each of the five locations, resulting in a total number of 15 uncertainties. Possible values of the identified uncertainties are summarized in Table 2.2.

Table 2.2 *Range of values for each type of uncertainty and average values used in the reference scenario.*

Uncertainties	*Possible values*	*Reference scenario*
Probability of failure	[0 – 1]	0.5
Max breach width B_{max}, [m]	[30 – 350]	175
Time to reach B_{max}, [days]	[1, 3, 6]	3

Figure 2.3 provides a schematization of the simulation model and the required modelling steps. The following subsections describe each step in details. The model is entirely implemented in the Python programming language.

2.4.1 Pre-processing

The pre-processing involves (1) calibration of the routing scheme and (2) adjustment of fragility curves to the flood protection standards in place.

Flood routing is modelled by applying a Muskingum method (Todini, 2007). In the Muskingum method the flood wave is routed by solving the continuity equation between the upstream and downstream ends of a river reach while aggregating any geomorphological and hydraulic characteristic into two parameters (Todini, 2007). In our model, we apply a Muskingum scheme for each two subsequent locations in Figure 2., which thus requires four different sets of calibrated parameters. Calibration is performed against the results of the *SOBEK*, a 1D hydraulic model, by following the method of least-squares as in (Karahan, 2012)**.**

Fragility curves represent the probability of failure of an embankment section given an hydraulic load. The study focuses on overtopping breaching mechanisms triggered by high water levels. Indeed, neglecting the effect of hydraulic loads such as water level duration and failure mechanisms such as piping is a simplification. This implies breaches are only possible on the ascending limb of the hydrograph leading to an overestimation of the flood attenuation effect after a breach. Fragility curves are adjusted in a way as to comply with the actual flood protection standards (in this case, 1/1250 for each stretch) by applying Crude Monte Carlo as described in Diermanse et al. (2014). For each stretch, given N realizations of water levels and critical water levels, the probability of failure can be defined as follows:

$$pf = \frac{1}{N} \sum_{j=1}^{N} I[Z_j < 0] \qquad 2.5$$

where Z is the limit state function, defined as the difference between critical water levels (strength) and water levels (load), I is one when Z is negative, and zero otherwise. The process of adjusting the fragility curves entails iteratively shifting them (thus changing critical water levels) until pf equals the target failure probability.

2.4.2 Event generation

An event is defined by the flood hydrograph, the conditions of the embankments system (embankment strength and the breach growth dynamic) and the adopted interventions (embankment height). Flood waves are generated by associating a sampled maximum discharge to a normalized hydrograph. Maximum discharges are generated following a Generalized Extreme Value distribution Type I, i.e. a Gumbel distribution, as in De Bruijn et al. (2014) and Diermanse et al. (2014):

$$P(Q < q) = e^{-e^{-\left(\frac{q-b}{a}\right)}} \qquad 2.6$$

where coefficients a and b are equal to 1316.45 $m^3 s^{-1}$ and 6612.5 $m^3 s^{-1}$, respectively. Such parameters are found by fitting the distribution to high discharges at Lobith, i.e. where the Rhine River enters the Netherlands. The Rhine then bifurcates into three branches, one of which is the IJssel River.

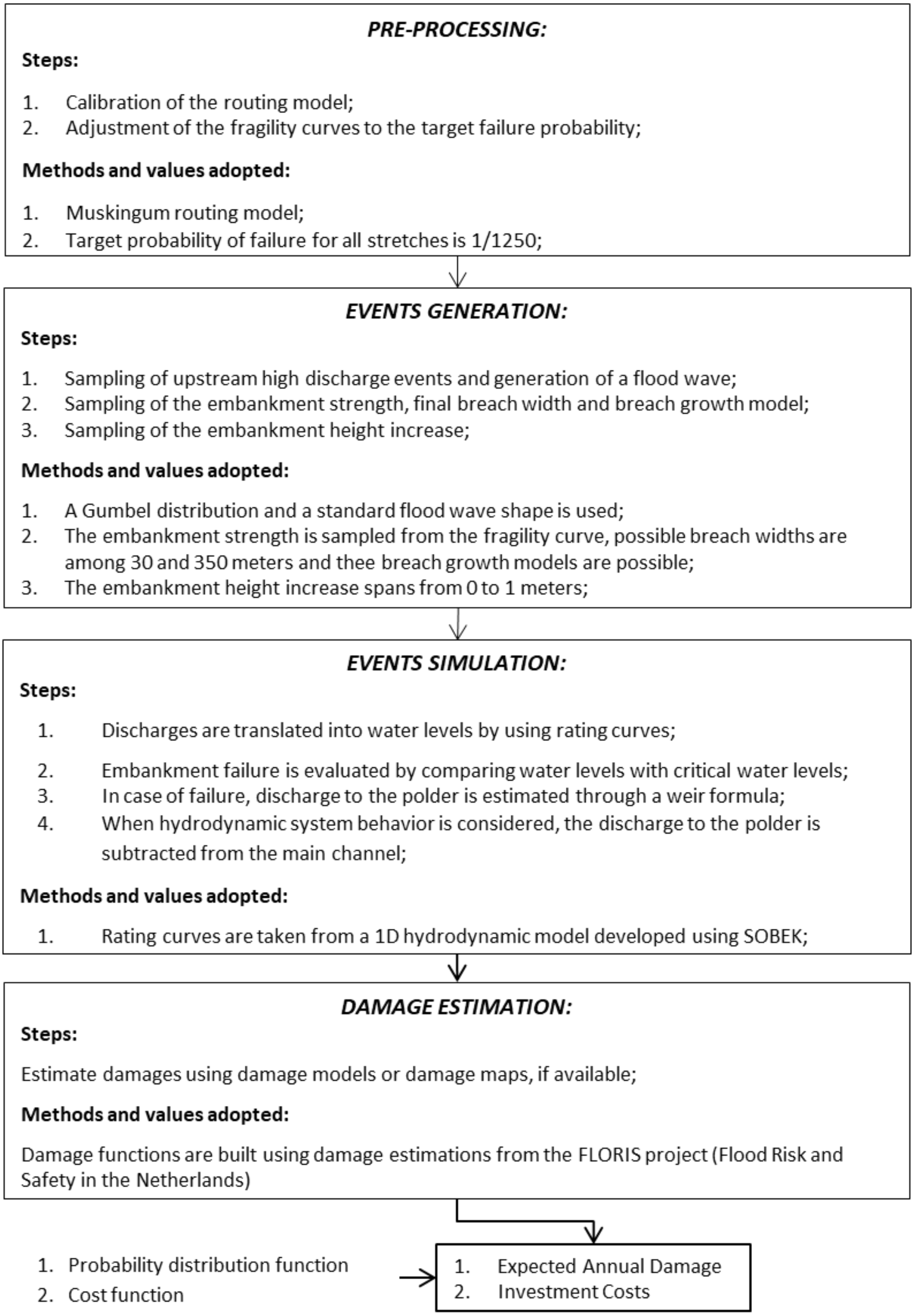

Figure 2.3 *Schematic representation of the flood risk system simulation model.*

High discharges at Lobith and the corresponding flood levels at an upstream location on the IJssel River have been compared using *SOBEK*. On average, *SOBEK* simulates the IIssel River as discharging about 15% of the water that enters at Lobith. We used this figure to adapt equation 2.6 in order to find a distribution of maximum discharges for the IJssel River. Expected annual damages are calculated based on 100 upstream high discharges. A flood hydrograph is then generated by multiplying the sampled maximum discharge with one of the plausible normalized hydrographs calculated for Lobith in the *GRADE* project (Generator of Rainfall and Discharge Extremes) (Hegnauer et al., 2014). The sampled 100 upstream discharges and the normalized hydrograph are reported in Figure 2.4. Finally, values of the exogenous uncertainties (embankment strength, breach growth rate and maximum breach width) and intervention (embankment height increase) are sampled.

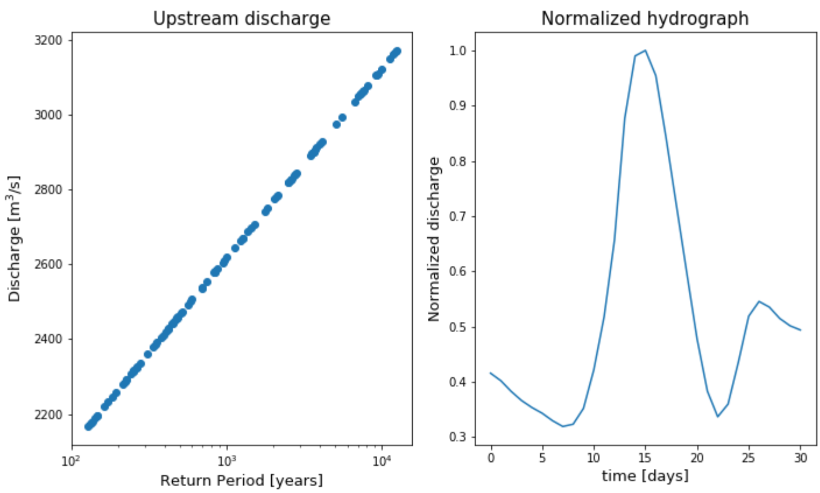

Figure 2.4 *Left: Sampled upstream high discharges and associated return period. Right: normalized hydrograph.*

2.4.3 Event simulation

As the flood hydrograph propagates through the river channel, failure probabilities and impacts on the hydrograph are evaluated at every location of interest. At each location (1) the coming discharge is translated into water levels through a stage-discharge relationship and (2) the water level is compared with the critical water level.

For each model run, water levels are compared with sampled critical water levels at each location and for each time step. If the water level exceeds the critical water level, a breach is simulated using a weir formula and water will flow from the river into the protected area. Downstream discharges will then become lower. When considering hydraulic system behaviour, this discharge is hence subtracted from that in the main channel. Conversely, when hydraulic system behaviour is ignored, the discharge in the main channel is held constant.

2.4.4 Damage estimation

Losses are estimated by comparing the modelled water levels with water level-damage functions. These functions are based on results of the VNK project (in Dutch: *Veiligheid Nederland in Kaart, in English FLORIS: Flood Risks and Safety in the Netherlands*) (Jongejan et al., 2015). VNK is a major flood risk analysis project which provides, for the areas considered in the present study, damage estimates for the 1: 125, 1: 1250, and 1: 12,500 per year floods.

2.5 Results and discussion

2.5.1 Generating alternatives assuming a reference scenario

As shown in Table 2.2, in the reference scenario embankment failure is supposed to occur as soon as the water level equals the one corresponding to the 0.5 failure probability and, when embankments fail, the breach will grow up to 175 meters after about 3 days.

Under the reference scenario, the optimization problem as defined in equation 2.4 is solved twice, namely by accounting for hydraulic system behaviour and neglecting it. Results are presented as a parallel plot in Figure 2.5 where each single line represents a solution.

For a fairer comparison of the outcomes, all optimal solutions in Figure 2.5, regardless whether they account for or ignore hydraulic system behaviour, are re-evaluated accounting for hydraulic system behaviour. This is because, ultimately, reality is such that upstream breaches do cause some degree of flood attenuation and the performance of each solution must therefore be evaluated accordingly. The question is whether ignoring this phenomenon during the design phase will lead to differences in the identified solution(s).

When neglecting hydraulic system behaviour, there is a single unique optimal solution that minimizes the total costs across all locations (blue line in Figure 2.5). Instead, when hydraulic system behaviour is taken into account, a set of 17 Pareto optimal solutions is identified (light orange lines in Figure 2.5). Thus, neglecting hydraulic system behaviour may lead decision makers to a solution based on *cognitive myopia* (Hogarth, 1981), i.e. a situation in which the problem formulation is too narrow and possible alternative courses of actions remain hidden. The wider set of solutions illustrates that trade-offs exist between locations when deciding upon optimal increases of embankment height.

Some solutions may lead to very low total costs upstream, by e.g. raising upstream embankments while neglecting the downstream hydraulic load

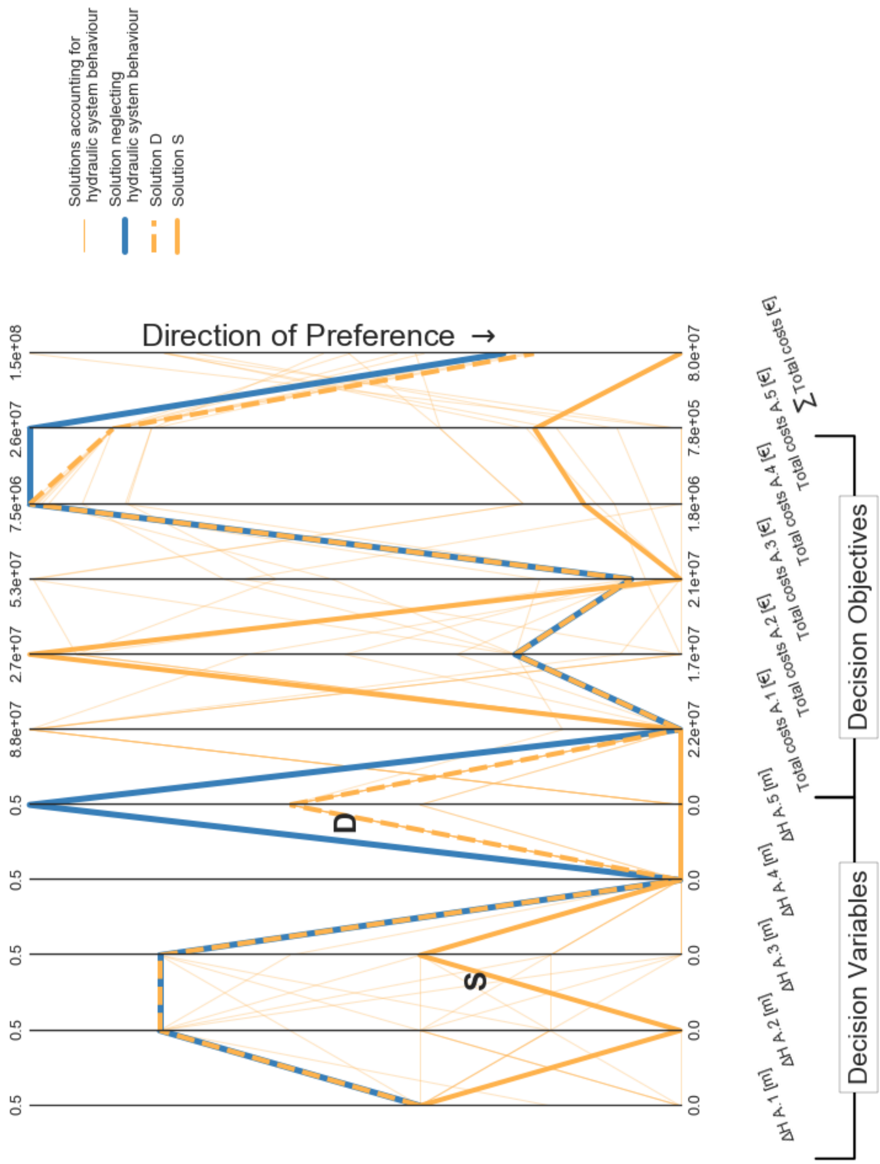

Figure 2.5 *Parallel plot of optimal solutions. The first five vertival axes indicate decision variables (i.e. degree of embankment rasing), the subsequent five axes indicate decision objectives scores (i.e. total costs) and the last axis indicates the system-wide total costs (i.e. sum of each decision objective score). The solution in blue represents the optimal solution found when hydraulic system behaviour is neglected. Solutions in light orange represent the approximate Pareto set of solutions found when hydraulic system behaviour is taken into account. Of these latter solutions, solutions D and S are depicted in bold as a dotted and continuous line, respectively.*

(thus risk) transfer; while other solutions may lead to very low downstream costs, by e.g. keeping upstream embankments low.

Overall, the single optimal solution found when ignoring hydraulic system behaviour represents a conservative choice of optimal embankment heights because it requires the highest embankment heights amongst all solutions. A policy maker could still choose to be conservative while acknowledging hydraulic system behaviour by, for instance, opting for solution D in Figure 2.5. Interestingly, these two conservative solutions are the same for all stretches except for the most downstream one, A.5. For this stretch, solution D can suffice with a lower embankment height and, also, incurs lower total costs than the optimal solution that is found when ignoring hydraulic system behaviour. Consequently, the optimal solution found neglecting hydraulic system behaviour is Pareto dominated by solution D.

Solution S represents the overall least cost solution, where embankments are raised at stretches A.1 and A.3 only. This leads to a situation in which location A.2 bears the greatest burden in terms of total costs and, by so doing, lower total system costs can be achieved. Thus, the optimal solution identified while neglecting hydraulic system behaviour is in fact Pareto suboptimal with respect to solution D and suboptimal from a system perspective with respect to solution S. Figure 2.6 helps investigating this further.

The left-hand panel of Figure 2.6 shows the expected annual damage, investment costs and total costs at stretch A.5 as a function of the embankment height. The embankment heights of the other stretches are held constant at the level required by both solution D and the optimal solution found when neglecting hydraulic system behaviour. When hydraulic system behaviour is taken into account, a lower expected annual damage (blue dotted line) results from the hydraulic load reduction due to upstream flooding. This reduced estimated expected annual damage causes a reduction of total costs (green dotted line) as well as a shift to the left of the minimum of the total cost curve, which moves from an optimal embankment raising of 0.5 m to 0.3 m.

The right-hand panel of Figure 2.6 shows the system total costs (i.e. the sum of all total costs) as a function of the degree of the total embankment height increase (i.e. the sum of all embankment height increase). In the figure, dots represent all solutions in terms of expected annual damage, investment costs and total costs. A line has been fitted through the points in order to obtain an approximated system-wide function through these three cost measures. Solution S is by far the system-wide least total costs solution and may be regarded as an outlier. However, even when neglecting solution S, the overall optimum is reached at a total degree of embankment height increase of approximately 1.1 m, which is lower than the 1.5 m required by the optimal solution found when hydraulic system behaviour is neglected.

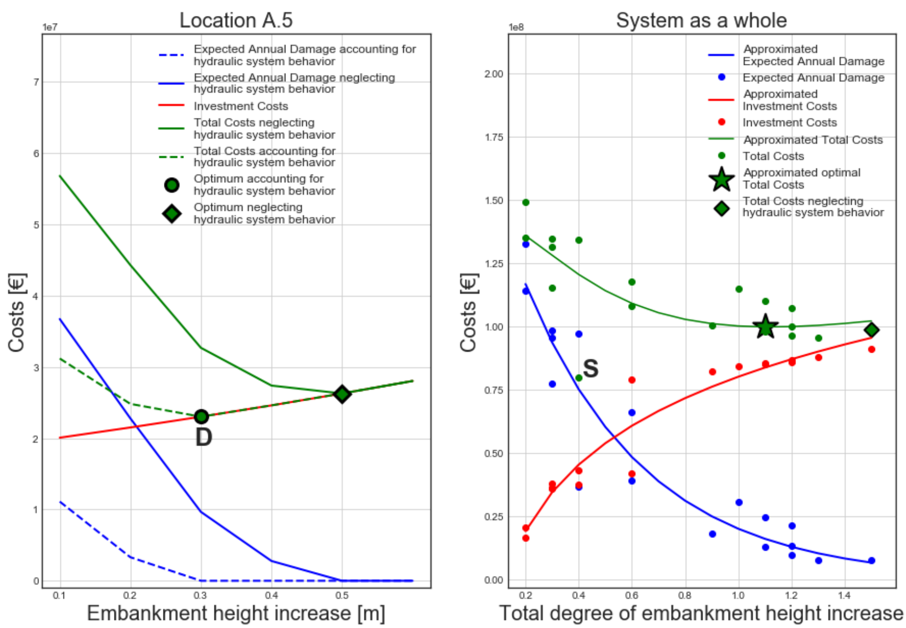

Figure 2.6 *Change in Expected Annual Damage (blue), Investment Costs (red) and Total Costs (green) for increasing embankments heights for location A.5 (left) and the system as a whole (right).*

2.5.2 Uncertainty analysis

In this section, all solutions previously found are evaluated under multiple scenarios. In this context, solutions are set of embankment heightening, while scenarios analyse the uncertainty of the solutions' performance by varying and combining parameters in the ranges given in Table 2.2. The overall aim of this section is to test the robustness of the previous findings, namely the conditions of sub-optimality of the solution found neglecting hydraulic system behaviour. This is accomplished by re-evaluating the decision objectives of each solution under uncertainties about the probability of failure, the final breach width and the breach growth rate. For the same reason stated in the previous section, all solutions are evaluated accounting for hydraulic system behaviour. A Latin Hypercube Sampling (LHS) technique is adopted to generate 2000 scenarios, from the value ranges specified in Table 2.2.

The aim of the analysis is to study the robustness of each solution (1) in retaining Pareto optimality and (2) with respect to the system-wide performance. In doing so, two different robustness metrics are adopted. For a review of robustness metrics the reader is referred to McPhail et al., (2018).

Robustness in retaining Pareto optimality is measured with a *satisfying* robustness metric, i.e. metrics that evaluate the range of scenarios having an acceptable performance. In this case, the acceptable performance relates to the capability of a solution to be amongst the set of Pareto solutions over all scenarios. Thus, for each solution, the likelihood of being amongst the Pareto set, i.e. the ratio between the number of scenarios in which a given solution is Pareto dominant and the total number of scenarios, is calculated.

Robustness with respect to the least system total costs solution is measured with a *regret-based* robustness metric, which is defined as follows:

$$Regret_{P_{j,s}} = P_{best,s} - P_{j,s} \qquad j = \{1,..,n\},\ s = \{1,\ldots,m\} \qquad 2.7$$

where n is the number of solutions and m is the number of scenarios. In other words, for a given scenario s and a solution j, regret is defined as the difference in performance P (i.e. system total costs) between the solution j and the best performing solution, i.e. the one resulting in the system's least total costs. Results are shown in Figure 2.7.

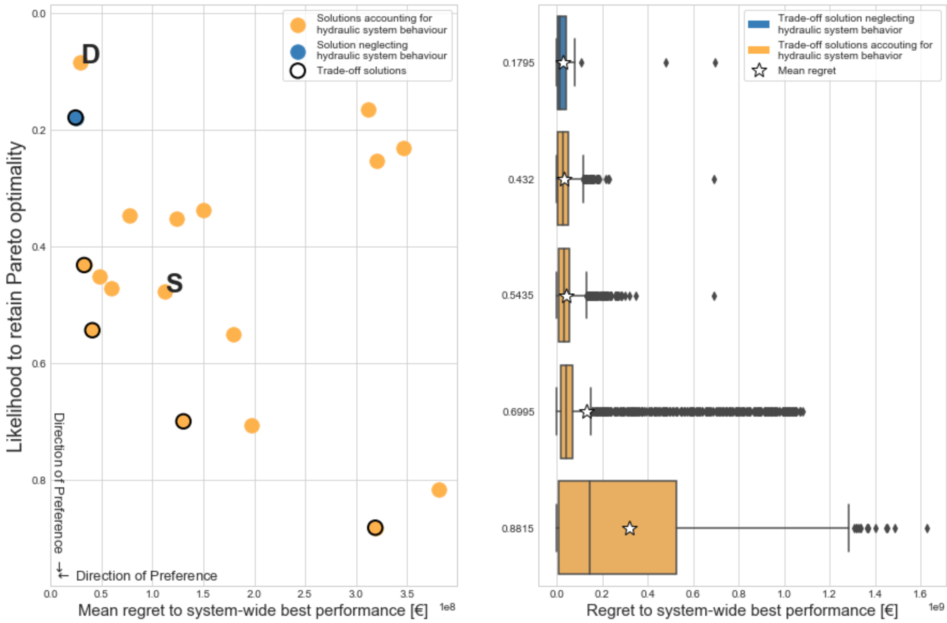

Figure 2.7 *Left: Likelihood to retain Pareto optimality (y-axis) and mean regret relative to system-wide performances (x-axis) of all solutions. Right: boxplots of the regret relative to system-wide performances of the trade-off solutions.*

In the left-hand panel, all solutions are plotted in terms of their likelihood to retain Pareto optimality and the mean regret to the best system-wide performance. An ideal solution would be found in the bottom-left side of the plot, i.e. having high capability of retaining Pareto optimality and low regret. Interestingly, none of the solutions perform in this way. Rather, a set of trade-off solutions can be identified, where improvement in the likelihood to retain Pareto optimality comes at the expense of regret to system-wide best performance, and vice-versa. Hence, the uncertainty analysis allows excluding from the set of plausible final solutions those outside the trade-off curve. This would not have been possible relying solely on the analysis under the reference scenario. Interestingly, solutions D and S are not among the plausible set of solutions. Moreover, the optimal solution found while neglecting hydraulic system behaviour, which is Pareto dominated under the reference scenario, does belong to this trade-off set of solutions. It represents the one that is least capable of retaining Pareto optimality but also the one that yields the least regret with respect to system-wide best performance. In that sense, it qualifies as a 'better safe than sorry' solution (Klijn et al., 2016). The right-hand panel shows the distribution of regret to system-wide best performance of the trade-off solutions. The related statistics are shown in Table 2.3.

Table 2.3 *Statistics of the regret to system-wide best performance of the trade-off solutions in Figure 2.7.*

	Regret to system-wide best performance [€]						
Likelihood to retain Pareto optimality	***mean***	***std***	***min***	***25%***	***50%***	***75%***	***max***
0.1795	2.4E+07	3E+07	0	4E+06	1.4E+07	4.3E+07	6.96E+08
0.432	3.3E+07	3.5E+07	0	5E+06	2.6E+07	4.9E+07	6.92E+08
0.5435	4.1E+07	4.7E+07	0	8E+06	3.1E+07	5.7E+07	6.9E+08
0.6995	1.3E+08	2.4E+08	0	2E+07	4.2E+07	7.1E+07	1.08E+09
0.8815	3.2E+08	3.8E+08	0	1E+07	1.5E+08	5.2E+08	1.63E+09

2.5.3 Scenario Discovery and Trade-off analysis

Scenario Discovery is used to investigate two distinct types of outcome:

a) The solution found neglecting hydraulic system behaviour does not retain Pareto optimality;

b) The solution found neglecting hydraulic system behaviour does retain Pareto optimality;

The results of this investigation are shown in Figure 2.8.

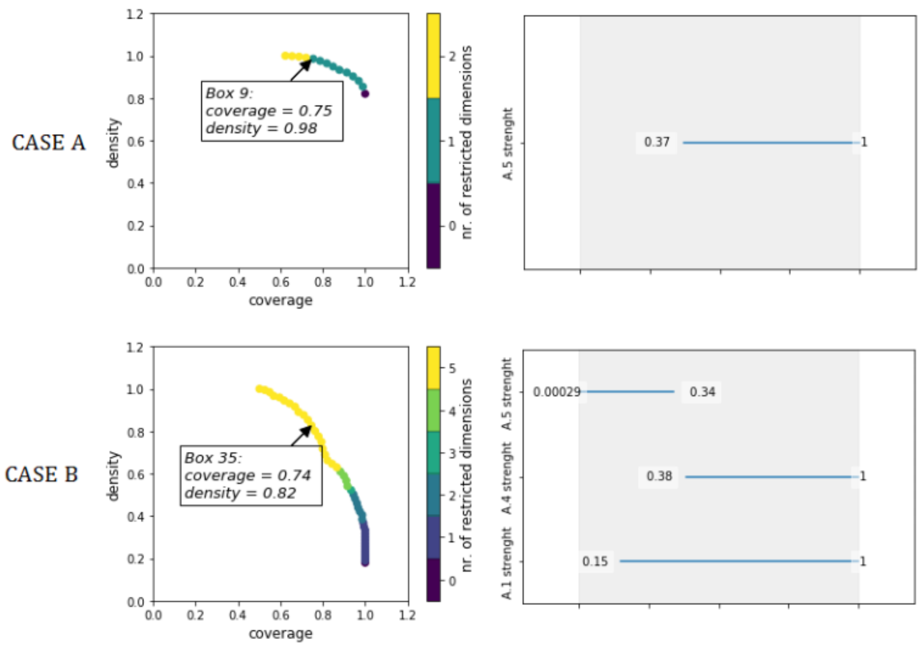

Figure 2.8 *Scenario Discovery results for cases when the solution found neglecting hydraulic system behaviour does not (CASE A) and does (CASE B) retain Pareto optimality. Each row shows two graphs relative to (1) the density-coverage trade-off trajectory resulting from PRIM's box-slicing process (left) and (2) which uncertain factors and the associated range of values best describe the cases of interest (right). Boxes with a coverage of at least 0.7 and a density of at least 0.8 are selected whilst non-significant values (i.e. values whose quasi p-value is higher than 0.05) are dropped.*

Case *a* is explained by scenarios where stretch A.5 is relatively strong. The interpretation is rather straightforward: when downstream stretches do not fail easily, a solution that overdesigns such embankments, as the one found neglecting hydraulic system behaviour, proves sub-optimal.

Case *b* is complementary to *a.* It occurs when stretch A.5 is weak whereas upstream stretches, e.g. A.4 and A.1, are relatively strong. Thus, when subject to flood events higher than the design flood, the non-failure of upstream stretches implies a transfer of loads downstream, where the embankments then fail instead. An overdesign of the downstream embankment stretches allows for better coping with the exacerbation of hydraulic load coming from upstream, thus preserving the Pareto optimality of such a solution.

The trade-off between Pareto dominance and regret to system-wide best performances is explored by looking at the relationship of these two measures with the degree of embankment height increase. In particular, Figure 2.9 shows that the mean regret decreases when increasing total degree of embankment height. This explains why conservative solutions, like the optimal solution found while neglecting hydraulic system behaviour, are among the ones leading to the least mean regret.

Conversely, Figure 2.10 shows that the likelihood of retaining Pareto dominance decreases with an increasing degree of embankment height at each location. This makes conservative solutions, like the optimal solution found while neglecting hydraulic system behaviour, to be among the worst performers in retaining Pareto optimality.

Under uncertainties on how, where and to what extent flood attenuation effects will take place, an approach that finds optimal embankment heights while neglecting them guarantees a low regret to system-wide total cost. At the same time, however, because of this neglect, the solution is not capable of guarantying optimality at each stretch, where lower investments would have been justified had flood attenuation been taken into account.

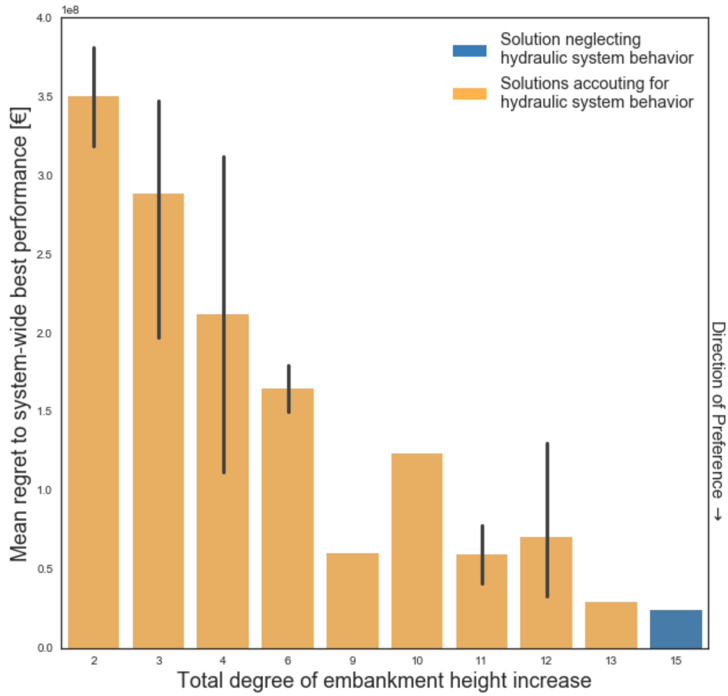

Figure 2.9 *Mean regret relative to system-wide performances for increasing degree of the total embankment height increase. Results for solutions where hydraulic system behavior is accounted for or neglected are depicted in orange and blue, respectively. When more than one solution have the same total degree of embankment height increase, a black vertical line is shown representing the error bars with a 95% confidence interval.*

Ultimately, the choice of a final plan is part of the decision-making process and it depends upon the preferences of decision makers with respect to the two decision robustness criteria. However, one could hypothesize what a reasonable solution would be under different contexts.

For example, under the assumption of centralized funding for flood risk management, policy makers may opt for the solution that neglects hydraulic system behaviour if they are confident that overspending downstream will not outweigh the saved total costs of the whole system. If funding is instead not centralized and a negotiated solution must be agreed upon, one that better retains Pareto optimality is more likely to bring consensus among parties.

Finally, one must be aware that considering economic risk only is too limited. Decisions should be made including a wider set of risk measures, e.g. societal and individual risk. De Bruijn et al. (2014) found that societal risk is overestimated when hydraulic system behaviour is not accounted for. Our results are in line with that, yet, due to the associated uncertainty, the question of '*how safe is safe enough*' still holds, especially when human lives are involved.

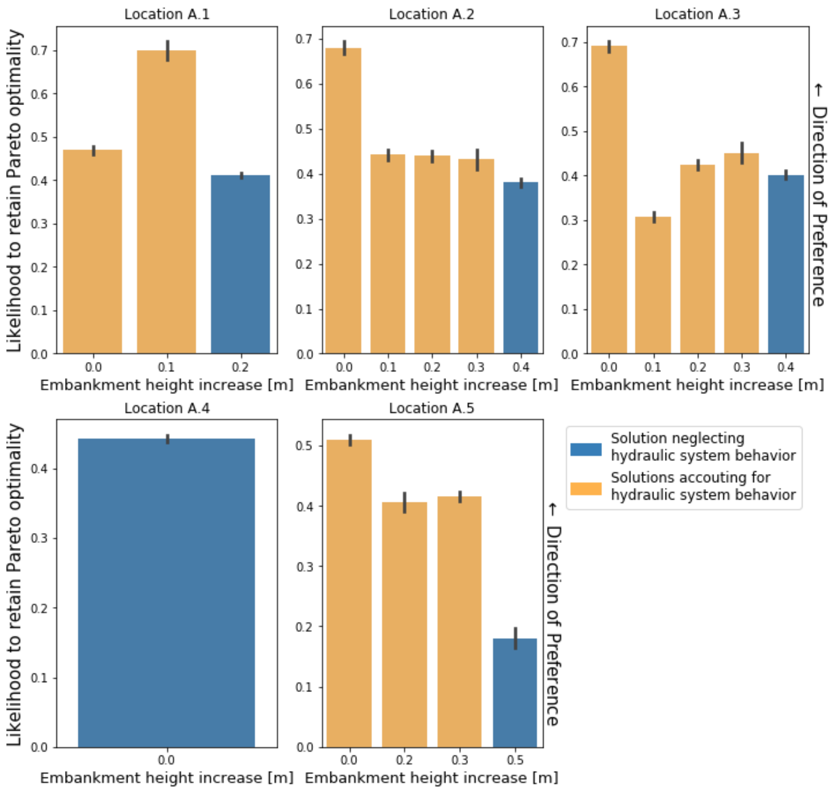

Figure 2.10 *Likelihood to retain Pareto optimality for increasing degree of the embankment height increase per location. Results for solutions where hydraulic system behavior is accounted for or neglected are depicted in orange and blue, respectively. The black vertical lines are error bars representing the 95% confidence interval.*

2.6 Conclusions

In the present chapter we investigated the effect of ignoring hydraulic system behaviour (i.e. the change in the hydraulic loads at one location as a consequence of embankment breaching at other locations) on making decisions about optimal embankment heights, exemplified by a case analysis of the IJssel River in the Netherlands. For the analysis we applied the Many-Objective Robust Decision-Making framework.

Current practice in flood risk management often ignores hydraulic system behaviour in establishing optimal embankment heights; this leads to a single optimal solution, i.e. a unique set of optimal embankment heights. In contrast, taking into account hydraulic system behaviour in the optimization problem widens the solution space substantially. Instead of finding one single optimal solution, our case revealed a Pareto set of 17 solutions. Current practice thus leads decision makers to a solution based on *cognitive myopia*, i.e. a situation in which the problem formulation is too narrow and possible alternative courses of actions remain hidden. Furthermore, under conditions of perfect knowledge about the behaviour of the embankment system, the solution that would qualify as optimal according to current practice proves in fact sub-optimal with respect to both downstream locations (i.e. it is not Pareto dominant) and with respect to the system as a whole (i.e. it is not the system-wide least total costs solution). These two conditions of sub-optimality were investigated further under uncertainty.

The uncertainty analysis revealed a trade-off between the ability to retain Pareto optimality under uncertainty on the one hand and the regret with respect to the least total system costs on the other hand. The optimal solution found following current practice is amongst the trade-off solutions. It shows the best system-wide performance, but also the least capability of retaining Pareto optimality. This lack of Pareto optimality is attributable to its poor performance on the most downstream embankment stretch, where money is spent unwisely, which is in line with what we found under the reference scenario. The good system-wide performance is instead attributable to the conservative nature of such a solution, where embankments are raised following a worst-case approach, i.e. neglecting the flood attenuation effects of possible upstream breaching. In other words, it rigorously applies the precautionary principle of 'better safe than sorry', at extra costs.

The modelling results suggest that policy makers willing to pursue flood risk management of large-scale systems, while considering risk transfers that take place within such system, must account for hydraulic system behaviour. This would make explicit decision conflicts arising among the parties involved, thus allowing, as demanded by the EU Flood Directive, a due consideration of fairness in the decision-making process. However, the proposed approach becomes computationally unfeasible if either applied to a substantially higher number of stretches or a more detailed and computationally demanding simulation model is employed. The proposed modelling framework can thus be used for identifying interesting solutions to be explored and tested further with more detailed models.

Further research will focus on developing a flood risk management plan while including a broader set of possible flood risk management strategies, societal and economic risk as well as other failure mechanisms. Furthermore, considerations of equity between stretches will be given thorough attention. A risk transfer decision objective will be formalised with the aim of studying its effects on the attractiveness of the solutions.

3 Efficient or fair? Operationalising ethical principles in flood risk management: a case study on the Dutch-German Rhine[2]

Abstract

Flood risk management decisions in many countries are based on decision-support frameworks which rely on cost-benefit analyses. Such frameworks are seldom informative about the geographical distribution of risk, raising questions on the fairness of the proposed policies. In the present work, we propose a new decision criterion that accounts for the distribution of risk reduction and apply it to support flood risk management decisions on a transboundary stretch of the Rhine River. Three types of interventions are considered: embankment heightening, making Room for the River, and changing the discharge distribution of the river branches. The analysis involves solving a flood risk management problem according to four alternative formulations, based on different ethical principles. Formulations based on cost optimization lead to very poor performances in some areas for the sake of reducing the overall aggregated costs. Formulations that also include equity criteria have different results depending on how these are defined. When *risk reduction* is distributed equally, very poor economic performance is achieved. When *risk* is distributed equally, results are in line with formulations based on cost optimization, whilst a fairer risk distribution is achieved. Risk reduction measures also differ, with the cost optimization approach strongly favoring the leverage of changing the discharge distribution and the alternative formulations spending more on embankment heightening and Room for the River, to re-balance inequalities in risk levels. The proposed method advances risk-based decision-making by allowing to consider risk distribution aspects and their impacts on the choice of risk reduction measures.

[2] This chapter has been accepted for publication on *Risk Analysis*, as: Ciullo, A., Kwakkel, J. H., de Bruijn, K. M., Doorn, N. & Klijn, F. Efficient or fair? Operationalizing ethical principles in flood risk management: a case study on the Dutch-German Rhine.

3.1 Introduction

In 2002, the Elbe River, in Germany, was hit by a severe flood. The federal states of Saxony (upstream) and Saxony-Anhalt (downstream) incurred about 8.70 and 1.75 million euros of losses, respectively. As a response, Saxony invested in flood protection measures. A decade later, in June 2013, the Elbe River was hit again by one of the most severe floods in decades (Schröter et al., 2015), which this time the newly reinforced embankments of Saxony could withstand. Losses amounted to about 1.19 million euros for Saxony and 1.92 million euros for Saxony-Anhalt (higher than those previously experienced) part of which is likely to be attributed to the increased protection level upstream (Thieken et al., 2016). This raised public concern about the fairness of the implemented measures. With the aim of limiting controversies of this kind, the EU Floods Directive 2007/60/EC provides guidelines to European Member States on flood risk assessment and management. One of its key guidelines relates to the so-called *solidarity principle,* according to which "measures are jointly decided for the common benefit" and "flood risk management plans […] shall not include measures which significantly increase risk upstream and downstream" (Directive 2007/60/EC, 2007).

The implementation of the EU Directive brings three main challenges. First, a whole system perspective must be adopted. Recently, Vorogushyn et al. (2017) called for an approach to flood risk management that accounts for interactions between atmosphere, catchments, river-floodplain and socio-economic processes. Second, and connected to the former point, upstream – downstream trade-offs and hydraulic interactions, i.e. effects of embankment breaches and cascading flooding between neighbouring protected areas, must be explicitly accounted for. De Bruijn et al. (2016), Courage et al. (2013), Apel et al. (2009), Vorogushyn et al. (2012) showed that neglecting hydraulic interactions leads to unreliable flood risk estimates, with risk being either overestimated or underestimated. Third, a thorough analysis of the *fairness of the geographical distribution* of flood risk is needed when deciding upon measures. Addressing this is not trivial, since defining what is meant by a *fair risk distribution* is a research problem in its own right. To illustrate the problem of what it means for a risk distribution to be fair, Hayenhjelm (2012) exemplifies two policies, which we slightly adjust to better fit the context of flood risk management. Assuming there are three areas A, B and C, from upstream to downstream, each having an initial flood risk level of 10^6 euros. There are two possible flood risk reduction policies, each requiring the same investments:

- **Policy 1**: areas A, B and C benefit of the same risk reduction of 1×10^5 euros. The final risks are equal to 9×10^5 euros each, which amounts to a total risk of 2.7×10^6 euros.
- **Policy 2**: areas A and B benefit of the same risk reduction of 4×10^5 euros, while area C has its risk increased. The final risks are equal to 6×10^5, 6×10^5 and 1.3×10^6 euros for A, B and C respectively, which amounts to a total risk of 2.5×10^6 euros.

Policy 1 allocates funds in such a way that every area gains the same benefit from it. In contrast, Policy 2 makes more efficient use of those funds, since the overall risk is lower. This, however, comes at the expense of area C. Which of the two policies is fairer? A policy-maker favouring economic efficiency would deem Policy 2 as fairer, as it brings a greater risk reduction for society as a whole. Another policy-maker might consider Policy 1 fairer, as it brings an equal risk reduction to all. And would the latter change her mind if areas A and B had started from a higher initial risk than area C? There is no unique answer to the question on what a *fair* risk distribution is. Yet, it is paramount to make the evaluation of the risk distribution an inherent part of the methods that are being applied to support large-scale flood risk management planning.

Current decision-support methods heavily rely on cost-benefit analysis (Kind, 2014), which strives for maximizing the overall aggregated benefit and often neglect risk distribution considerations (Hansson, 2007). Johnson et al. (2007) find that when funding for flood protection is allocated relying on cost-benefit analysis, resources will not be targeted to reduce risk of the most vulnerable living in areas where the (low) exposed value does not justify large investments. To address this issue, there have been attempts to improve cost-benefit analyses by applying distributional weights to the aggregation of benefits and costs (Kind et al., 2017) in order to value the worse-off more. Similarly, Adler (2011) proposes the use of a continuous prioritarian social-welfare function for transforming peoples' preferences for a project into a measure of overall social welfare. The proposed function is an increasing and convex function, which thus gives more importance to the marginal increase in well-being of those with lower initial well-being levels. Although these approaches do consider risk distribution, they are subject to two, interrelated, limitations. First, risk distribution is *not* a policy objective *per se,* as policies are ranked based on the optimization of total costs or social welfare, which thus remain the only policy objective. Second, the aggregation of all benefits into a single objective leads to a loss of information as it can hide important trade-offs and thus adversely bias risk-based decision support (Kasprzyk et al., 2016). To address the former limitation, a decision criterion which allows accounting for risk distribution needs to be defined. As for the latter limitation, Many-Objective Evolutionary Algorithms (MOEAs) are typically used (Coello Coello et al., 2007).

MOAEs allow identifying management strategies by optimizing the system under study while balancing many conflicting criteria. Quinn et al. (2017) introduced the concept of rival framings, where MOAEs are used to explore the influence of alternative policy problem formulations on the policy outcomes. This approach is particularly relevant when alternative theoretical frameworks are available for addressing the same policy problem, like assessing *fairness* in risk distribution as discussed above.

Previous flood risk management studies adopting MOEAs focused on either optimizing overall costs and expected risk separately (Woodward et al., 2014a; Woodward et al., 2014b; Garner et al., 2018) or total costs (i.e. summing costs and expected risk) for different geographical areas (Ciullo et al., 2019). To our knowledge, formulations where geographical risk distribution as such is considered as a policy objective to be optimized have never been explored.

The present study proposes a new decision criterion that accounts for the geographical distribution of risk and uses MOEAs to optimize both total costs *and* equity in risk distribution. The aim is to explore the policy implications of adopting alternative ethical principles in the way fairness is conceptualized and operationalized. We do so by solving a flood risk management problem according to *four* alternative *problem formulations,* i.e. the policy problem to be solved, each corresponding to a different way of operationalizing fairness. Although the study is primarily methodological in character, we develop it on a case study of the transboundary area of the German-Dutch Lower Rhine River in order to connect as close as possible to a realistic and geographically differentiated flood risk situation.

After discussing alternative ethical principles and introducing the new decision criterion in section 3.2, we introduce the case study area in section 3.3, we briefly describe the simulation model, measures and outcomes in section 3.4, and introduce the four problem formulations in section 3.5. Finally, we explain the adopted method in section 3.6, present and analyse the results in section 3.7 and discuss them in section 3.8.

3.2 The risk distribution problem and the proposed decision criterion

In this section we introduce the philosophical basis of cost-benefit analysis, we discuss the risk distribution problem and the way it has been tackled. After that, we introduce ethical theories dealing with the problem of fairly allocating risk and, finally, we introduce the new decision criterion to account for risk distribution and its inclusion in an optimization framework.

Cost-benefit analysis is the dominant paradigm in risk policy (Hayenhjelm et al., 2012). It is essentially motivated by the desire to efficiently allocate scarce economic resources. In cost-benefit analysis, policy alternatives are deemed feasible if and only if the sum of expected benefits exceeds the sum of expected costs, with the most preferable policy being the one maximizing the net benefits (i.e. benefits minus costs).

There are three major problems with cost-benefit analysis applied to flood risk management. First, intangible damages, including loss of human lives, need to be monetized in order to include them in the analysis (Kind, 2014). Second, in cost-benefit analysis, risk is typically defined as the expected value of flood damage in each given year. Expected values, however, do not capture society's risk aversion, i.e. the societal higher concern for rare and catastrophic flood events than for frequent, less impacting, ones (Merz, Elmer, & Thieken, 2009). Third, as Hansson (2007) points out, by aggregating costs and benefits, cost-benefit analysis relies on the assumption of *interpersonal aggregation*, where it is assumed that one person's or group's disadvantage can be fully compensated and justified by another person's or group's advantage. It is thus acceptable to treat the involved parties in such a way that it results in an asymmetric distribution of benefits, as long as a greater benefit to society at large can be achieved (Hayenhjelm, 2012). In response to the third issue, distributive weights may be applied in the process of aggregating costs and benefits (Kind et al., 2017). Defining distributive weights requires specifying people's utility function (Adler, 2011). Typically, the better off people are, the lower the increase in marginal utility and vice-versa. Therefore, although *interpersonal aggregation* is still required, the use of distributive weights allows accounting for people's different levels of well-being.

It has been demonstrated that ranking policies through cost-benefit analysis with distributive weights, in that it requires to specify people's utility function, is in fact equivalent to the use of Social Welfare Functions (SWF) (Adler, 2011). SWF are used to assess the social welfare of policies based on individual utilities, with the best policy being the one maximizing social welfare. Specifying the form of SWF is crucial. Adler (2011) propose the use of continuous prioritarian SWF, i.e. an increasing and strictly concave function such that there is a decreasing marginal moral value for increasing utility levels. This implies that higher weight is given to increases in utility of people with initially lower wealth. Therefore, both cost-benefit analysis with distributive weights and SWF as defined by Adler (2011) strive for overall efficiency while accounting for interpersonal risk distribution. However, the distribution of risk is *not* a policy objective *per se*, as policy evaluation is solely based on the maximization of aggregated welfare. Alternative ethical theories, such as egalitarianism and prioritarianism, do, instead, require risk distribution to be the ultimate goal of policy evaluation (Lamont & Favor, 2017).

Strict egalitarianism conceives inequality as such not to be justifiable on moral grounds, thus requiring a perfectly equal distribution of benefits. Strict egalitarianism is, however, subject to the so-called *levelling down objection* (Hayenhjelm, 2012; Lamont & Favor, 2017; Gosepath, 2011): for the sake of equality, everybody may end up being equally worse off, which is obviously undesirable. An alternative to egalitarianism is prioritarianism, according to which benefits should be prioritized to the worst-off (Parfit, 1997). According to prioritarianism, inequalities are justified if they benefit the worst-off.

Egalitarianism and prioritarianism differ in what they consider to be the main concern. Egalitarianism is concerned with *relative* levels, i.e. benefit distribution is unfair if and only if one person is worse off than another person. Prioritarianims, instead, is concerned with *absolute* levels, i.e. benefit distribution is unfair if the level of well-being of the worse-off is deemed unfair, regardless other people's levels. Irrespective of the reason why a distribution is deemed unfair, there is the need to complement cost-benefit analysis goals of economic efficiency with benefit distribution goals in order to build the *pluralistic* decision framework advocated by Johnson et al. (2007) where system-wide objectives such as reducing aggregated costs and benefits are achieved while ensuring that all interested parties have an equal opportunity of having their risk reduced.

We propose a decision criterion to account for the distribution of benefits between e.g. affected individuals, groups or, as applied in the present study, geographical areas. The approach is illustrated in Figure 3.11, where the top figure shows a stylized flood risk system with two flood protected areas, A and B, and the bottom figure provides a visualization of the proposed criterion. In particular, the distribution of benefits is quantified by the distance *d* between the two flood-protected areas, A and B, in terms of a generic outcome of interest *k* which quantifies the benefits of a given policy (namely the difference in performance between the policy and the status quo) with its exact definition to be agreed upon based on what is the entity that ought to be distributed. The bisector is the line of equal benefits, i.e. a condition where area *A* and B have the same *k*. The status quo is given by the point of origin.

As an example, we shall consider point *P'*, representing a policy with performances k'_A and k'_B, with $k'_B > k'_A > 0$. The distance between point *P'* and the line of equal benefits is:

$$d = \frac{|k'_A - k'_B|}{\sqrt{2}} \qquad 3.1$$

Moving from point *P'* (where $k'_B > k'_A$) to the closest point on the bisector (where $k_B = k_A$) implies a *reallocation* in the performance of indicator *k* from area B to area A. In general, the smaller the distance, the closer one is to an equal distribution of benefits. Care must be taken, however, not to incur in a situation in which, for the sake of equity, everybody is worse off. This is the case of point *P''*, where $k''_A > 0, k''_B < 0$ and minimising the distance *d* would imply a tendency to a situation where $k''_A < 0, k''_B < 0$, i.e. where both indicators perform worse than in the status quo. Therefore, in using this new distance criterion, we constrain the analysis to the $k_A, k_B > 0$ domain.

In light of the introduced concepts of cost-benefit analysis, egalitarianism and prioritarianism, and using the introduced decision criterion, we define four problem formulations in section 3.3.5 to manage flood risk for the case study described in section 3.3.3.

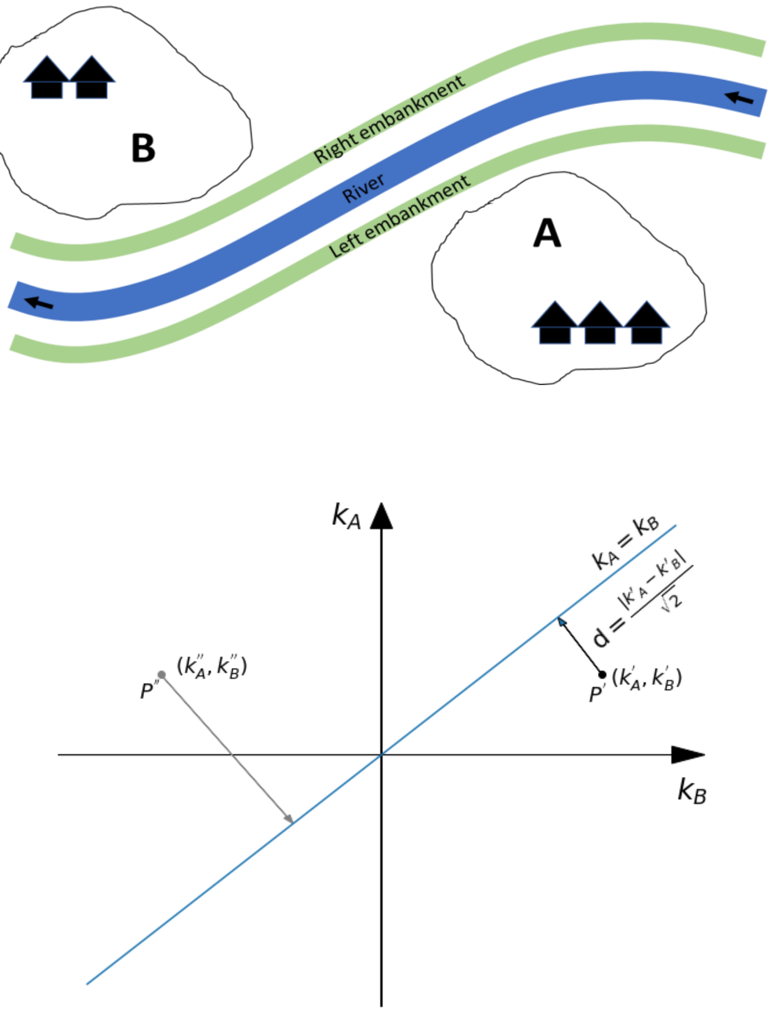

Figure 3.11 Top: Stylized representation of a flood risk system with two flood protected areas, A and B. Bottom: visualization of the geometric approach used to quantify the distribution of benefits among areas. The axes represent the outcome indicator of area *A*, k_A, and area B, $\boldsymbol{k_B}$. The bisector is the line of equal benefits, i.e. a condition where area *A* and B have the same *k*. Points P' and P'' indicate the effect of two distinct policies on the outcome indicators. The distance *d* indicates the geometric distance between a point to the bisector line, i.e. *d* indicates how *far* the distribution of benefits brought by a given policy is from an equal distribution.

3.3 The case study

The present study focuses on the 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 3.12). The Dutch Rhine bifurcates into three distributaries, the Waal River to the southwest, the Nederrijn to the west and the IJssel River to the north. The study area thus includes parts of German and Dutch territories.

In Figure 3.12, the administrative country border is depicted in grey and the thick closed lines represent the so-called *dike-ring areas,* i.e. alluvial plains that are protected from flooding by connected embankments. Six macro-areas of interest are identified based on the *dike-ring areas* and results in the following sections will refer to these areas. Names of each geographic area are shown in Table 3..

Table 3.1 *The geographic areas of interest.*

Identifier	***0***	***1***	***2***	***3***	***4***	***5***
Name	Waal River South	Central River area	Nederrijn-Lek North	IJssel River valley	Ooij Düffelt polder	German Rhine North

Furthermore, we recognize seventy potential breach locations of interest, i.e. places where the flood protection might fail resulting in flooding. Breach locations in red affect transboundary dike-ring areas, implying that flooding causes damage in both countries, regardless of the country in which the breach is located. In fact, all considered potential breach locations in Germany result in transboundary flooding.

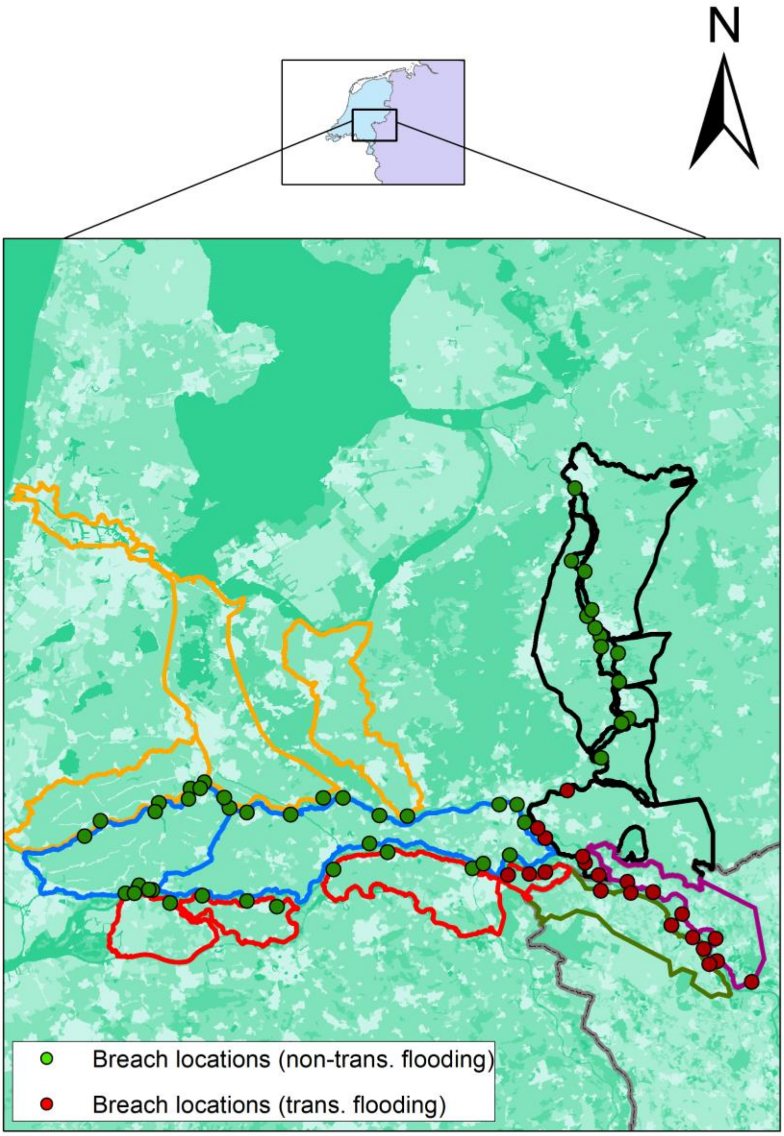

Figure 3.12 Case study area. Six macro-areas of interest are identified: four Dutch areas (*area 0*, in red; *area 1*, in blue; *area 2*, in orange; *area 3*, in black) and two German areas (*area 4*, in green; *area 5*, in purple). The administrative country border is depicted in grey. Dots represent breach locations, with red dots indicating breaches leading to damage in both countries.

3.4 The simulation model, measures and outcomes

The proposed simulation model is a fast, integrated metamodel (Haasnoot et al., 2014). It builds upon the one introduced in Chapter 2, which was developed for the IJssel River (approximately *area 3* in Figure 3.12). There are two main differences, however. First, a more diverse set of possible flood risk management measures. In Chapter 2, only embankment heightening was considered; the current version also includes making *Room for the River* and influencing the discharge distribution over the three river branches. Second, a damage model was developed to ensure consistency in damage assessment in both countries. We describe the above-mentioned differences in the following sections and provide a schematic representation of the model's inputs and outputs in Figure 3.13. We refer the reader to Chapter 2 for a detailed description about the model.

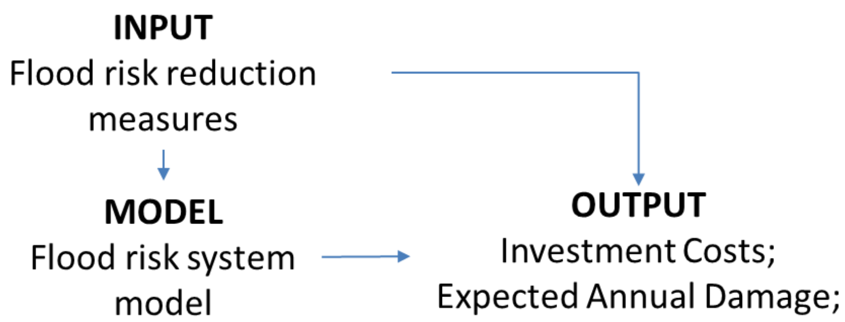

Figure 3.13 Schematic view of inputs and outputs of the simulation model. More information on the simulation model are provided in Chapter 2.

3.4.1 Flood risk reduction measures

Three flood risk reduction measures are possible: embankment heightening, making room for the river, and changing the discharge distribution at the bifurcation points. Embankments can be raised up to 1 meter, with steps of 10 centimetres. Embankment raising costs are simulated as in Eijgenraam et al. (2017):

$$I = \begin{cases} 0 & if\ u = 0 \\ (c + bu)e^{-\lambda(W+u)} & if\ u > 0 \end{cases} \qquad 3.2$$

where u is the degree of embankment heightening; parameters c and b are fixed and variable costs, respectively; λ is a scale parameter and W is the cumulative embankment heightening over the entire planning period, establishing increasing costs per heightening unit as embankments become higher. As in the present work a single optimal embankment height is identified, W is assumed to be equal to zero. Parameters c, b and λ are assigned per stretch of the embankment system and their values are provided by De Grave & Baarse (2011).

As for making room for the river, there are 156 Room for the River projects available to choose from along the *Dutch Rhine,* based on an existing database (Van Schijndel, 2005). For our simulation, a project can simply be either implemented or not. Costs of Room for the River projects range from 50.000 euros to about 2 billion euros.

As for making changes to the discharge distribution, there are two bifurcation points of interest; the default flow distributions are 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. There are no costs associated with changing the discharge distribution as it may be accomplished by adjusting the hydraulic structures currently in place.

3.4.2 Damage estimation

Due to the transboundary nature of the problem at hand, consistency of damage estimates between the two countries is paramount, thus the exposure data as well as the adopted damage model should come from the same source and rely on the same assumptions.

We use exposure data from the CORINE Land Cover dataset (EEA, 2016) and the global flood depth-damage functions proposed in Huizinga et al. (2017). These provide normalized damage functions per land use category per continent as well as a country-wise maximum damage value. The final flood depth-damage functions result from the multiplication of the two and they are thus country-specific.

The CORINE Land Cover dataset distinguishes 44 classes while the global flood depth-damage model provides damage functions for only a few land use categories: residential, commercial, industrial, agricultural, infrastructural and transportation, referred to here as 'JRC Land-use categories'. Each CORINE class is related to percentages of JRC land-use categories. For example, the CORINE land use class 111 consists for 50 % of "residential", for 5 % of "commercial" and for 18 % of "transport". Therefore, the final damage functions of each CORINE class result from the weighted sum of damage functions for each JRC land-use category, with the weights being the percentage of land-use categories in each class. The CORINE classes, the percentage of JRC land-use category per class can be found in (Huizinga, 2007).

Damage is calculated based on flooding simulations from the VNK project (in Dutch: *Veiligheid Nederland in Kaart, in English FLORIS: Flood Risks and Safety in the Netherlands*) (Jongejan et al., 2015). VNK is a major flood risk analysis project which relies on flooding simulations for three flood levels: the design flood levels as well as those that are expected 10 times more frequently and 10 times less frequently. Each of the three VNK flooding simulations has a return period and a water level in the river associated with it. Consequently, for each location a relationship can be established between return periods, water levels in the river and damages. Damages of flood events with return periods other than the three simulated are found by linear interpolation.

Finally, VNK also provides a maximum water depth map per *dike-ring area*, meaning that no higher water depths can be reasonably expected. A maximum damage per *dike-ring area* can thus be calculated, which is used as upper boundary in case the superimposition of damage estimates of different breach locations in the same *dike ring* would exceed this maximum.

3.4.3 Model outcomes

The model produces eight outcomes of interest, viz. the *present value of expected annual damage, EAD* in each of the six areas in Figure 3.12 and the *investment costs, I* of a given policy for the two countries. The latter are the sum of the costs of heightening the embankments and those of the implemented Room for the River projects. We refer to total costs as the sum between the present value of expected annual damage and investment costs. The present value of expected annual damage is defined as follows:

$$EAD\ (T, r) \ = \sum_{t=1}^{T} \frac{\int_{H_{min}}^{+\infty} p(H)L(u,H)dH}{(1+r)^t} \qquad 3.3$$

where L is the flood damage (€); H is the water level in the river (m + m.s.l.), 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 probability density function of a given water level H; T is the planning period (i.e. 200 years), r the discount rate (3.5 percent per year). Clearly, lower (higher) values of discount rate increase (decrease) investments. However, using a single value suffices our scope of exploring the differences regarding where investments are directed across formulations, as the same discount rate would anyway apply to all of them.

3.5 The problem formulations

In this section we introduce four alternative problem formulations for the case study, based on the theories and decision criterion introduced in section 3.2. Furthermore, connections of the four formulations and their underlying principles to either previous studies or established practice in flood risk management are provided.

The first and second problem formulations follow a cost-benefit analysis approach. The third and fourth complement cost-benefit analysis by also using the new decision criterion but they differ in their conceptualisation of the outcome indicator *k*, i.e. in what ought to be distributed. In the risk ethics literature, the following have been proposed as entity to be distributed: economic resources, final risk levels, and degree of risk reduction (Doorn, 2015). We focus on the latter two.

Ideally, when applying the new decision criterion, the distance is calculated between each pair of areas. However, in so doing the number of decision criteria to be optimized in a case such as the one in Figure 3.12 would soon become too large. That is why in the present work the distance is calculated between each area *i* and all the other ones, as if they were a single area. Referring to the bottom panel of Figure 3.11, the axes would thus represent the outcome indicator of area *i*, k_i, and the aggregation of all areas but area *i*, $k_{\Sigma_{j,j\neq i}}$.

In all problem formulations, *investment costs I* in the Netherlands (areas from 0 to 3) are subject to a maximum investment constraint of 1 billion. In Germany (areas 4 and 5), because there are fewer locations and embankment heightening is the only possible intervention, the total maximum investment costs are still below what is practically reasonable to invest. Thus, no investment cost constraint is applied.

In the mathematical formalization of the problem formulations provided in the next subsections, indices *i* and *j* refer to the five flood protected areas in Figure 3.12 and can thus take value from 0 to 5.

3.5.1 First Problem Formulation: Cost-Benefit Analysis (CBA)

The first problem formulation follows a cost-benefit approach (in the remainder, *CBA*) and it is defined as follows:

$$\text{minimize} \quad \sum_{i=0}^{i=3}(I_i + EAD_i)\ ; \qquad \sum_{i=4}^{i=5}(I_i + EAD_i); \qquad 3.4$$

$$\text{with} \quad \sum_{i=0}^{i=3} I_i \leq 10^9\ €;$$

This formulation is equivalent to the one adopted in previous studies like those of Brekelmans & Hertog (2012), Kind (2014) and Eijgenraam et al. (2017).

3.5.2 Second Problem Formulation: Constrained Cost-Benefit Analysis (cCBA)

The second problem formulation constrains the cost-benefit analysis approach (in the remainder, *cCBA*) by guaranteeing that no area is worse than in the status quo. It is defined as follows:

$$\text{minimize} \quad \sum_{i=0}^{i=3}(I_i + EAD_i); \qquad \sum_{i=4}^{i=5}(I_i + EAD_i); \qquad 3.5$$

$$\text{with} \quad \sum_{i=0}^{i=3} I_i \leq 10^9\ €;$$
$$EAD_i \leq EAD_{0|i}\ , \qquad \forall\, i \in (0, 1, 2, 3, 4, 5);$$

This formulation constrains cost-benefit analysis, and thus resembles the principles of the Dutch flood risk management policy, where differentiation of protection levels based on economic considerations is aimed for while at the same time basic security is provided to all citizens (Jonkman et al., 2011; Van Der Most, 2010).

3.5.3 Third Problem Formulation: Egalitarian

In the third problem formulation, in addition to minimizing total costs, the distance between performance indicators $k_i, k_{\Sigma_{j,j\neq i}}$ is minimized, with the two indicators being defined as follows:

$$k_i = \frac{(EAD_{0|i} - EAD_i)}{\sum_j EAD_{0|j}}$$

$$k_{\Sigma_{j,j\neq i}} = \frac{\sum_{j,j\neq i}(EAD_{0|j} - EAD_j)}{\sum_j EAD_{0|j}}$$

where risk reductions are normalized over the total initial risk ($\sum_j EAD_{0|j}$) for convenience. This problem formulation seeks for an *equal distribution of risk reduction* (difference between the initial risk level EAD_0 and the final risk *EAD*) and it thus qualifies as an *egalitarian* problem formulation. As such, this formulation resembles the flood risk policy principles of many countries which apply equal protection standards to all areas, e.g. Austria (Thaler & Hartmann, 2016). The problem formulation reads as follows:

minimize $\quad \sum_{i=0}^{i=3}(I_i + EAD_i); \quad \sum_{i=4}^{i=5}(I_i + EAD_i);$ 3.6

$$\frac{\left|k_i - k_{\Sigma_{j,j\neq i}}\right|}{\sqrt{2}}, \qquad \forall\, i, j \in (0, 1, 2, 3);$$

$$\frac{\left|k_i - k_{\Sigma_{j,j\neq i}}\right|}{\sqrt{2}}, \qquad for\ i = 4, j = 5;$$

with $\quad \sum_{i=0}^{i=3} I_i \leq 10^9$ €;

$$EAD_i \leq EAD_{0|i}, \qquad \forall\, i \in (0, 1, 2, 3, 4, 5);$$

Thus, there are seven decision objectives to be minimised. Two cost objectives and five distance objectives. With respect to the latter, four objectives concern the four areas in the Netherlands and the remaining one concerns the two German areas together.

3.5.4 Fourth Problem Formulation: Prioritatian

The fourth problem formulation is similar to the third. The main difference is that the performance indicators k_i, $k_{\Sigma_{j,j\neq i}}$ are now defined as:

$$k_i = \frac{(EAD_{0|i} - EAD_i)}{EAD_{0|i}}$$

$$k_{\Sigma_{j,j\neq i}} = \frac{\sum_{j,j\neq i}(EAD_{0|j} - EAD_j)}{\sum_{j,j\neq i} EAD_{0|j}}$$

In this problem formulation, an *equal distribution of relative risk reduction is sought*. The *relative risk reduction* is defined as the difference between the initial risk level EAD_0 and the final risk *EAD*, normalized by the initial risk level. This means that, in order to minimise the distance, areas with a higher initial risk will benefit from larger risk reductions. This formulation, therefore, prioritizes interventions to higher risk areas and in this it qualifies as a *prioritarian* formulation. It reads as follows:

$$\text{minimize} \quad \sum_{i=0}^{i=3}(I_i + EAD_i); \quad \sum_{i=4}^{i=5}(I_i + EAD_i); \qquad 3.7$$

$$\frac{\left|k_i - k_{\Sigma_{j,j\neq i}}\right|}{\sqrt{2}}, \quad \forall\, i, j \in (0, 1, 2, 3);$$

$$\frac{\left|k_i - k_{\Sigma_{j,j\neq i}}\right|}{\sqrt{2}}, \quad \text{for } i = 4, j = 5;$$

$$\text{with} \quad \sum_{i=0}^{i=3} I_i \leq 10^9\ €;$$

$$EAD_i \leq EAD_{0|i}, \quad \forall\, i \in (0, 1, 2, 3, 4, 5);$$

This formulation, in that it relies on the principle of prioritizing interventions to higher risk areas, resembles the flood risk management approach followed in the United Kingdom, where expenditures for flood defenses are allocated taking into account the presence of deprived areas (Penning-Rowsell et al., 2016).

3.6 Method

The four problem formulations are solved using the Many Objective Evolutionary Algorithm (MOEA) (Coello Coello et al., 2007) ε-NSGAII (Kollat & Reed, 2005). MOEAs represent metaheuristic approaches to find a Pareto-approximate set of solutions, i.e. solutions for which it is impossible to improve a single objective without decreasing the performance of at least one other objective.

In the MOEA search, expected annual damages are calculated based on 10 upstream high-flood waves (i.e. with probabilities of less than 1:125 per year). A larger number would require longer computation times and make the optimization unfeasible, as the total number of required evaluations becomes too large. Once optimal policies are identified, however, their performance is re-evaluated for a larger sample of 2500 river flood waves. After that, a final set of policies is selected such that each policy (irrespective of the formulation it derives from) is Pareto dominant in terms of total costs in the two countries and expected annual damage at the six flood-protected areas. This guarantees that no policies that after the re-evaluation exhibit higher total costs and higher risks at all areas - and which are thus undefendable - are considered. Finally, in order to quantify inequality, we use the Gini index.

The Gini index is widely used in welfare economics in order to measure income inequality, and is defined as follows:

$$G = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}|x_i - x_j|}{2n^2\bar{x}} \qquad 3.8$$

where x is an observed value, n is the number of values and $\bar{x}$ is the mean value.

The analysis is carried out through the Exploratory Modelling and Analysis Workbench (EMA-Workbench) (Kwakkel, 2017), an open source toolkit developed in the Python programming language.

3.7 Results

In what follows, we use the term policy to address a specific combination of interventions, comprising different locations and degree of (1) raising embankments, (2) making Room for the River and (3) changes to the discharge distribution. As explained in section 3.3.6, the analysis presented below relies on policies which, after the re-evaluation, are Pareto dominant in terms of total costs and expected annual damages.

First, results are shown based on decision objectives. In particular, policies' performances are assessed in terms of aggregated total costs, investment costs and final risk levels of the two countries (Figure 3.14) and final risk levels of each geographic area (Figure 3.15 and Figure 3.16). Second, policies are shown in terms of decision variables for each geographic area (Figure 3.7). Last, the Gini index and total costs for the two countries are compared (Figure 3.8).

Figure 3.14 shows total costs, investment costs and final risks of the two countries for each problem formulation. It is worth stressing that the *CBA* and *cCBA* are based on optimizing total costs only, thus a Pareto front can be clearly recognised. These problem formulations reach very low total costs, implying very low investment costs and aggregated final risks. Policies from *egalitarian* and *prioritarian* lead to higher total costs. Interestingly, *egalitarian* requires higher investment costs and results in larger final expected damage, whereas *prioritarian* only requires higher investment costs with expected damage levels being comparable to those reached by the formulations based on cost-benefit analysis.

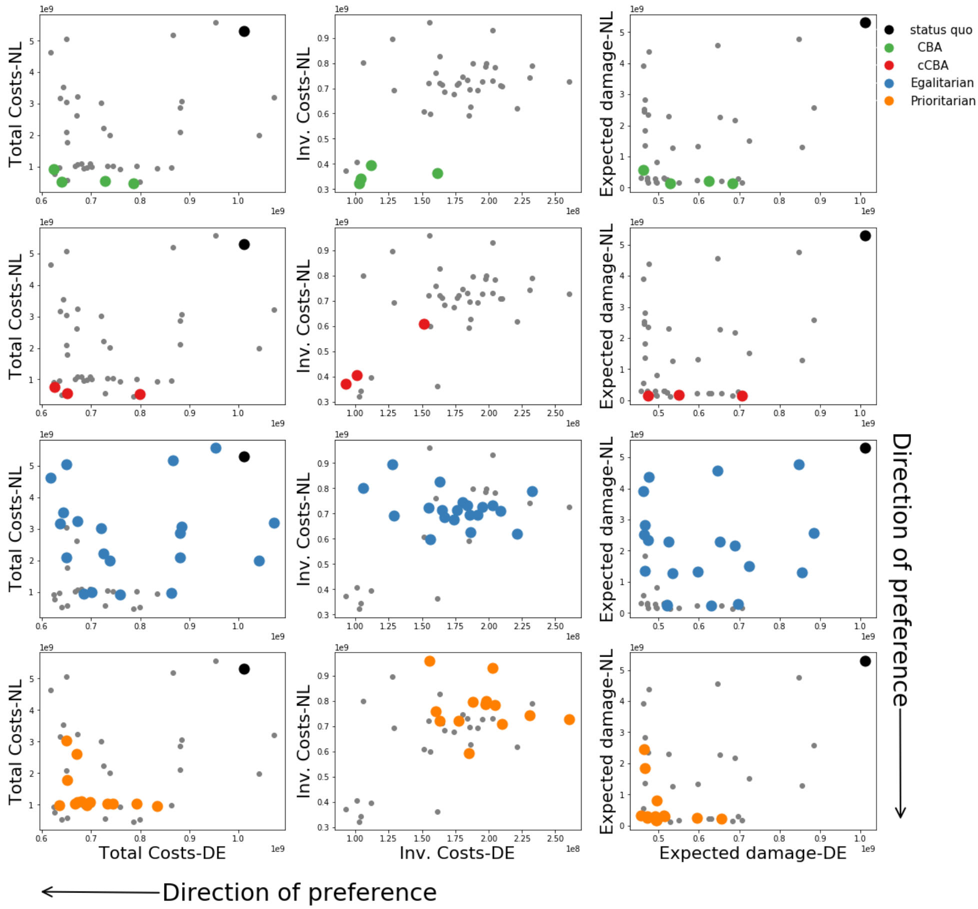

Figure 3.14 Total costs (left column), Investment costs (mid-column) and final risk (right column) of the Netherlands (y-axes) and Germany (x-axis) for all problem formulations ordered starting from the top row. In each box all policies are plotted (grey dots) and those belonging to the problem formulation of interest are highlighted. The black dot represents the status quo. The black arrows indicate the direction of preference, i.e. the lower total costs, the better, with an ideal policy having the lowest total costs in Germany and the Netherlands.

Finally, it is found that an improvement with respect to the status quo is reached by all problem formulations except for *egalitarian*, where some policies result in higher total costs than the status quo, because the investments are higher than the achieved aggregated risk reduction.

Figure 3.15 shows final risk levels both in absolute terms as well as normalized over the initial value. In the case of normalized risk levels, crossing the dotted horizontal line means a risk increase with respect to the initial level. The figure shows the results across geographical areas and for each problem formulation. Figure 3.16 shows complementary results, where absolute final risk levels are shown across problem formulations and for each area.

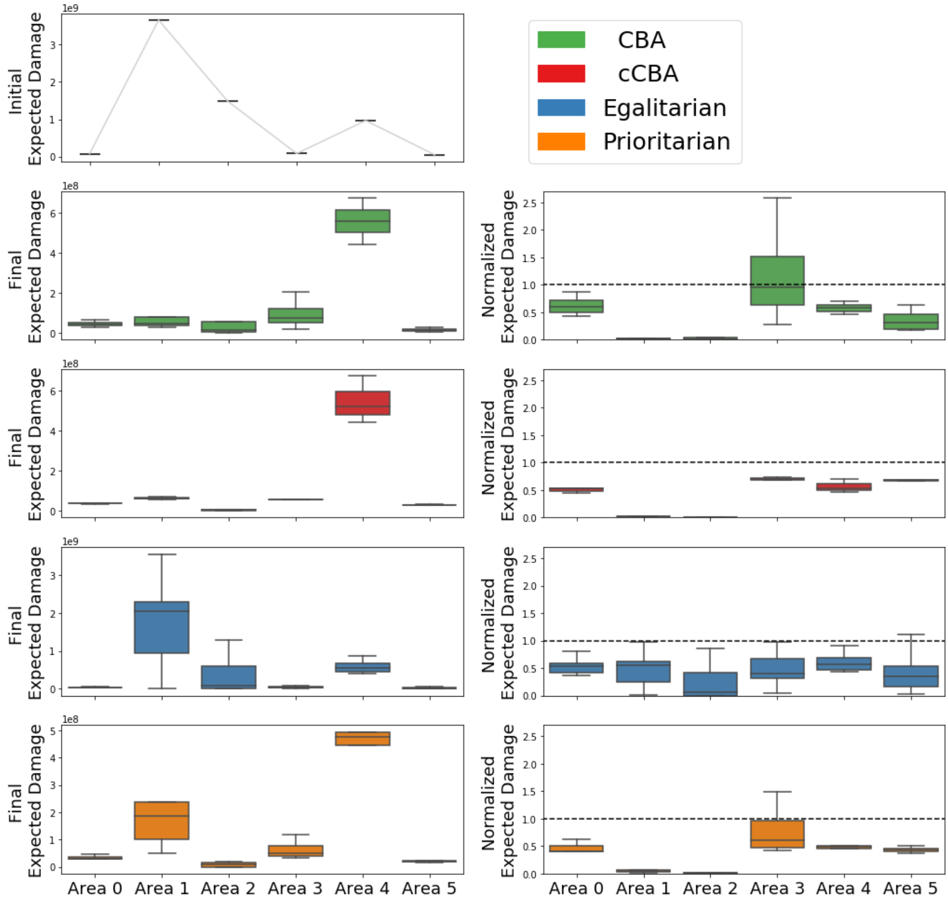

Figure 3.15 Left column: Initial risks (first row) and final risks for each problem formulation. Right column: Final risk normalized over initial risk values for each problem formulation. The dotted lines represent a value equal to one, i.e. the status quo. Each colour represents a problem formulation as indicated in the legend.

Interestingly, results on the left column of Figure 3.15 show that only *egalitarian* maintains the same ranking of risk levels across geographical areas with respect to the initial situation. This is in line with the definition of this formulation, where risk reduction is distributed equally across areas. In the other problem formulations, the area with the largest final risk is area 4, which is, however, the area with the third largest risk in the initial situation. Areas 1 and 2, which are those with the largest initial risk, have their risk decreased. This especially occurs in the *CBA* and *cCBA*, meaning that a unit of investment cost provided the largest risk reduction in these areas. *Prioritarian* is in line with these two formulations but provides less risk reduction to area 1. At the same time, however, as can be seen from Figure 3.16, *prioritarian* is the best performer of all formulations for area 4, which is the area where final risk is the largest.

The right column of Figure 3.15 shows a risk increase in area 3 for *CBA* in about 50% of the cases with respect to the status quo. This means that a risk reduction for the system as a whole is achieved at the expense of one area. This is a direct consequence of the aggregated cost efficiency nature of this formulation, which is known as the *aggregation worry* (Hayenhjelm, 2012). Related to this, *CBA* is also the worst performer in area 3 (see Figure 3.16). Although less frequently, also *prioritarian* can lead to risk increase in area 3. However, this only occurs after re-evaluating under the larger sample and, therefore, it is not due to the way the formulation is defined.

Formulation *cCBA* is the only one that always leads to an improved situation for all areas. This is in line with the definition of this formulation, which is still met after the re-evaluation under the larger sample. As can be seen from Figure 3.16, *cCBA* can however perform poorly for low risk areas like area 5. Finally, normalized risk levels of *egalitarian* suggest a comparable distribution of benefits among all areas, which, however, can lead to very poor performances in high risk areas, as can be seen from the performance in areas 1 and 2 in Figure 3.16.

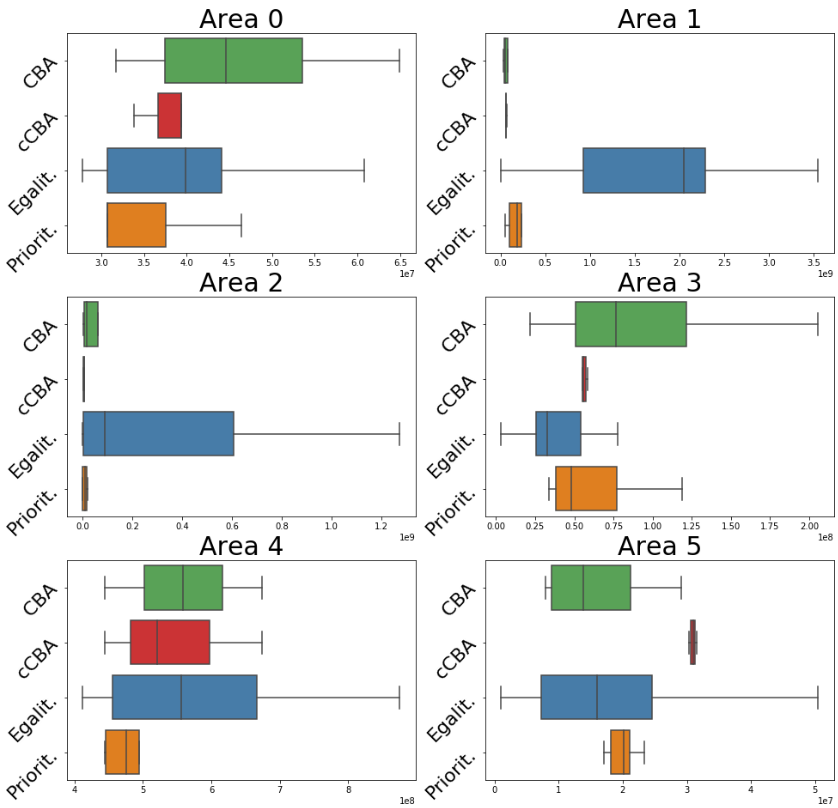

Figure 3.16 Boxplots of final risk levels across problem formulations for all geographical areas. Each colour represents a problem formulation as reported on the y-axis.

To sum up, *CBA* performs very well for high risk areas at the expense of one other area, where risk increases. The *cCBA* formulation brings a benefit to all areas but compared to the other formulations it can perform poorly for initially low risk areas. *Egalitarian* distributes risk reduction equally across all areas, and in so doing it performs poorly for all initially high-risk areas. *Prioritarian* performs similarly to *CBA* and *cCBA* in terms of allocation of risk reduction, but it is never the worst performer, as it is instead the case for both *CBA* and *cCBA*. In particular, if one focuses on final risk at area 4 under *prioritarian*, although this area has the highest final risk amongst all areas (Figure 3.15), it still has the lowest final risk when compared to what results from the other problem formulations (Figure 3.16).

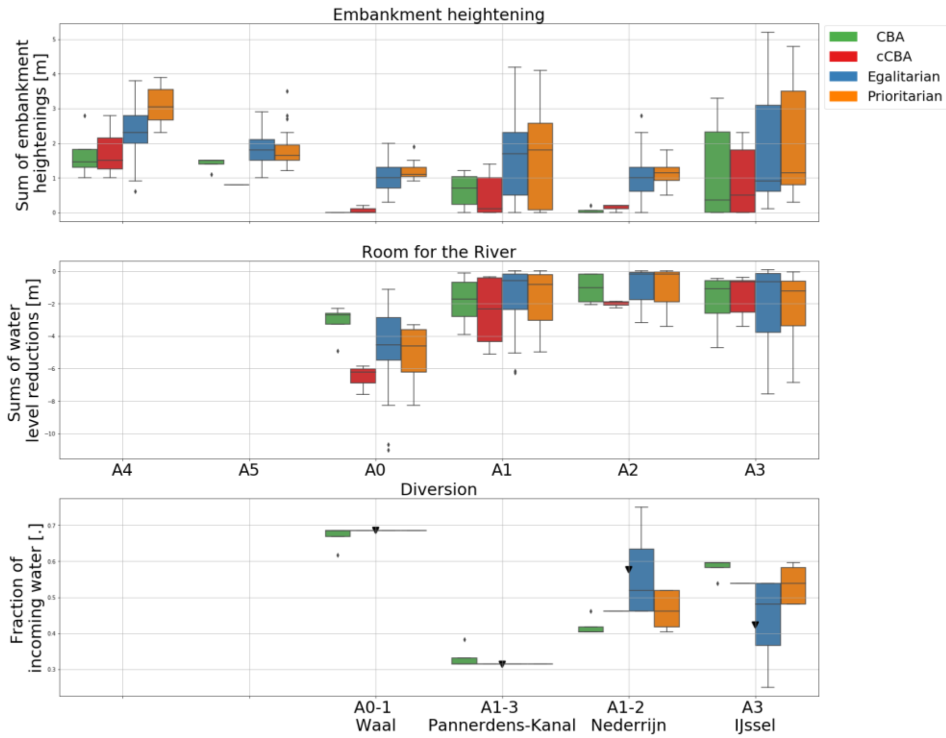

Figure 3.17 Boxplots of decision variables of the Pareto approximate sets where each colour represents a problem formulation as indicated in the legend. The first row shows levels of embankment heightening. The second row shows the degree of water level lowering obtained from making room for the river. In the first and second rows German areas are reported first. The third row shows the fraction of incoming water discharged to each branch: the Waal (affecting areas A0 and A1), the Pannerdens Canal (affecting areas A1, A2 and A3), the Nederrijn (affecting areas A1, A2) and the IJssel (affecting area A3). The default distribution (i.e. no policy change) is shown by the black triangle.

Figure 3.17 shows the identified optimal policies in terms of required interventions for all problem formulations. Changing the discharge distribution affects more than one area, therefore, in Figure 3.17, the name of the river branch is specified along with the affected areas. From top to bottom, rows show boxplots expressing the sum of the embankment heightening, the sum of the water level lowering due to making Room for the River and the fraction of the discharge diverted to each branch. It is worth stressing that, at the second bifurcation, similar distributions may imply quite different discharge into the branches, being a distribution defined as the fraction of incoming water, whose value of course depends on the discharge distribution at the first bifurcation. Finally, at each bifurcation point, decisions on the fraction of water sent to each branch are complementary, with their sum being always equal to one.

In terms of raising embankments, *egalitarian* and *prioritarian* lead to higher embankments everywhere. Interestingly, *cCBA* leads to lower German embankments in area 5 for the sake of protecting the downstream area 3 along the IJssel River. In terms of discharge distribution, *CBA* supports sending slightly less water to the Waal than what is currently done and, consequently, more into the other branches. All remaining problem formulations keep the current discharge distribution at the first bifurcation point. At the second bifurcation point, most of the water is sent to the IJssel, with the Nederrijn having its discharges substantially reduced. Yet, there are some differences across problem formulations.

Overall, *cCBA* is more conservative in terms of discharge distribution (i.e. closer to the status quo) than *CBA*. This reveals how important discharge distribution policies are in regulating risk levels across the system and in guaranteeing that none of the areas has its risk disproportionately increased. *Egalitarian* and *prioritarian* imply similar embankment heightening and Room for the River projects along areas 1 and 2. In *prioritarian*, however, the Nederrijn receives less water, resulting in an overall higher protection level than in *egalitarian* (as can be also seen in Figure 3.16).

Figure 3.18 shows the performance of the policies in terms of systems' total costs (i.e. sum of total costs in Germany and the Netherlands) and two different evaluations of the Gini index. The Gini index is evaluated in terms of expected damage and expected damage reduction. In this figure, only those policies which do not increase risk in any area are considered. Policies are shown in the 3D space and in the three 2D spaces, to highlight the Pareto front between each pair of decision criteria (i.e. plots *a, b, c*). An ideal policy would be found in the bottom-left corner of each of these plots. A trade-off between total cost (i.e. efficiency) and the Gini-index scores (i.e. equal distribution of benefits) emerges, in both evaluations of the Gini index (i.e. plots *a, b*).

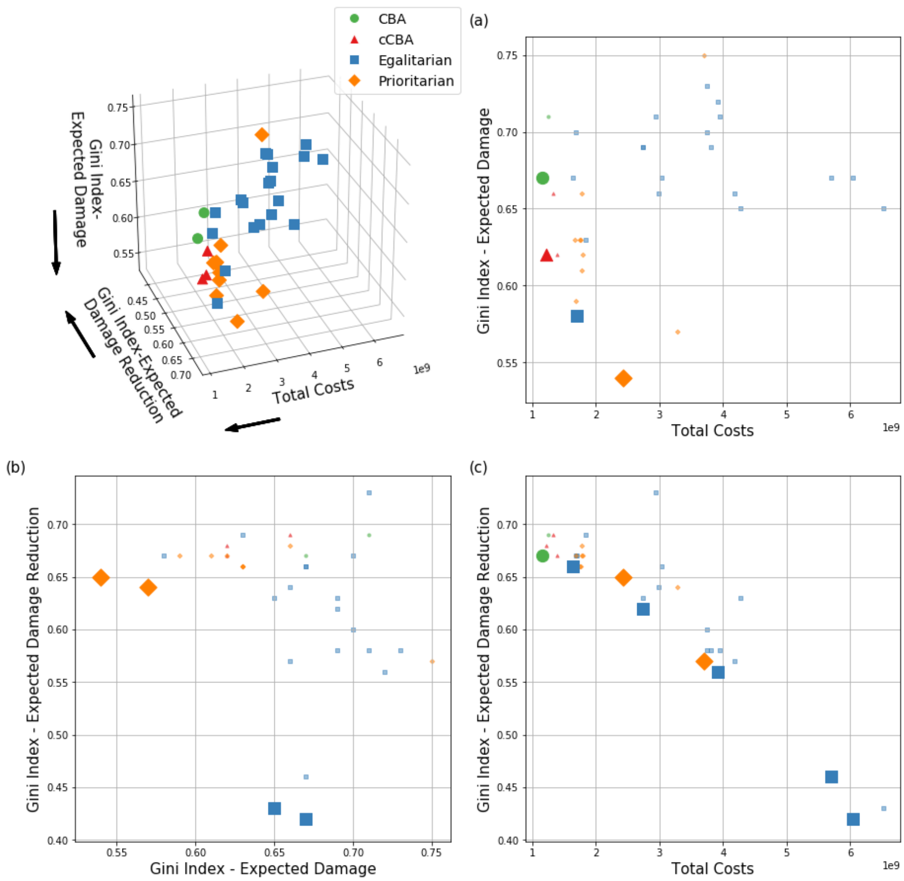

Figure 3.18 Performance of policies in terms of total costs, the Gini index for final levels of expected annuald damages and the Gini index for reduction in expected annual damage from the staus quo. The top-right panel shows performances in the 3D space and the direction of preference of each decision criterion, whereas the other panels show each a different 2D projection of the 3D panel.

The most efficient policy is obtained from *CBA*, and this is in line with the nature of the formulation. In plot *(a)*, a slight increase in terms of equity can be achieved with *cCBA* and the lowest Gini can be reached with *prioritarian*. The same results are found in plot *(b)*, where, however, higher equity (low

Gini) is reached by *egalitarian*. This is in accordance with the way expected damage distribution is conceptualised in the two formulations. In the case of *egalitarian*, expected damage is distributed regardless the initial levels of each area, thus trying to achieve the most equal distribution of expected damage reduction. In contrast, *prioritarian* prioritizes investments in higher initial expected damage areas, thus levelling the gap in terms of final levels of expected damages. This is also evident in plot *(c)*, where the two evaluations of the Gini index are compared. The best performers (low Gini) in terms of expected damage reduction belong to *egalitarian*, while *prioritarian* leads to lower Gini when expected damages are considered.

3.8 Discussion and conclusions

In the present study we propose a new decision criterion to properly account for the distribution of benefits of a given policy across geographical areas. The criterion is used to explore the policy implications of adopting alternative ethical principles in supporting flood risk management decisions. The area of application is the Lower Rhine River.

Four ethical principles are considered, each leading to a different problem formulation. The first and second problem formulations (*CBA* and *cCBA*, respectively) are based on minimizing total costs, the difference being that in *cCBA* no risk increase with respect to the status quo is allowed in any area. In the third problem formulation (*egalitarian*) risk reduction is distributed equally among areas. The fourth problem formulation *(prioritarian*) distributes risk by prioritizing areas with larger risk.

Because of the aggregation of costs and benefits, *CBA* leads to the so-called *aggregation worry*, i.e. it performs well for some areas at the expense of other areas where risk increases. Although *cCBA* overcomes this, it leads to an unbalanced risk distribution by favouring some areas at the cost of others. *Egalitarian* increases the equity of the implemented policies; however, it performs very poorly for high risk areas and, in general, it costs more and yet results in larger aggregated risk. *Prioritarian* reduces expected damages following the same allocation pattern as *CBA* and *cCBA*. It never performs as the worst formulation and it achieves the highest risk reduction in the area that is worst off compared to the other formulations. In other words, it seems to be economically efficient while limiting unbalances in benefit distribution between areas. This latter point is achieved by investing more in comparison to *CBA* and *cCBA* but at the same spending money more wisely (from an economic viewpoint) than *egalitarian*.

Although presented in the context of flood risk management, the proposed approach is general. It improves model-based decision support by enabling to account for risk distribution. The approach reveals otherwise hidden trade-offs between risk reduction and risk distribution objectives, thus broadening the spectrum of policy objectives most cost-benefit analyses rely on. Furthermore, as it is found that the choice of *what* ought to be distributed matters, the proposed approach allows taking into account the effects of alternative distributional choices on the performance of policies and, as such, it enables policy makers to operationalize alternative ethical principles and to elicit their preferences in balancing efficiency in risk reduction and equity in risk distribution.

Finally, the proposed framework relies on a decision criterion that is defined based on area-wide performances – i.e. on changes in overall risk of flood protected areas. As these areas can generally be very large and diverse in terms of internal socio-economic conditions, future research may focus on advancing the presented approach by adopting a finer resolution. On the one hand, this will increase the complexity of the analysis as it will require dealing with a larger number of interested parties and, therefore, of decision objectives to optimize. On the other hand, it will allow accounting for risk shifts while also taking into account the socio-economic peculiarities of the various communities living within a given area and, therefore, differentiating between wealthy and deprived communities.

4 A Robust Decision Making approach to the identification of flood protection measures under deep uncertainty.

Abstract

Flood risk management recently and urgently calls for a system perspective, which requires dealing with hydraulic interactions, i.e. the effects of levee breaching at one location on the hydraulic loads elsewhere along the river. Considering hydraulic interactions requires knowledge of levees probability of failure as a function of hydraulic loads, commonly represented through fragility curves. Fragility curves are computed through reliability analysis which, however, focuses on a limited number of failure mechanisms, and depends on extensive geotechnical knowledge, which may not be available or accurate. Thus, conducting risk analysis based on such curves may lead to implementing measures which are inadequate to deal with uncertainties in levee breaching. An alternative method to reliability analysis, Robust Decision Making (RDM), does not require to specify fragility curves and it allows identifying robust measures, which i.e. perform well under a wide range of plausible responses of the levee system. RDM, however, in that it does not require to specify fragility curves, may neglect useful information as e.g. the fact that levee breaching probabilities reasonably increase for increasing water levels. By building on RDM, we propose a method which makes use of fragility curves but dispenses with specifying them upfront. In this way, the method first identifies robust measures in view of levee breaching uncertainties and only after assesses how alternative hypotheses of fragility curves affect the robustness of the identified measures. We demonstrate it along the Po River aiming at identifying the preferred measures between levee raising and levee strengthening.

4.1 Introduction

Recent studies in flood risk management urge the adoption of a system perspective, which requires accounting for hydraulic interactions involving rivers, levees, and protected floodplains (Vorogushyn et al., 2017). Accounting for hydraulic interactions leads to more realistic flood frequency analysis (Apel et al., 2009) and more accurate individual and economic risk figures (Courage et al., 2013; De Bruijn et al., 2016), acknowledges increases in downstream hydraulic loads due to upstream measures (Vorogushyn et al., 2012), and ultimately widens the spectrum of flood risk management alternatives, potentially increasing optimality in the design of the system (Ciullo et al., 2019).

Accounting for hydraulic interactions requires assessing measures considering the behavior of the entire flood risk system. When dealing with embanked systems, this requires a thorough modeling of the levees failure mechanisms by performing a reliability analysis (Bachmann et al., 2013). The outputs of a reliability analysis are the so-called fragility curves, i.e. curves quantifying the probability of levees failure as a function of hydraulic loads (e.g. water level, flow velocity, flood duration, etc.). Fragility curves are used to simulate failure mechanisms such as overtopping (Apel et al., 2006; Mazzoleni et al., 2017), piping and macro-instability (Vorogushyn et al., 2009; Mazzoleni et al. 2014; Curran et al., 2018). Generating fragility curves is not a trivial task as it requires extensive knowledge of the geotechnical properties and behavior of the levee which, especially in case of large-scale systems, may not be available or accurate at all locations of interest.

Even assuming perfect knowledge of the levee system, and thus assuming that a reliable probabilistic assessment of levees failure from overtopping, piping or macro-instability is possible, unexpected breaching can still occur. In January 2014, for example, a levee failure occurred during a minor flood event along the Secchia River, Italy, causing about 500 million dollars damage (Orlandini et al., 2015). The breach was not due to any of the aforementioned known failure mechanisms (D'Alpos et al., 2014). Levee stability was instead compromised by animal burrows (Orlandini et al., 2015; D'Alpos et al., 2014), the presence of which was not foreseen. Only the occurrence of this event could trigger extra monitoring activities that led to the identification of a nearby levee stretch close to collapse due to the same cause and thus prevented an additional failure. It is however paramount to not only rely on the effectiveness of emergency responses but, instead, to also account for the possibility of unexpected failures in the planning phase of flood risk management measures.

In the context of planning under uncertainty, alternatives to reliability analysis are available which are better suited to accomplish the goal of dealing with unexpected system responses (Shortridge et al., 2017), one of which is Robust Decision Making (RDM) (Lempert et al., 2006). RDM allows the identification of *robust* measures, i.e. measures which perform adequately given a wide range of plausible behaviors of the system, e.g. levee response to hydraulic loading, thus reducing undesired impacts from unexpected events like the one of January 2014. Unlike reliability analysis, RDM does not rely on a probabilistic representation of uncertainty and robustness of measures is assessed regardless the likelihood of the considered plausible behaviors of the system, e.g. levee response to hydraulic loading. In the context of flood risk management planning, however, this latter aspect may be problematic as, in fact, although levee failure probabilities may be unknown or hard to quantify, one can still be able to assess what hydraulic loads (e.g. values of water levels) are more or less likely to cause levee failure. This information needs to be accounted for in a decision support framework for flood risk management planning. Recent studies address the problem of integrating probabilistic information into the RDM framework using Bayesian statistical models (Shortridge and Zaitchik, 2018) or Bayesian Networks (Taner et al., 2019). In the present work, we propose the use of a statistical technique known as Importance Sampling (Diermanse et al., 2014).

By combining RDM with Importance Sampling, we propose a method that brings together the benefits of both reliability analysis and RDM as it allows (1) to identify measures that reduce the impact of unexpected breaching and, (2) still make use of probabilistic information to choose the measure that performs better under alternative assumptions about levees response to hydraulic loading, i.e. under alternative fragility curves. In particular, as in standard RDM, the proposed method allows to identify robust flood protection measures and, after that, to assess how well these measures perform had the analysis been carried out under alternative hypothesis of the fragility curves. In so doing, the risk analysis is not constrained *a priori* based on a single specification of the fragility curve, but it rather relies on an *a posteriori* approach, which allows exploring uncertainty in the definition of fragility curves.

We apply the proposed method to the Lower Po River, Italy, focusing on two alternative structural measures: levee heightening and levee strengthening. The study is structured as follows: section 4.2 describes the method, section 4.3 describes the case study, the simulation model and the analysis, section 4.4 presents the results of the case study and discusses them, section 4.5 provides conclusions.

4.2 Method

The proposed method builds on the Robust Decision Making (RDM) framework proposed by Lempert et al. (2006). RDM proves to be useful when the input factors are deeply uncertain, i.e. *when experts do not know or cannot agree on the probability distribution of these factors* (Lempert, 2002). In such a context, RDM enables one to identify robust measures against uncertain input factors without requiring an *a priori* specification of the probability distribution of such factors. For example, in the context of flood risk management, an RDM analysis would identify instances in which the system under study undergoes high damages and plan measures that limit all such instances from occurring, regardless their likelihood of occurrence. In many cases, however, although a thorough characterization of probabilities cannot be established, one may still be capable to assess whether some values of the input factors (e.g. breaching water levels) are more or less likely than others to lead to a certain outcome (e.g. high damage). Neglecting this information is a limitation of standard RDM which has been tackled in the literature by e.g. applying Bayesian statistical models (Shortridge and Zaitchik, 2018) or Bayesian Networks (Taner et al., 2019). We address this problem by using Importance Sampling (Diermanse et al., 2014), and propose the procedure schematized in Figure 4.1, which can be briefly summarized in the following steps:

1. *Problem framing*: charachterize the system under study, the policy objectives and the policy measures.
2. *Quasi-Monte Carlo analysis*: generate model outputs by homogeneosuly exploring the input space and testing every combination of input factors.
3. *Scenario Discovery*: identify what combinations of input factors lead to (undesirable) model outcomes and propose measures which limit their occurrence. Carry out quasi-Monte Carlo analyses again (step 2) to assess the performance of the new measures.
4. *Assess robustness*: Quantify the robusness of the proposed measures as the regret of implementing that measures, i.e. how bad they perform compared to the best performing measure for each combination of input factors.
5. *Explore alternative probability density functions*: Apply the Importance Sampling weightening relative to alternative distributions of the input factors and explore how they affect the robustness of measures.

Each step is explained in more details in the following sections. The last section draws a comparison between the standard and the proposed frameworks to support flood risk management planning of embanked flood risk systems.

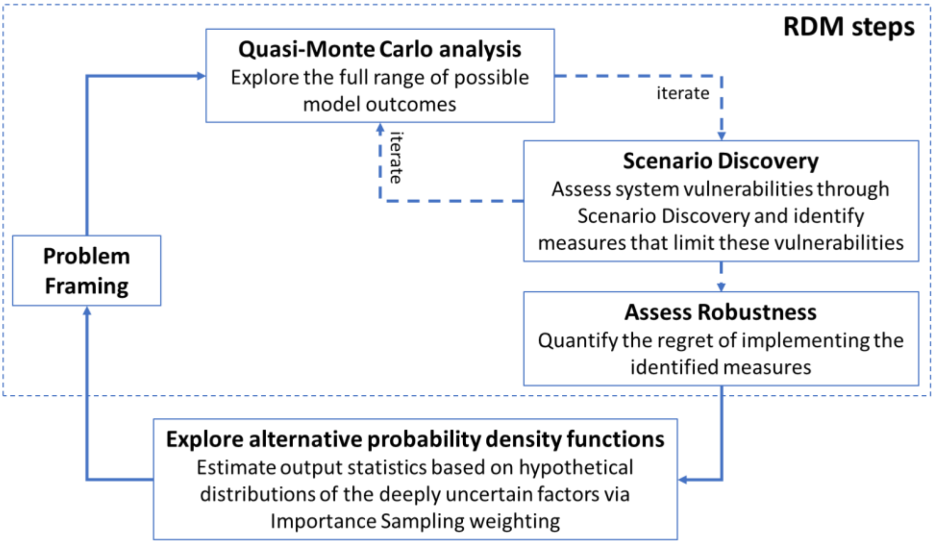

Figure 4.1 *Step-by-step representation of the proposed Robust Decision Making approach to flood risk management.*

4.2.1 Problem framing

This step requires formulating the policy problem, specifying its scope, decision objectives and possible measures. For example, in a context such as the one of this thesis, it requires specifying what flood-protected areas are of interest, the type of available measures (e.g. levee heightening) and the outcomes of the analysis (e.g. damage, casualties etc.).

4.2.2 Quasi-Monte Carlo analysis

The quasi-Monte Carlo analysis generates a database of model outcomes which is investigated further through a procedure known as Scenario Discovery (Bryant and Lempert, 2010). A quasi-Monte Carlo analysis requires the use of a sampling strategy that maximizes the coverage of the input space such as Latin Hypercube or low-discrepancy sequences like the Sobol sequence (Sobol, 1967). Compared to pseudorandom sequences, these sampling techniques have the property of more evenly distributing the sampled points over the domain of the input factors. In so doing, provided that a sufficiently high number of simulations is carried out, the model is evaluated across every combination of input factors and the full range of possible model outcomes is thus explored.

4.2.3 Scenario discovery

Scenario Discovery is used to map model outputs generated with the quasi-Monte Carlo analysis to input factors and their value range. In other words, after identifying cases of interest in the model outcome space, Scenario Discovery allows identifying what combinations of input factors lead to those cases.

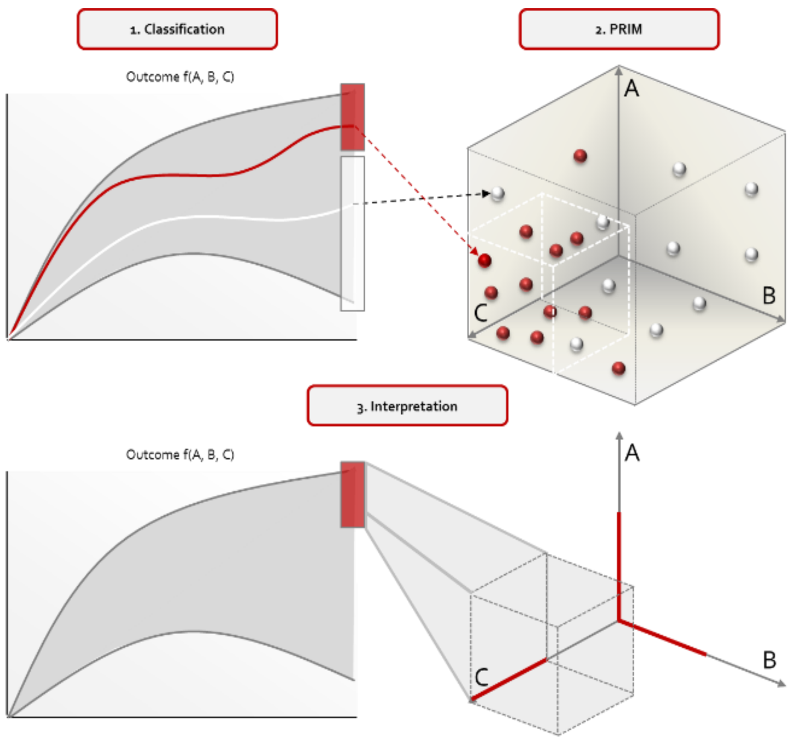

Figure 4.2 *Steps in Scenario Discovery using the Patient Rule Induction Method (PRIM), from Greeven et al. (2016).*

Typically, after identifying undesirable performances of the system under study, Scenario Discovery is used to identify what values of input factors lead to these undesirable performances and, based on that, allows defining management measures. It requires three steps (Bryant and Lempert, 2010): output classification, factor mapping (PRIM) and interpretation. The three steps are described below and schematized in Greeven et al. (2016).

Classification

The output variable is transformed into a binary variable indicating undesirable outcomes, e.g. those above a certain threshold. For example, assuming the output is composed by flood damage values, these will be transformed into a binary vector where e.g. undesirable events are given by those values exceeding a certain damage threshold (i.e., range of red dots in Figure 4.2), and desirable ones by those not exceeding it (i.e., white dots).

The Patient Rule Induction Method (PRIM)

After identifying undesirable outcomes, statistical algorithms are used to identify values of uncertain model input factors (e.g., variables A, B and C in Figure 4.2) leading to such outcomes. One of the most widely used algorithm for this is the Patient Rule Induction Method (PRIM) algorithm (Friedman and Fisher, 1999).

PRIM identifies a series of multi-dimensional boxes, i.e. subspaces in the input factors space, each explaining some of the undesirable outcomes. Two indicators are used to describe the characteristics of each box: coverage and density. Coverage represents the fraction of undesirable outcomes inside a given box over the total number of undesirable outcomes. Density represents the fraction of undesirable outcomes with respect to the total number outcomes (desirable and undesirable) inside the box. Ideally, a box has high coverage and density.

As an example, Figure 4.3 shows a plausible PRIM result of a box such as the one identified in Figure 4.2, assuming that the outcome *f(A,B,C)* is flood damage and factors *A, B* and *C* are high water levels at two different locations along an hypothetical river and peak discharges, respectively. Let's assume also that undesirable outcomes are high flood damages. For each identified input factor, PRIM reports the full range of possible values (grey area) and indicates what subrange of values (thick blue line) is responsible of producing high flood damages. In the proposed example, peak discharges from 14.000 m^3/s to 17.000 m^3/s, breaching water levels below 25.3 m a.s.l. and below 25.4 m a.s.l. are identified. Based on that, one may e.g. either decide to build flood retention areas to reduce flood peaks within the identified range or strengthen levees at the two identified locations.

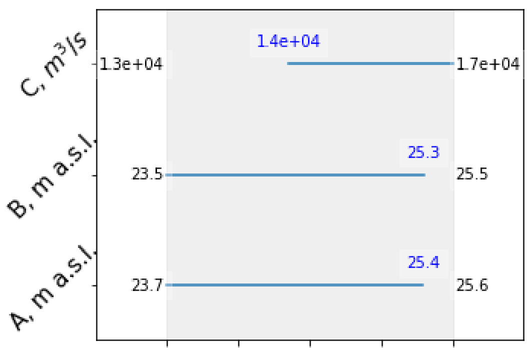

Figure 4.3 *Example of a box identified by PRIM. For each factor, the grey area shows the full range of possible values and the thick blue horizontal line shows the range of values which leads to the outcome values of interest.*

Interpretation

It is important to assess the significance of the identified input variables and their value ranges. Two diagnostic tools have been proposed by Bryant and Lempert (2010): resampling tests and quasi-p values. Resampling tests consists of re-running the PRIM algorithm under bootstrapped samples of the input factors assessing how frequently a given factor is selected by PRIM in describing the density and coverage of the box under investigation. Quasi-p values estimate the likelihood that the box identified by PRIM constrains a parameter by chance. Thus, the lower the quasi-p values, the more the analyst is confident that a given parameter has not been constrained by chance. Finally, in addition to resampling tests and quasi-p values, it is crucial that the series of identified boxes are critically interpreted by evaluating their actual meaning and possible relevance to the system being studied.

4.2.4 Assess robustness

In order to evaluate the robustness of the measures identified through Scenario Discovery, new quasi-Monte Carlo analyses are carried out, each for every identified measure. Robustness is calculated as the regret of adopting a given measure. In particular, assuming that the performance metric P (e.g. costs, flood damage, etc.) must be minimized (i.e. the lower, the better), then regret R can be defined as follows:

$$R_{i,m} = P_{i,m} - \min_{m \in M} P_{i,m} \qquad \forall i \in I, m \in M \qquad 4.1$$

where I is the set of all combinations of input factors and M the set of measures. Essentially, for each generated outcome, *the regret R of a given measure is defined as the difference between the actual performance of that measure and the best performance registered, across measures, for that quasi-Monte Carlo run*. Thus, if the regret of a given measure is always zero, it means that it is the best performing measure under all possible combinations of the uncertain input factors. Obviously, the lower the regret of adopting a measure, the more robust it is.

4.2.5 Explore alternative probability density functions

When dealing with deep uncertainties, there is disagreement among experts about the probability distribution of these uncertainties. It is thus paramount to fully acknowledge such disagreement and explore how the performance of measures changes based on alternative hypotheses about the probability distribution of deeply uncertain factors (e.g. breaching water levels). In order to address this very issue without resorting to additional quasi-Monte Carlo analyses, we apply Importance Sampling.

Typically, Importance Sampling is used to increase the efficiency of Monte Carlo analysis. For example, if trying to assess the probability of very unlikely events through Monte Carlo integration, reaching convergence could require an unfeasible number of simulations. Importance Sampling consists in replacing the original sampling distribution with an alternative one such that the probability of sampling events of interest increases, thus reducing the number of simulations required to reach convergence. The probability of occurrence as if the original probability distribution were used can then be assessed through reweighting. More formally, assuming a simulation model having a set of input variables **x**, with a multivariate distribution function *F,* and output variable *y*; then **x** can be sampled using an alternative distribution *H,* with the probability of *y* exceeding the value y^* being defined as (Diermanse et al., 2014):

$$P[y > y^*] = \frac{1}{n} \sum_{i=1}^{n} 1_{[y_i > y^*]} \, c_i \qquad 4.2$$

where *n* is the number of simulations, $1_{[...]}$ is an indicator function which is equal to 1 if $y_i > y^*$ and 0 otherwise and c_i is the correction factor (weight) for Importance Sampling, which is defined as follows:

$$c_i = \frac{f(x_i)}{h(x_i)} \qquad 4.3$$

with *f* and *h* being the density functions of *F* and *H*, respectively.

In the context of the proposed method, however, the aim is *not* to increase the efficiency of the Monte Carlo analysis, where the actual distribution is known. Importance sampling is used here to explore *hypotheses* about the unknown actual distribution instead. First, an importance sampling distribution *h* is used to simulate all events that can plausibly happen, assuming them as equally probable, i.e. using a uniform distribution *h*. Then, statistics of the output variables are calculated had the analysis been performed with a different distribution f (e.g. a given hypothesis of the deeply uncertain factors distribution) thus exploring the *belief* experts and policy makers have about the functioning of the system.

As statistics of the output variables, Frequency-Regret (FR) curves are introduced. Similar to Frequency-Number of fatalities (FN) curves, which are widely applied in flood risk analysis to assess the exceedance probability of the number of fatalities (see e.g Jonkman et al., 2011; De Bruijn et al., 2014), FR curves allow assessing the probability of regretting the adoption of a given measure. Furthermore, an acceptance criterion similar to the one applied for FN curves (Jonkman et al., 2003) can be defined as C/r^{α}, where r stays for regret levels and C and α are parameters reflecting the level of potential regret one is willing to tolerate. As an example, Figure 4.4 shows three FR curves showing cases in which the tolerable level is exceeded (i.e. higher FR curve), just met (i.e. FR curve tangent to the tolerable level) and fully satisfied (i.e. lower FR line). A plot such as the one in Figure 4.4 can either show performances of three different measures or the performance of the same measure under three different hypothesis of the deeply uncertain factors distribution.

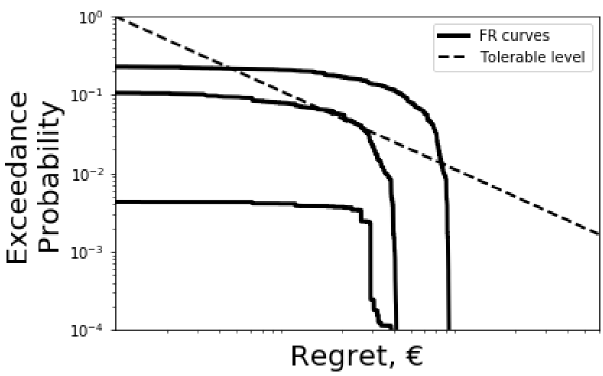

Figure 4.4 *Example of three Frequency-Regret (FR) curves for which the tolerable level is (1) exceeded (i.e. higher FR curve), (2) just met (i.e. FR curve tangent to the tolerable level) and (3) fully satisfied (i.e. lower FR line).*

4.2.6 Comparison between the standard and the proposed frameworks to support flood risk management decisions

Finally, the proposed procedure differs substantially from the standard approach adopted in flood risk management decision support. Figure 4.5 describes the main steps followed by (a) a standard probabilistic analysis used to rank flood risk reduction measures, and (b) the one proposed in this study. Typically, an arbitrary set of measures is ranked based on expected performances evaluated following assumptions about the response of the levee system due to hydraulic loading (e.g. through the definition of fragility curves) made upfront. Instead, in the proposed approach, measures are first identified as those reducing high flood damages, then, the regret of adopting these measures is assessed and, finally, measures are ranked according to alternative hypotheses about the uncertainty on the stability of the levee system.

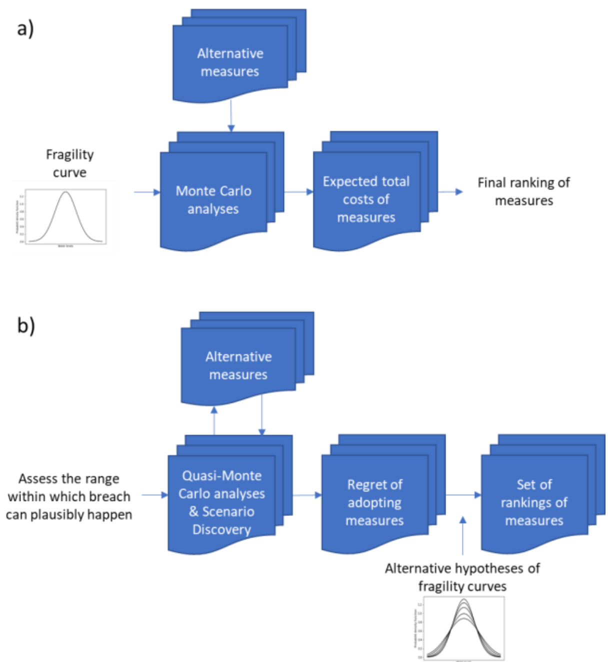

Figure 4.5 *Decision support frameworks in flood risk management: a) Typical framework, b) Proposed framework.*

4.3 Application to the Lower Po River

The proposed method is applied to find structural flood risk reduction measures on the lower reach of the Po River, in Northern Italy (see Figure 4.6), between the gauges of Borgoforte and Pontelagoscuro (with a total length of about 115 kilometers). We focus on a flood-protected areas (purple areas in Figure 4.6) for which the levee system is designed to withstand a 200-year flood, and where thus flooding is expected for the 500-year flood. The aim is to reduce flood damage in the flood-protected areas by heightening or strengthening the levees. This section first introduces the simulation model (section 4.3.1) and then provides details on how the proposed method is applied to identify robust flood protection measures for the case study (section 4.3.2).

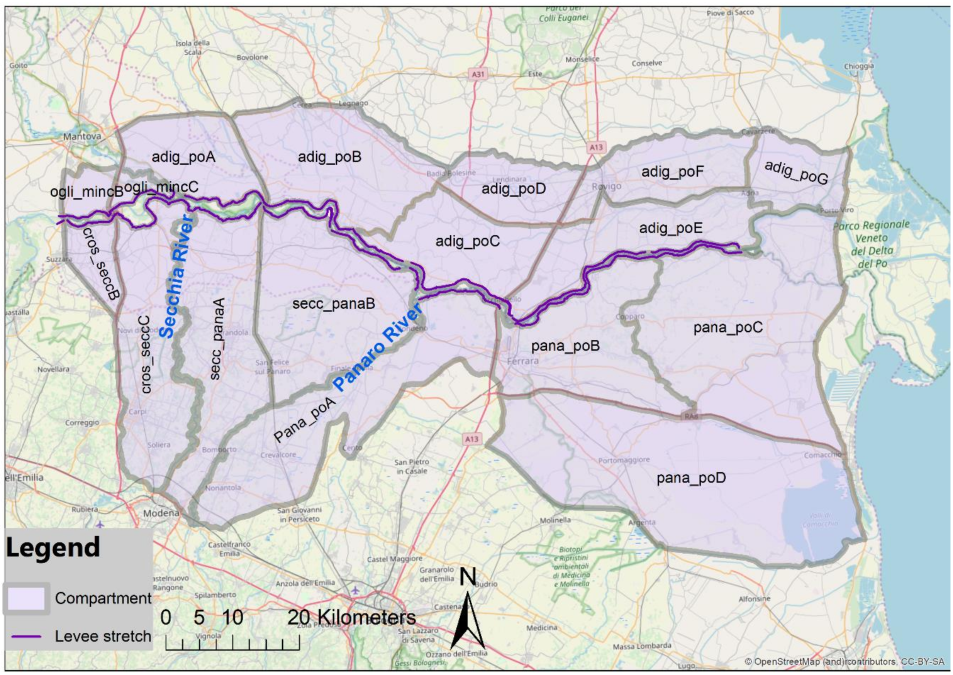

Figure 4.6 *Representation of the case study area. The thick grey lines delimit the dike-protected areas (i.e. compartments) and the purple lines depict the dike stretches where structural measures can be implemented.*

4.3.1 The simulation model

The modeling framework involves three main steps: (1) the generation of hydrological events along the Po River and its main tributaries Secchia and Panaro, (2) the propagation of the generated events using a hydrodynamic model, (3) the assessment of economic damage. In the following subsections, we briefly introduce the modeling steps.

Generation of hydrological events

We focus on the generation of alternative 500-year return period events (i.e. events that are expected to cause flooding in the compartments) at the upstream Po river cross-section of Borgoforte. A Gaussian copula is then used to explain the dependence between the generated events along the Po River and those of its main tributaries Secchia and Panaro.

Events along the Po River at Borgoforte are generated based on the Flow-Duration-Frequency (FDF) curve derived by Maione et al., (2003) as well as the 48 historical flood hydrographs of the Po at Borgoforte reported in Tanda et al. (2001). All generated events must comply with the FDF reduction curve, as it establishes a decreasing relationship for the 500-year event at Borgoforte between the flood wave duration D and the maximum average discharge Q_D. This latter represents the discharge value of a rectangular flood wave of base D whose volume equals the maximum volume of the actual flood wave evaluated across all possible time windows of width D. The historical hydrographs, instead, are clustered in order to establish a relationship between flood wave duration D and flood wave shapes.

The aim is to generate 500-year events of decreasing peak flow for increasing duration and vice-versa such that the FDF curve is always met. The procedure is summarized in three steps. First, a duration D is sampled between 24 and 192 hours (duration range of historical events), then, the corresponding Q_D on the proposed FDF curve is found and, finally, a flood wave shape is assigned based on the clustered historical hydrographs.

Figure 4.7 shows results of 100 generated events. The left panel of Figure 4.7 shows the distribution of the peak discharge of the simulated events and *the* 500-year peak discharge (Q500) normally considered for the Po River; the center panel shows the generated events having a decreasing flood peak with increasing duration; and the right panel shows the relationship proposed by Maione et al. (2003), which is met by all generated events.

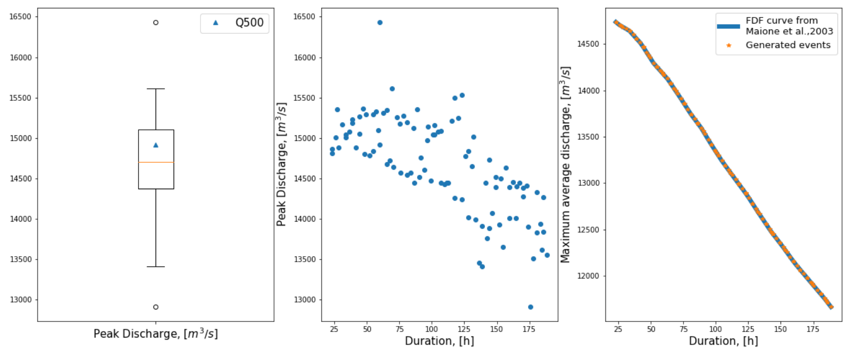

Figure 4.7 *Characteristics of 100 generated events for the Po river at Borgoforte: peak discharge distribution compared with the 500-year (Q500) event typically considered by the Po River Basin Authority (left); decreasing relationship between peak discharge values and flood wave durations (center); maximum average discharge and duration for all generated events compared with the relationship proposed by Maione et al. (2003).*

The correlation between events of the Po River and those of the tributaries is modelled using data available on the Hypeweb platform of the Swedish Meteorological and Hydrological Institute (SMHI). These data consist of 29 years of simulated daily mean discharge for the three rivers and are used to generate a Gaussian copula between volumes and discharges of the Po, Secchia and Panaro rivers. After generating the 500-year event of the Po River as described above, events of the tributaries are found by conditional sampling of the Gaussian copula.

Hydrodynamic Model

Flood hazard is simulated with a quasi-2D model implemented through the HEC-RAS software (Domeneghetti et al., 2015). In the model, the main river is represented through cross-sections retrieved from a LiDAR digital elevation model with a 2 meters spatial resolution. The levee-protected floodplain is subdivided into 17 compartments, which are modelled as storage areas connected to each other and/or to the main channel by means of lateral structures or connections that reproduce existing levees. The hydrostatic behavior of each storage area is represented through volume-level curves, therefore, in case of flooding, water levels can be estimated from the water volumes exchanged with the main channel and/or adjacent storage areas. These curves are built using a 10 meters resolution DEM available for all Italy (TINITALY, see Tarquini et al., 2012) of the compartment.

Economic impact assessment

For practical reasons, we only focus on economic damage to residential buildings. To do so, we use the Hypsometric Vulnerability Curves approach proposed by Domeneghetti et al. (2015) and the damage function developed by Carisi et al. (2018).

Typically, the hypsometric curve of an area provides the percentage of the total area below a certain elevation. The Hypsometric Vulnerability Curve combines this information with the land-use of the area thus providing the percentage of a land use class below a given elevation. Therefore, if combined with damage functions, the hypsometric vulnerability curve is a useful simplified graphical tool to quantify aggregated flood damage of large areas.

We calculate Hypsometric Vulnerability Curve relative to urban areas in all compartments. To do so, we use data of residential buildings available from the geodata web-platforms of the three Italian regions in the case study i.e. Emilia-Romagna, Lombardia and Veneto. Data about asset values of buildings are retrieved from the Italian Revenue Agency (in Italian, *Agenzia delle Entrate*, AE). Asset data are provided in terms of euros per square meter (€/m^2) for different types of buildings and all Italian municipalities every six months. We define an asset value per compartment as the weighted average of all asset values where weights are given by the extent of urban area of the municipalities in that compartment.

As depth-damage curve, we use the square root regression model (i.e. $y = \beta \cdot \sqrt{x}$) developed by Carisi et al. (2018) using empirical loss data of the Secchia River 2014 flood. We account for the uncertainty in the proposed relation by using alternative regression models generated from the distribution of the fitting parameter.

4.3.2 Description of the analysis

The analysis aims at (1) assessing flood damage in the current system corresponding with 500-year flood events, (2) identifying the most influential uncertain factors, (3) proposing measures, (4) assessing their robustness and (5) evaluating the effect on robustness of alternative hypotheses about levees fragility curves. To do so, we follow the method introduced in section 4.2 and illustrated in Figure 4.1.

Problem framing

The outcomes of interest are flood damages from the 500-year events at each compartment and for the system as a whole (i.e. sum of damage for each compartment).

We identify 52 levee stretches in the case study area. Structural measures differ from stretch to stretch and relate to levee raising or strengthening. The Interregional Agency for the Po River (AIPO) provided us with approximate estimations of investment costs related to these two types of structural measures. Levee raising, assumed to take place using in-situ material, was estimated to cost between 80 to 100 €/m^2 (i.e. 80 to 100 € to raise the levee crest by one meter for a one-meter long levee). Levee strengthening is assumed to be much more expensive. Cost estimates range between 2000-4000 €/m (i.e. strengthening of a one-meter long levee) depending on the complexity of the structural measure and the levee geometry. It is assumed that, after strengthening, only overtopping without breaching can cause flooding.

Finally, it is worth mentioning estimates of investment costs are based on expert knowledge and are therefore uncertain. Changes in these estimates will indeed change results. The proposed methodology, however, is valid regardless the costs estimate used in the analysis.

Quasi-Monte Carlo analysis

The analysis considers several sources of uncertainty, including:

- the flood hydrograph for the upstream river cross-section in terms of: *duration*, *shape*, *peak* and *volume*;
- the flood hydrograph for the two main tributaries in terms of *peak* and *volume*;
- water levels triggering the breach formation at each of the 52 levee stretches;
- the flood damage model;

for a total of 60 input uncertain factors. Water levels triggering breaching are treated as deeply uncertain factors, i.e. they are assumed to be uniformly distributed between the level of the levee crest and the lowest level at which a breach can physically be triggered. This latter is established, for each levee, as the highest point between the floodplain's height and the height of the levee-protected area. This guarantees the necessary hydraulic gradient for a breach to plausibly develop. In the case study, this is estimated to be approximately 2 meters below the *initial* crest level for all levee stretches. It is worth stressing that we are not ultimately interested in understanding *how* breaching occurs (e.g. due to overtopping, macro-instability or piping). Rather, the aim is to explore *what happens if* failure occurs at a given water level.

The impact of uncertainties on the estimation of flood damage is analyzed with a quasi-Monte Carlo analysis, where 4500 runs are carried out using a Sobol sampling sequence (Sobol, 1967). A quasi-Monte Carlo analysis is carried out for the status quo as well as for all structural measures identified through Scenario Discovery.

Scenario Discovery

Scenario Discovery is used to identify cases where flood damage in each compartment is higher than the 3rd quartile. As we focus on structural measures, and as breaching water levels at all levee stretches are considered as uncertain factors (like factors A,B and C in Figure 4.2), Scenario Discovery provides an indication about what stretches, when failing, are likely to lead to the indicated level of damage. Based on Scenario Discovery outputs as well as on a broader consideration on the geometry of the levee system, we identify critical levee stretches and define structural measures, i.e. where to raise or strengthen levees. After these measures are defined, their performance is assessed through a new quasi-Monte Carlo analysis.

Assess Robustness

Robustness is calculated as the regret of adopting a given measure as in equation 4.1. In particular, we assess regret of societal costs, i.e. total damages caused by the 500-year event, high total costs and low total costs. As for the latter two, total costs are equal to the sum of total damages and investment costs and, as the latter are calculated using lower and upper estimates (as in described in the *Problem framing* subsection), two estimates of total costs are provided.

It is worth stressing that, as flood damage relate only to the 500-year event, assessing total costs implies evaluating investments solely on the objective of reducing catastrophic flooding and not, as it is more commonly done (Ciullo et al., 2019; Kind, 2014), on reducing expected annual flood damage. This, however, is merely due to the scope of our application and does not depend on the proposed framework, which can be applied also when flood risk is assessed.

Explore alternative probability density functions

This step allows exploring the performance of structural measures under various alternative hypotheses of the levees fragility curves. We explore three different hypotheses of fragility curves, *f*. Under our assumptions, all fragility curves are normally distributed, with the location and scale parameters reported in Table 4.4**.** Figure 4.8 shows the three fragility curves (*f1*, *f2*, *f3*) and the sampling distribution. The hypothetical fragility curves are a function of the levee height, so to account for the effect of levee heightening in also increasing levee stability.

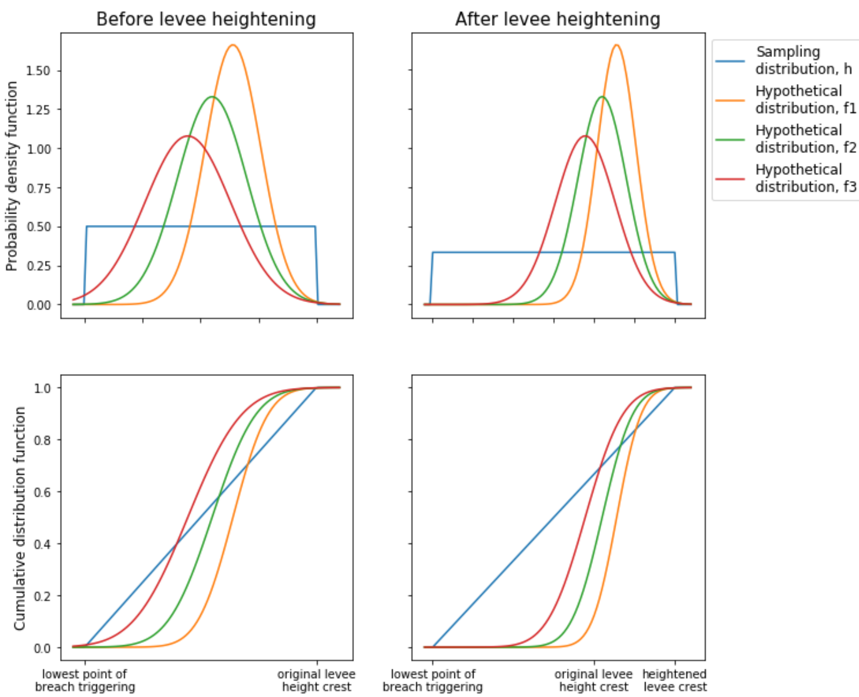

Figure 4.8 *Hypothetical fragility curves in terms of probability density function (top row) and cumulative distribution function (bottom row). The left column shows the three curves in the original situation, while the right columns shows how the curve may change in response levee raising*.

Table 4.4 *Mean and standard deviation of the three alternative normally distributed fragility curves, where* $\overline{x}$ *represents the levee height.*

	Hypothetical distribution *f1(x)*	**Hypothetical distribution *f2(x)***	**Hypothetical distribution *f3(x)***
Mean	$\bar{x}$ - 3*0.24	$\bar{x}$ - 3*0.3	$\bar{x}$ - 3*0.37
Standard deviation	0.24	0.3	0.37

4.4 Results and discussion

4.4.1 Quasi-Monte Carlo analysis and Scenario Discovery

The quasi-Monte Carlo analysis of the current system (*status quo,* blue boxplot in Figure 4.11) reveals that five compartments are flooded by the 500-year event. They are mostly located upstream, as breaching at these compartments results in an unloading effect downstream, which are then not flooded.

In order to identify which stretches to implement structural measures on, Scenario Discovery is carried out for each compartment to find breaching water levels leading to extremely large flood damage (i.e. larger than the 3rd quartile). Figure 4.9 shows results of the identified boxes of interest (like the one in Figure 4.3) for each affected compartment.

Only for one compartment (*Cross_seccB,* top left panel in Figure 4.9) high flood damages are due to (among other factors) flood waves along the Po River having high volumes. High values of the coefficient of the quadratic damage model, instead, are responsible for large flood damage at all compartments. Moreover, for each compartment, breaching water levels at some, critical, locations are identified as causing high flood damage. Identifying these critical locations provides a crucial indication on where measures ought to be applied.

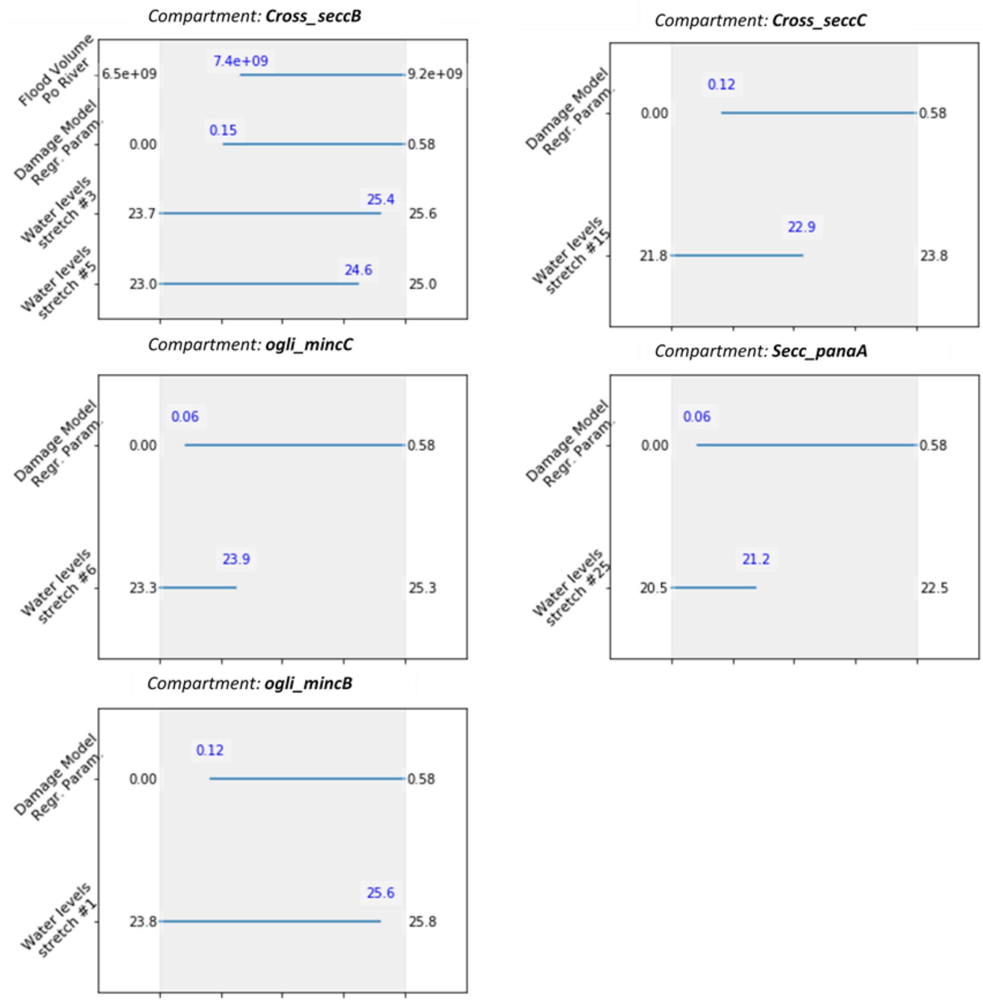

Figure 4.9 *Scenario Discovery results. Uncertain parameters and value ranges leading each compartment to flood damage higher than the 3rd quartile. Flood volume is expressed in cubic meters, breaching water levels in meters above sea level and the damage model regression parameter is adimensional.*

Two types of alternative measures are considered possible, i.e. *raising* or *strengthening* the levees. As far as *raising* is concerned, a choice on the degree of heightening ought to be made. Ideally, this decision is taken based on expert judgment as well as on broader economic and social considerations involving stakeholders of the flood-protected areas. In the present work, heightening at critical levee stretches is based on considerations relative to the height of nearby levees. As for *strengthening*, instead, it is sufficient to identify critical stretches and to assume they are strengthened in such a way that no breaching can occur. In order to make the two measures comparable, both *raising* and *strengthening* are applied to the same set of stretches.

In compartment *Cross_seccB*, two stretches are identified as relevant locations of investment in flood protection, i.e. number 3 and 5. Levee at stretch 5 has an average levee crest level of 25 m a.s.l., while levee at stretch 3 is higher with an average levee crest level of 25.65 m a.s.l.. Although not identified by Scenario Discovery as relevant, the stretch between 3 and 5, i.e. stretch 4, with average levee crest level of 25.5 m a.s.l., is also considered as part of the intervention. As the lowest average levee height along the compartment on the other side of Po River is about 25.8 m a.s.l., levees at stretches 3, 4 and 5 are heightened up to this level. Following similar reasoning, levee raising of 100, 70, 50, 30 centimeters is applied to one levee stretch of each of the four compartments *Cross_seccC, Ogli_minC, Ogli_minB, Secc_panaA* respectively. In total, the procedure leads to investments in 7 stretches, which are shown in Figure 4.10. The performance of both *raising* and *strengthening* is assessed through quasi-Monte Carlo analysis.

Figure 4.11 shows results of the quasi-Monte Carlo analyses for each compartment and the system as a whole (total damage) in the *status quo* (i.e. no measures are implemented, blue boxplot), after *raising* (orange boxplot) and *strengthening* (green boxplot). Looking at the total damage, both *raising* and *strengthening* improves the current situation, as they bring lower damage than *status quo*. In the case of *strengthening,* however, this benefit is much more remarkable. In *cros_seccB*, like in the system as a whole, the

500-year damage is highest in the current situation and lowest after *strengthening*. This is the compartment were most damage occurs.

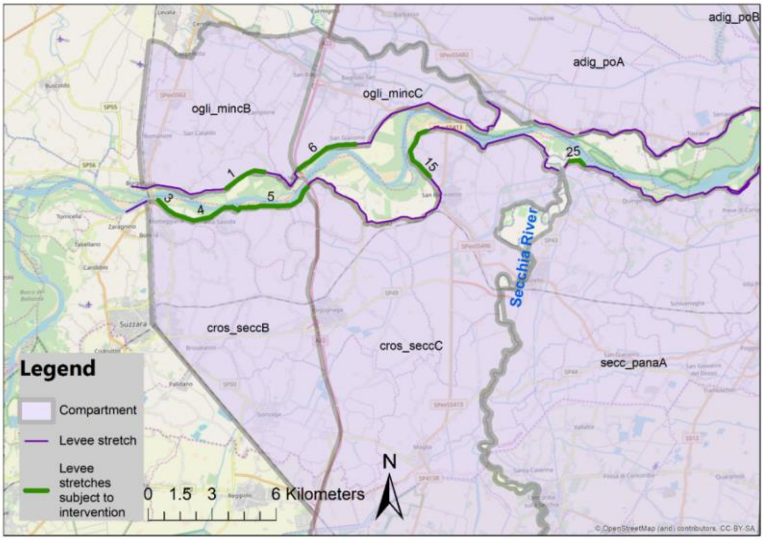

Figure 4.10 *Location of the stretches identified to undergo structural measures*.

In other compartments, the effect of *raising* and *strengthening* on the 500-year damage differs. For *secc_panaA*, for example, both *raising* and *strengthening* increase flood damage with respect to the *status quo.* Even more interestingly, *adig_poE* suffers damage only under *strengthening.* This happens because, if, on the one hand, implementing structural measures brings damage reduction at the stretches where these measures are applied, it causes, on the other hand, a damage shift downstream. This phenomenon seems exacerbated under *strengthening* where levees are strong enough that no breaching occurs.

4.4.2 Assess robustness

Figure 4.12 shows the regret of adopting *raising*, *strengthening or* maintaining the *status quo*. When considering only total damages, *strengthening* is clearly the best performer, as it always brings zero regret.

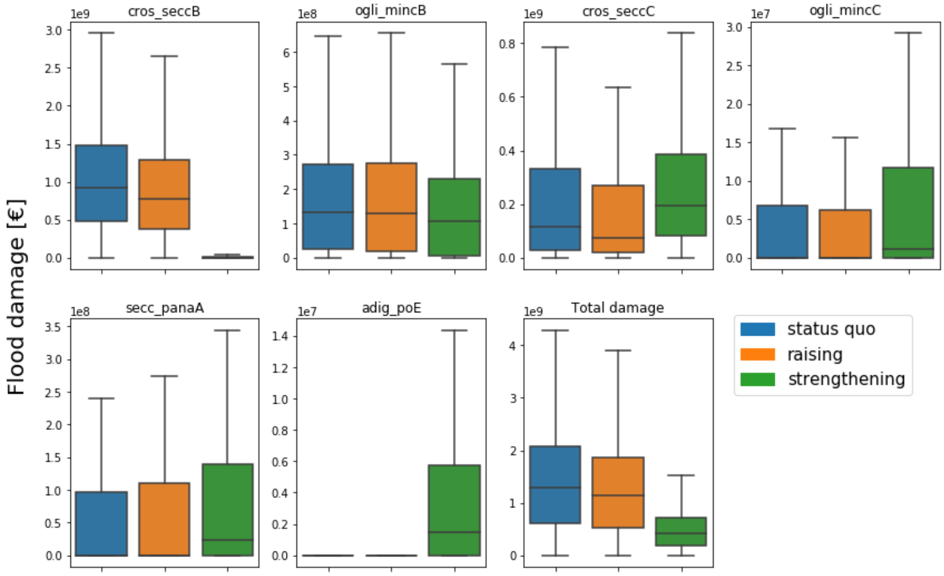

Figure 4.11 *Flood damage from the 500-year event at each compartment in the current system (blue), after raising (orange) and strengthening (green) the levees.*

When investment costs are considered, as this intervention is very expensive, regret starts to increase. Yet, in the case where total costs are estimated based on low investment costs (center), *strengthening* is still the best performer. When the highest investment costs are considered (right), *raising* brings lower regret.

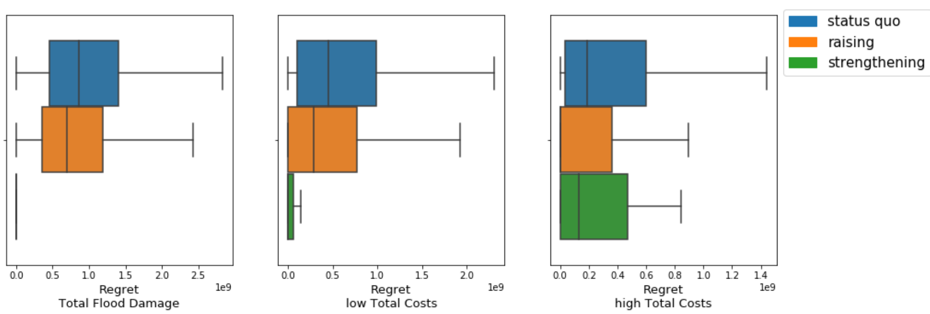

Figure 4.12 *Regret of maintaning the status quo (i.e. doing nothing, blue), raising (orange) and strengthening (green) the levees based on total damage (left), low (center) and high (right) estimated total costs (i.e. sum between total damage and investment costs).*

4.4.3 Explore alternative probability density functions

Results about the effect on robustness of the alternative fragility curves and cost estimates are shown in Figure 4.13. From left to right, columns show FR curves where regret is calculated in terms of total damage (left column) and total costs based on low (center column) and high (bottom column) investment costs estimates. Rows show results based on fragility curves in Figure 4.8. As a reminder, from *f1* to *f3*, uncertainty about breaching water levels increases. The tolerance level is shown in each panel as a continuous straight line of the form C/r^{α}, similarly to how it is defined for FN-curves (Jonkman et al., 2003), where r stays for regret levels, α is equal to one and C is such that the lowest regret value, i.e. 10 million, has probability equal to one. At this regard, unlike the FN curves, where even having one fatality is undesirable and thus a very low value of C is required, here regret is expressed in economic terms and it is assumed that a certain regret of 10 million is acceptable. The exact definition of α and C is indeed a value-laden choice which reflects the overall attitude of policy makers towards regret and values chosen in this chapter serve the only scope of introducing the proposed methodology.

When looking at regret based on total flood damage (i.e. left column), *strengthening* always brings zero regret and thus this is the most robust measure. Furthermore, the acceptability of *status quo* and *raising* changes for different assumptions of the fragility curves. *Status quo* is acceptable only under *f1*, while *raising* is acceptable under *f1* and *f2*. When uncertainty about breaching water levels is large, i.e. under *f3*, none of these two measures is acceptable. Similar conclusions can be drawn by looking at regret based on low total costs (i.e. center column), although in this case regret of *strengthening* is never zero. Under *f1*, all measures are below the tolerance level. As uncertainty about breaching water levels grows, *status quo* and *raising* are no longer acceptable starting from *f2* and *f3* respectively. *Strengthening* is always below the level of tolerance, although it is tangent to it under *f3*. As investment costs grows (i.e. right column), *raising* overperforms *strengthening* under all assumptions of the stability of the levee system.

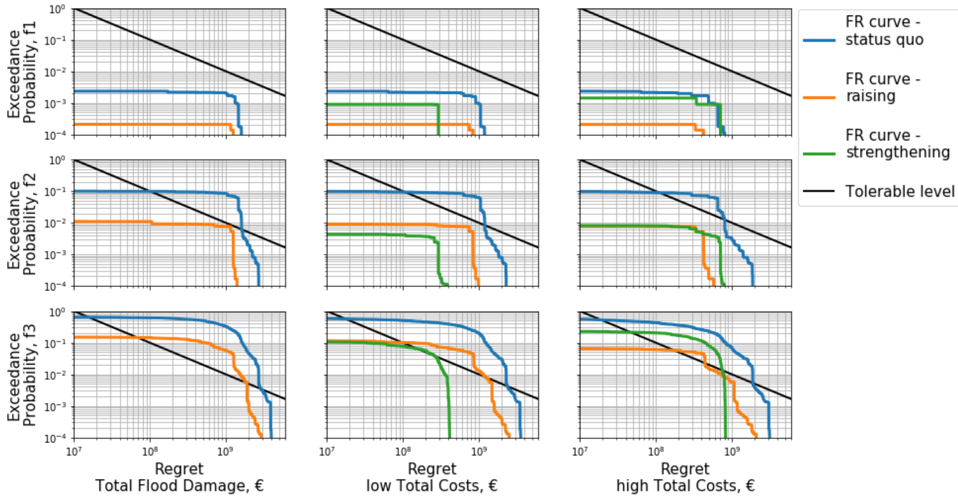

Figure 4.13 *Frequency-Regret curves of maintaning the status quo (i.e. doing nothing, blue), raising (orange) and strengthening (green) the levees based on total damage (left column), low (center column) and high (right column) total costs (i.e. sum between total damage and investment costs) according to three alternative assumptions f1 (top row), f2 (center row), f3 (bottom row) of the fragility curves.*

Interestingly, under *f1 strengthening* has a performance equivalent to *status quo.* This means that the extensive investments required by *strengthening* to prevent unexpected breaching are not effective in a situation in which breaching would have occurred only close to the crest of the levees (i.e. in *f1*). Under *f2*, however, *status quo* is no longer acceptable while *strengthening* still is. Under *f3*, *strengthening* is clearly above the tolerance level with *raising* only slightly exceeding it. Even in this case, however, *strengthening* brings lower maximum regret values than *raising*.

To summarize, *status quo* is only desirable when uncertainty on the levee system is low (i.e. *f1*) but it is always outperformed by both *raising* and *strengthening*. The choice between these latter two is dictated by the estimation of investment costs. When these are low or absent (i.e. case where only total damage is considered) *strengthening* is the best measure.

When investment costs are high, *raising* overperforms *strengthening,* with this latter even exceeding the tolerance level when uncertainty is high (i.e. *f3*). Still, however, *strengthening* avoids high regret values, which are instead found in *raising*.

4.5 Conclusions

In the present chapter we introduce a method to support the identification of flood protection measures in a context in which there is lack of knowledge about the probabilities of breaching water levels, i.e. on the definition of fragility curves. The method builds on Robust Decision Making, thus allowing to identify robust protection measures against uncertain levee breaching, and combines it with Importance Sampling in such a way that it allows exploring the effect of alternative hypotheses of fragility curves on the robustness of the identified measures.

The method is general and, in order to show its potential, we applied it to address the challenge of identifying structural flood protection measures, i.e. raising or strengthening levees, along the lower stretch of the Po River. The aim of this application is twofold. First, we aim at identifying what structural measures reduce flood damage in a context of hydrological, levee breaching and damage assessment uncertainty. Then, we explore the effect of different levels of confidence about the distribution of levee breaching uncertainties on which measure is to be preferred.

We find that, when looking at flood damage reduction only, levee strengthening is by far the best option. As this option is very costly, however, its desirability decreases when investment costs are considered. Yet, if investment costs are low and the uncertainty about levee stability is large, levee strengthening is preferable to levee raising. When uncertainty about levee stability is small and investment costs are high, however, levee strengthening can be equivalent as doing nothing as a very expensive measure would be put in place to prevent unexpected breaching while in fact breaching would occur only close to the crest of the levees. In this case, levee raising is the most preferable measure.

As the choice on the most preferred intervention heavily depends on the level of uncertainty about the levee stability as well as on the investment costs, the proposed method can be used to support policy makers in assessing the level of confidence at which they should shift from e.g. preferring either levee raising or levee strengthening or even doing nothing.

Finally, although the present work focused on structural flood protection measures, we find that uncertainty in damage modelling might explain most large flood damage estimations. This implies that a great effort is needed to reduce the uncertainty of damage estimates and that actions to reduce flood vulnerability may also be needed, as solely flood protection does not suffice. Thus, future research may focus on applying the proposed method to assess the robustness of both structural and non-structural measures. In addition, it is crucial that effects of *beliefs* about sources of uncertainty other than levee stability, e.g. hydrological and socio-economic uncertainties, on robustness will be studied further.

5 Systemic flood risk management: the challenge of accounting for hydraulic interactions[4]

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 designing policies not only striving for risk reduction, but also accounting for risk transfers across flood-protected areas. In the present chapter, we compare the performance of policies identified according to the current approach with those of two alternative formulations: one acknowledging hydraulic interactions and another one 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 find 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.

[4] This chapter was published as: Ciullo, A., de Bruijn, K. M., Kwakkel, J. H. & Klijn, F. (2019). Systemic Flood Risk Management: The Challenge of accounting for hydraulic interaction. *Water* 11(12): 2530.doi.org/10.3390/w11122530.

5.1 Introduction

It is well known that structural flood risk reduction measures alter the river's hydraulic regime, as demonstrated by e.g. increased downstream flood peaks due to upstream dike heightening (Di Baldassarre et al., 2009) or downstream flood load reduction due to upstream flooding (De Bruijn et al., 2016; Van Mierlo et al., 2007). These phenomena are hereafter referred to as *hydraulic interactions*.

Vorogushyn et al. (2017) 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 (Directive 2007/60/EC, 2007) 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 behaviour of such infrastructures is hard to predict, and there have been cases of unexpected failures in the past (Orlandini et al., 2015). Furthermore, beside 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 (Hansson, 2007). Previous flood risk management studies (Brekelmans and Den Hertog, 2012; Eijgenraam et al., 2017; Kind, 2014) based on cost-benefit analysis focused on optimizing measures 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. Minimising 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 (Hayenhjelm, 2012).

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) 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 chapter 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 (Kasprzyk et al., 2013). First, for each problem formulation, optimal policies are identified under a deterministic scenario using a Many Objective Evolutionary Algorithm Coello Coello et al. (2007). 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 chapter is structured as follows. Section 5.2 introduces the case study. The simulation model is detailed in section 5.3. Section 5.4 presents the method in more details. Section 5.5 reports results, with subsection 5.5.1 introducing the optimal policies identified under the deterministic scenario and subsection 5.5.2 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 5.6.

5.2 Case study

The Rhine River begins in the Alps and reaches the North Sea in the Netherlands after about 1320 kilometers. From upstream to downstream, several sections can be identified (Silva et al., 2001): 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* (Lammersen and Kroekenstoel, 2005). 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 5.1). 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.

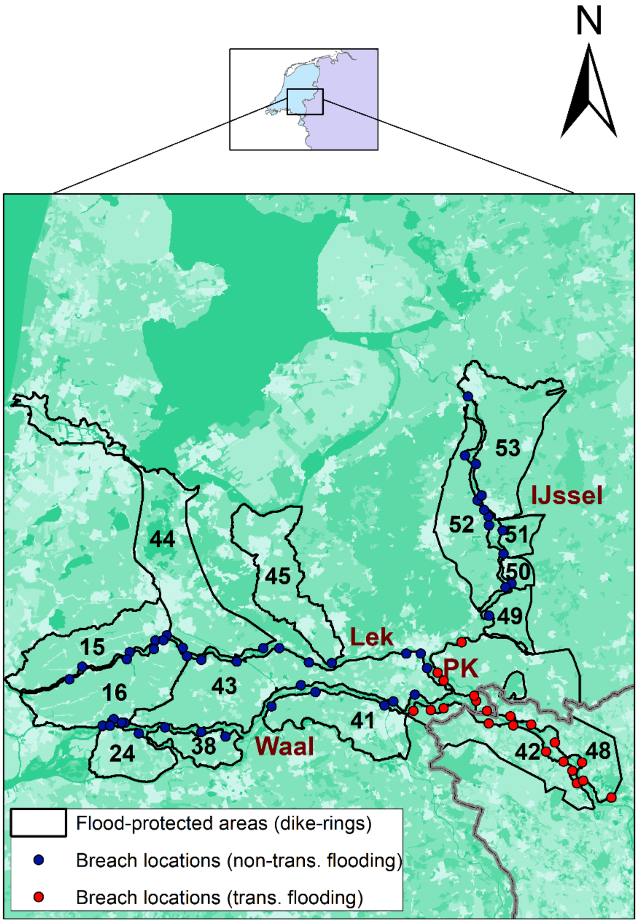

Figure 5.1 *Transboundary case study area with the grey line representing the administrative border. Black thick lines represent dike-rings, i.e. dike-protected areas, with the code relative to each dike-ring reported within. Dots are breaching locations, with flooding at the red dots causing transboundary 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 5.1, the thick closed lines represent so-called *dike-ring areas,* i.e. 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.

5.3 Simulation model

The simulation model builds upon the model introduced in Chapter 2, which was developed for the IJssel River. The model is developed following the XLRM framework proposed in Lempert et al. (2003) but with slightly adapted terms. In the framework, *X* are the *exogenous uncertainties*, i.e. factors outside the control of the decision-maker; *L* (of lever) are *policies*, i.e. alternative strategies or interventions the decision-maker wants to explore; *M* (of measure) are *outcomes of interest,* i.e. 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*, i.e. 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 5.2 and described below.

5.3.1 Policies

From a range of possible flood risk reduction measures and policy instruments (FLOODsite, 2009), 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 meter, with steps of 10 centimeters. As for making room for the river, an existing database (Van Schijndel, 2005) 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.

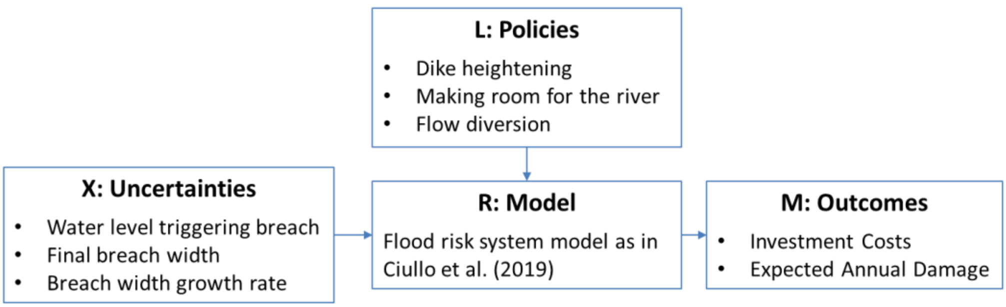

Figure 5.2 *The XLRM framework of the simulation model used in this study.*

5.3.2 Model uncertainties

Model uncertainties are summarized in Table 5.1. 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 5.1, there are 210 uncertain factors.

Table 5.1 *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 meters	The final breach width can be reached in 1, 3 or 6 days

5.3.3 Model outcomes

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:

$$EAD\ (T, r) \ = \sum_{t=1}^{T} \frac{\int_{H_{min}}^{+\infty} p(H)L(u,H)dH}{(1+r)^t} \qquad 5.1$$

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 probability density function 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 Eijgenraam et al. (2017):

$$I \ = \begin{cases} 0 & if\ \bar{h} = 0 \\ (c + bu)e^{-\lambda(W+u)} & if\ \bar{h} > 0 \end{cases} \qquad 5.2$$

where $\bar{h}$ 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 De Grave and Baarse (2011). 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.

5.4 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 (Kasprzyk et al., 2013). 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.

5.4.1 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:

$$\text{minimize} \quad \sum_i (I_i + EAD_i) \quad \forall \ i \in I \qquad 5.3$$

$$\sum_j (I_j + EAD_j) \quad \forall \ j \in J$$

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 ΔR = $(EAD_0 - EAD)$ 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 5.3.

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. ΔR = 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.

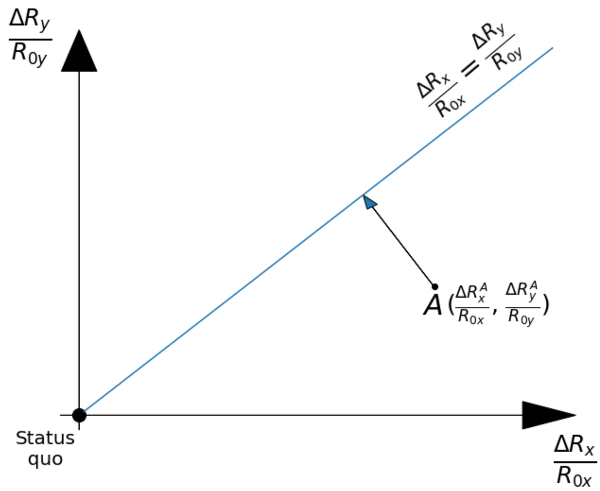

Figure 5.3 *An example visualizing how relative risk reduction of two areas x and y following a policy A can be compared with respect to a situation of perfect equal distribution.*

The point of equal benefits is located on the bisector line, with the distance from point A to such line which is given by:

$$d = \frac{\left|\frac{\Delta R_x^A}{R_{0x}} - \frac{\Delta R_y^A}{R_{0y}}\right|}{\sqrt{2}} \qquad 5.4$$

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:

$$\text{minimize} \quad \textstyle\sum_i (I_i + EAD_i) \quad \forall \quad i \in I \qquad 5.5$$

$$\textstyle\sum_j (I_j + EAD_j) \quad \forall \quad j \in J$$

$$\max_{x,y} \frac{\left|\frac{\Delta R_x}{R_{x0}} - \frac{\Delta R_y}{R_{y0}}\right|}{\sqrt{2}} \quad \forall \quad x, y \in I \cup J, x \neq y$$

$$\text{with} \quad EAD_{0,x} \geq EAD_x \quad \forall \quad x \in I \cup J$$

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

5.4.2 Generating alternatives

Optimal flood risk reduction policies are identified using Many Objective Evolutionary Algorithms (MOEAs) to find a Pareto-approximate set of solutions (Coello Coello et al., 2007), 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 ε-NSGAII search algorithm is used (Kollat and Reed, 2005). 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 5.2.

The convergence of ε-NSGAII to the approximate Pareto front is measured through two performance metrics known as ε-progress (Hadka and Reed, 2013) and hypervolume (Zitzler et al., 2003). 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.

Table 5.2 *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 meters	The final breach width is reached in 3 days

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.

5.4.3 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 subsection 5.3.2 and summarized in Table 5.1 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.

5.4.4 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 (Giuliani and Castelletti, 2016; Kwakkel et al., 2016; McPhail et al., 2018). McPhail et al. (2018) provide 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 (1950) 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 subsection 5.4.1. 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 (Hurwicz, 1953) combined these two metrics in what is known as the optimism-pessimism rule, consisting of their weighted average:

$$Hurwicz\ Criterion\ = (1 - \lambda) \min_p \max_s O_{p,s} + \lambda \min_p \min_s O_{p,s} \quad 5.6$$

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 5.3. 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.

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.

Table 5.3 *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

5.5 Results

The analysis was carried out through the Exploratory Modelling and Analysis Workbench (EMA-Workbench) (Kwakkel, 2017), 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 (Gini, 1921) 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 in the next subsection and, after, in terms of their robustness against uncertainties relative to hydraulic interactions under different risk attitudes.

5.5.1 Generating alternatives

Optimal policies for each of the three problem formulations given the reference scenario are shown in Figure 5.4. 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.

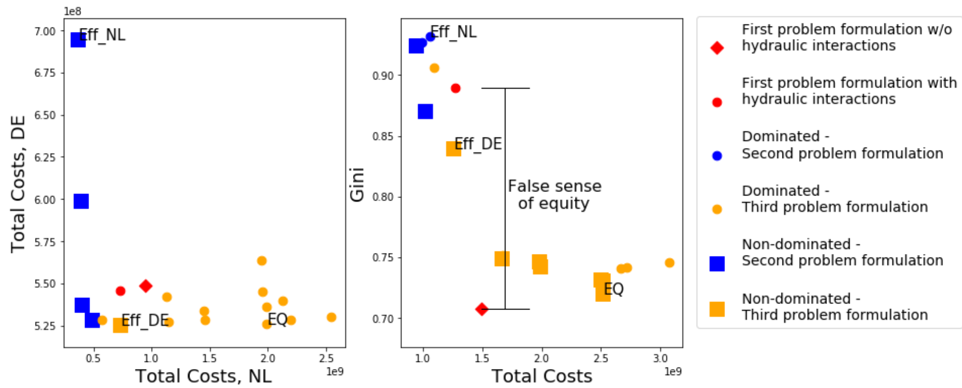

Figure 5.4 *Results from the epsilon-NSGAII search under a reference scenario for the three problem formulations. By showing all policies from the three formulations together, a Pareto front across formulations can be identified (i.e. squares in both panels).*

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 5.4.

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 e.g. 43, 44, 45. Second, two dike ring areas along the IJssel, namely 52 and 49 in Figure 5.1, 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 5.4, 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 5.5, 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 5.5 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.

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

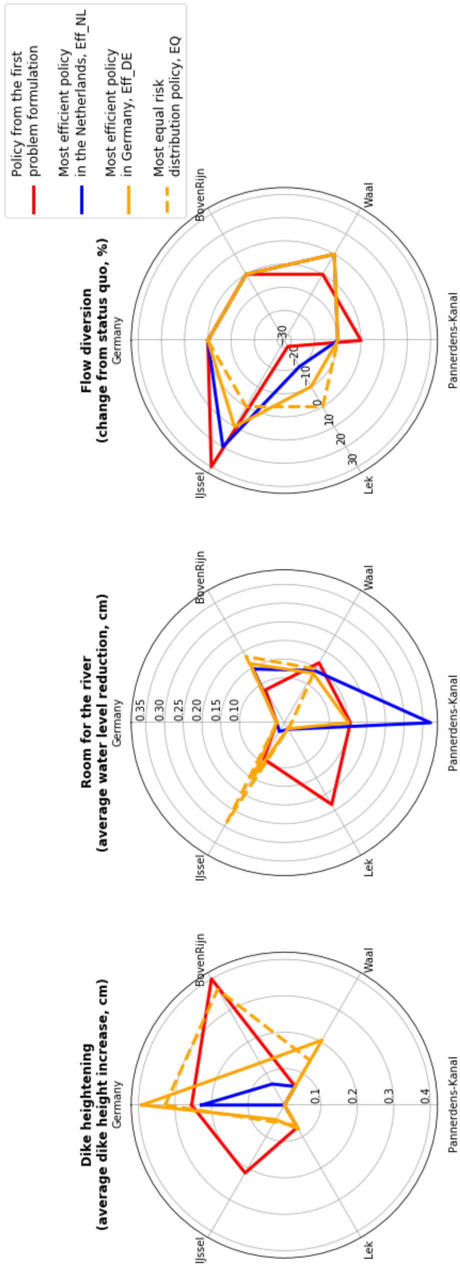

Figure 5.5 *Spider diagram of the risk management measures of the four selected policies. Values refer to six areas: German territory and five major Dutch river branches, the Boven-Rijn, the Waal, the Pannerdensch-Kanaal, the Lek and the IJssel. For each of these areas, dike heightening is expressed 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 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.

5.5.2 Evaluating robustness under different attitudes towards risk

Figure 5.6 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 subsection 5.4.4. 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.

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.

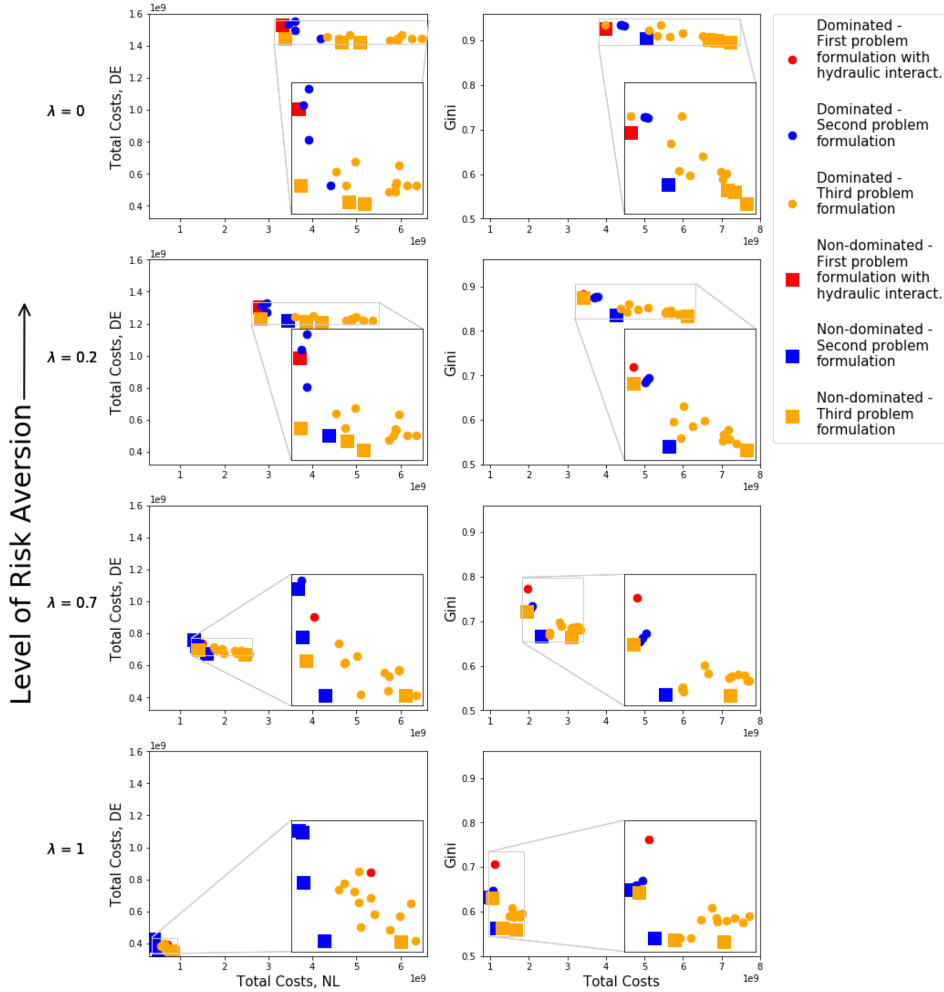

Figure 5.6 *Evolution of the Pareto front across formulations for different risk attitudes (i.e. increasing risk aversion from bottom row to top row). Left: trade-offs between total costs in Germany and the Netherlands. Right: trade-off between efficiency and equity of the system.*

The 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 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.

5.6 Discussion and conclusions

In the present chapter 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 equity of risk distribution 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 (Kasprzyk et al., 2013): 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 by Ciullo et al., 2019 in a smaller-scale case study.

The 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.

6 Conclusions and discussion

The overarching research question of this thesis as introduced in Chapter 1 is:

> *How to improve flood risk management planning in order to account for risk-distribution across flood-protected areas and the deeply uncertain hydraulic interactions?*

where improvements are evaluated with respect to the standard approach to flood risk management planning, regarded as the one which (1) evaluates flood risk management strategies based on local cost optimization objectives, thus not adopting a system view and ignoring hydraulic interactions, and (2) treats uncertainties relative to embankment breaching as well-characterized, thus failing to properly address these uncertainties when it is hard to characterize them well and they could instead be treated as deep uncertainties.

In order to answer the main question, four sub-questions have been formulated. Answering these sub-questions is instrumental in tackling the main research question. Thus, this chapter first answers each sub-question based on the findings of the previous chapters and, next, it provides a general framework answering the main question. Then, by drawing on the findings of the main case studies (i.e. the IJssel, the Lower Rhine, and the Po rivers), general considerations for systemic flood risk management planning are provided. Finally, the relevance of the findings is discussed for both flood risk management research and policy making.

6.1 Conclusions

6.1.1 Answering the five research sub-questions

1. *To what extent does taking into account the uncertain effects of hydraulic interactions influence the choice of flood risk management strategies?*

This research question is answered in Chapter 2. To answer this question, optimal embankment heights along a stretch of the IJssel River were identified according to two different approaches: by including and by ignoring hydraulic interactions respectively. A comparison of the results revealed that acknowledging hydraulic interactions requires a fundamental change in the approach to the optimization problem in flood risk management in that it turns a single-objective decision problem into a many-objectives one, as risk-reduction goals of different flood-protected areas are in conflict. Indeed, when hydraulic interactions are neglected, regardless the specification of five distinct total cost objectives (i.e. one for each protected area in the case study), only one strategy is identified as optimal. This strategy is in fact the one that would have been found by optimizing for one single decision objective, i.e. the system total costs. When hydraulic interactions are considered, instead, a Pareto set of strategies is found. This Pareto set shows a trade-off across flood-protected areas. When comparing the one strategy identified by ignoring interactions with the set of Pareto optimal strategies, the former leads to downstream over-dimensioning of the embankment height, and thus overspending. Due to this overspending, the one strategy shows poor capacity to efficiently allocate total costs downstream. Due to such overspending, however, it performs well in terms of overall total costs reduction when uncertainties in embankment failures are considered. It thus qualifies as a *better safe than sorry* strategy. Overall, taking into account hydraulic interaction increases the range of potential options, helps visualising trade-offs between flood-protected areas, and may thus contribute to better-informed decision-making.

2. *What is the influence of adopting different ethical principles about the distribution of benefits across flood-protected areas on the identification of flood risk management strategies?*

This research question is answered in Chapter 3, where implications in terms of strategies adopted and their performance have been explored for four alternative formulations of the same flood risk management problem, with each formulation being defined according to a different ethical principle. One formulation, which resembles Cost-Benefit Analysis (*CBA)*, strives for minimizing total societal costs; a second formulation, which constrains Cost-Benefit Analysis *(cCBA)*, minimizes total costs with the constraint that none of the flood protected areas is allowed to experience a risk increase; a third formulation, inspired by egalitarianism (Parfit, 1997) (*egalitarian)*, minimizes total costs and also maximizes equity in the distribution of risk-reduction across flood-protected areas; and a final formulation, inspired by prioritarianism (Parfit, 1997) (*prioritarian)*, similar to the previous one but which maximizes equity of relative risk-reduction across flood-protected areas, i.e. risk-reduction normalized over the value of initial risk.

A trade-off between efficiency (measured in terms of total costs) and equity (measured as distribution of either risk-reduction or final risk levels) was found. *CBA* results in the most efficient strategies being taken, i.e. lowest system total costs. However, it leads to a larger flood risk in some flood-protected areas (i.e. along the IJssel River). This implies that, in the course of optimizing overall risk-reduction, for the sake of protecting some flood-protected areas, risk is transferred to other areas. *cCBA,* given the applied constraint, overcomes this issue. By so doing its efficiency decreases but equity increases in comparison to *CBA*. *Egalitarian* and *prioritarian* both result in decreased efficiency and increased equity in comparison to *cCBA* (and thus also to *CBA*). However, the best performer in terms of equity depends on how this is defined and measured. If equity is measured in terms of distribution of risk-reduction, then *egalitarian* leads to the largest equity, as this formulation tends to distribute equal risk-reduction to all protected areas. If equity is expressed as distribution of final risk levels, *prioritarian* qualifies as the most equal formulation, as more risk-reduction is provided to areas that have higher initial risk, thus levelling down differences in risk levels across areas. Overall, both *egalitarian* and *prioritarian* achieve larger equity at the expense of higher investment costs than *CBA* and *cCBA*. *Egalitarian* allocates these extra costs inefficiently as low overall risk-reduction is achieved. *Prioritarian,* instead, allocates the extra investments more efficiently and, therefore, it better combines risk-reduction and risk-distribution objectives.

In terms of the adopted flood risk management measures, three types of measures are explored: raising embankment, making room for the river and changing the discharge distribution at the bifurcation points. As for raising embankments, *egalitarian* and *prioritarian* lead to higher embankments everywhere than *CBA* and *cCBA*. The latter two require very similar heightening with the interesting exception of embankments in Germany, which are significantly lower in *cCBA,* for the sake of protecting the downstream areas along the IJssel River because of the applied constraint of not increasing risk anywhere. In terms of discharge distribution, virtually all problem formulations require more water to the IJssel, with the Nederrijn having its discharges substantially reduced. The only exception being some *egalitarian* strategies, which do contrast this change as they allocate equal risk-reductions. This shows how important regulating the discharge distribution is in controlling risk-reductions across the system.

3. *How can different assumptions about the deep uncertainties associated with embankment failure be taken into account in evaluating the performance of flood risk management strategies?*

This research question is addressed in Chapter 4, in which a method is proposed for ranking flood risk management strategies by treating embankment failure as deeply uncertain, where i.e. disagreement among experts or lack of knowledge exists in the accurate assessment of its probabilities. The method is described in panel *b* of Figure 4.5.

In line with Robust Decision Making (Lempert et al., 2006) (RDM), the method applies iterative stress-testing and refining of strategies to identify critical stretches where flood protection levels should be increased. This procedure consists of quasi-Monte Carlo analyses and Scenario Discovery of the flood risk system. The quasi-Monte Carlo analyses aims at assessing flood damages resulting from all scenarios of embankment failure which can plausibly happen, regardless of their likelihood of occurrence. After a quasi-Monte Carlo analysis, Scenario Discovery is applied to assess which stretches result in large flood damage when they fail. A subsequent quasi-Monte Carlo analysis is then run again with protection measures implemented at these stretches. After strategies are identified, their performance is evaluated based on the regret of choosing any of them under each embankment failure scenario. Alternative hypotheses are then put forward about the likelihood of such scenarios happening and the probability of regretting a given measure is adjusted accordingly. Finally, a set of rankings of strategies, each corresponding to a different hypothesis, is assessed.

The capability of the proposed procedure in dealing with deep uncertainties about embankment failure is twofold. First, protection measures are identified based on the identification of critical stretches. These stretches are critical regardless the probability of failure of the embankments and, indeed, they represent intrinsic vulnerabilities of the flood risk system. Thus, enhancing protection at these stretches implies reducing the system vulnerability to any scenario of embankment failure.

Second, and most importantly, assumptions on the likelihood of each embankment failure scenario, i.e. assumptions about fragility curves, are *a posteriori* attributed to the outcomes of the robustness analysis carried out at the previous step. In other words, this approach enables assessing the performance of strategies had the analysis been carried out with alternative specifications of the fragility curves. In such a way, the analysis is not constraint *a priori,* as it would be when it is conducted based on a single fragility curve specified upfront, but rather enables alternative beliefs about the functioning of the embankments to be explored and included.

4. *How does a system approach which addresses the challenges of accounting for hydraulic interactions improve flood risk management planning?*

This research question is addressed in Chapter 5. The analysis confirmed some of the findings of the proof-of-concept study carried out in Chapter 2 to answer research question 1. Indeed, the cost optimization approach that neglects hydraulic interactions provides only one risk management solution which, due to downstream overinvestments, allocates economic resources inefficiently when compared with solutions found using alternative approaches which do take into account interactions.

As far as the first challenge of adopting a system approach is concerned, i.e. considering risk-distribution across flood-protected areas, the current risk-based approach leads to a false sense of equity as the seemingly equal distribution of final risk levels estimated when neglecting hydraulic interactions is, in fact, among the most unequal ones when hydraulic interactions are considered. 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. An alternative approach which builds on the *prioritarian* formulation introduced in Chapter 3 yields substantially more equal distributions.

As for the second challenge of adopting a system approach, i.e. treating embankment failure uncertainties as deep uncertainties, the current risk-based approach only performs as efficient with respect to system total costs when a risk-averse attitude towards uncertain hydraulic interactions is taken. This matches the conservative, *better safe than sorry* nature of this approach, as also highlighted in Chapter 2. With less risk-averse attitudes, however, this approach is suboptimal to approaches which do account for hydraulic interactions both in terms of efficiency and in terms of equity, meaning that more money is spent than in the most efficient formulation. These additional expenses, however, are not aimed at increasing equity, but rather at protecting against too pessimistic damage estimates downstream.

The proposed approach is considered an improvement to the current risk-based approach in that it allows the identification of a much broader set of risk management strategies, characterised by both larger efficiency and enhanced equity under all assumptions about uncertain hydraulic interactions except for the most pessimistic one, in which case the current risk-based approach qualifies as more efficient.

6.1.2 Answering the main research question

Given the conclusions above, which were related to the four sub-questions, an answer to the main research question is now provided. The question reads as follows:

> *How to improve flood risk management planning in order to account for risk-distribution across flood-protected areas and the deeply uncertain hydraulic interactions?*

Figure 6.1 summarizes the answer to the main question by proposing a decision support framework which is considered more appropriate than the current approach, with this latter identified as the one in which flood risk management strategies are evaluated based on local optimization objectives and uncertainty in hydraulic interactions is well-characterized.

The proposed decision support framework is characterized by the following steps: generation of strategies, assessment of the performance of strategies under uncertainty, evaluation of strategies based on performance metrics and, finally, ranking of strategies. A stepwise comparison of the proposed approach and the current approach is given in order to illustrate why the former is considered more appropriate.

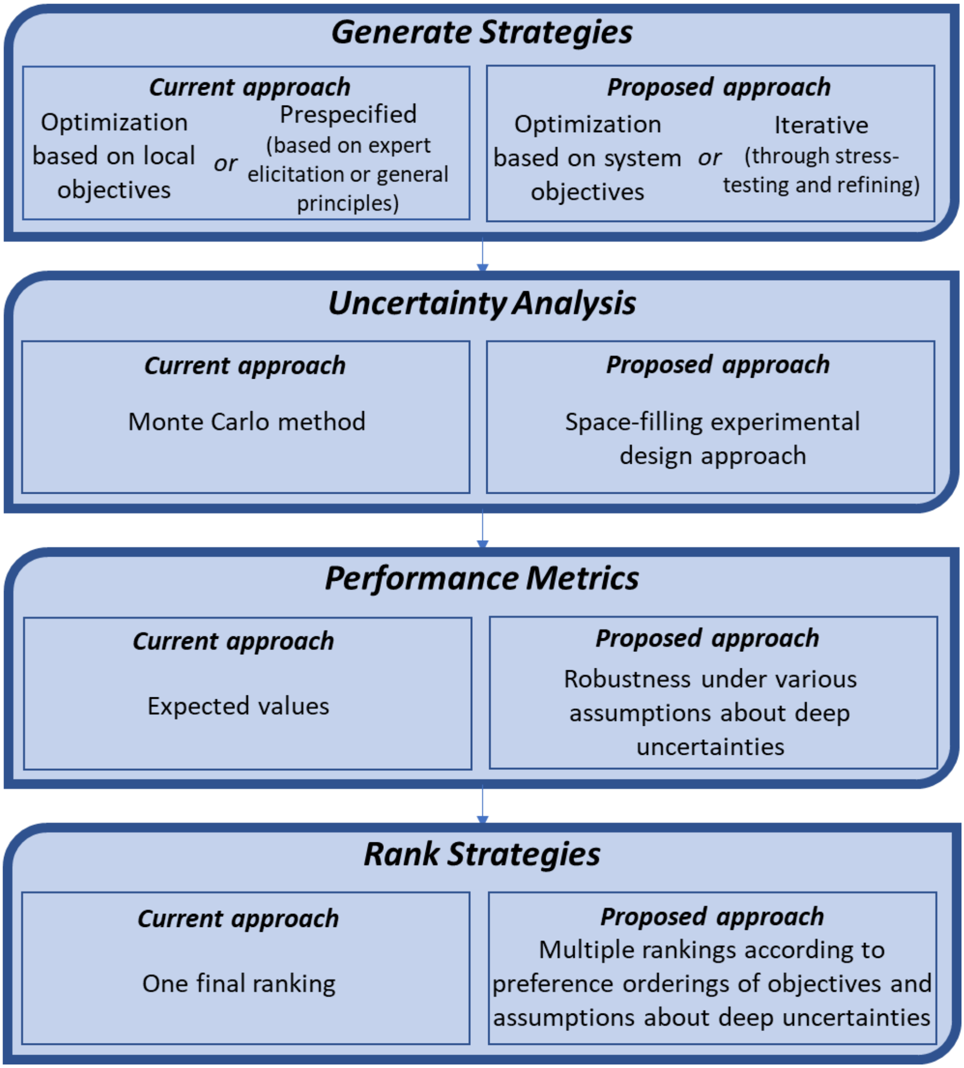

Figure 6.1 *Comparison between the current and the proposed approach to flood risk management*.

Generate Strategies

Traditionally, flood risk management strategies are developed with the aim of reducing risk locally. Strategies are either first identified based on expert elicitation or general guiding principles and then evaluated through a cost-benefit analysis, loss-of-life risk analysis or multi-criteria analysis or they result from local optimization procedures. The identified strategies, however, as they rely on expert judgment or general planning principles and only focus on local objectives, fail (1) at proving robustness with respect to unexpected responses of the embankments to hydraulic loading, thus to uncertain hydraulic interactions, and (2) at providing risk reduction trade-offs between flood-protected areas as well as trade-offs between efficiency in risk reduction and equity in risk distribution. In the proposed framework, the aim is to assess strategies for the system as a whole. Strategies are selected through either an iterative stress-testing and refining procedure (as in Chapter 4) in order to identify strategies which reduce vulnerabilities in the system, e.g. cases of unacceptably large flood damage, or result from system-wide optimization (as in Chapters 2, 3 and 5) in order to account for the presence of multiple and possibly conflicting stakes between the various flood-protected areas in the same flood risk system.

Perform an Uncertainty Analysis

Typically, this step is carried out using Monte Carlo analysis assuming well-characterized probability distributions of the uncertain factors. This assumption, however, does not hold when hydraulic interactions are deeply uncertain. In the proposed decision support framework, in line with Exploratory Modeling and Analysis, the use of a space-filling experimental design approach, e.g. using a Latin Hypercube sampling technique or quasi-Monte Carlo methods which makes use of low-discrepancy sampling techniques, is proposed (as done in Chapter 2 and 5 using Latin Hypercube and Chapter 4 using quasi-Monte Carlo). In so doing, the uncertainty analysis aims at assessing the performance of strategies under uncertain hydraulic interactions by evenly exploring the uncertainty space of how hydraulic interactions can take place, regardless their probability of occurrence. Thus, one carries out a stress-test of flood risk management strategies and she is able to assess under what strategies and under what conditions acceptable performances are attained.

Assess Performance Metrics

Typically, the ensemble of performances generated through the Monte Carlo analysis is aggregated into informative statistics, e.g. expected performances of flood risk management strategies. These expected performances are, however, not meaningful under conditions of deep uncertainty, and assessing performances based on such a metric would hamper the identification of strategies which are robust against e.g. unforeseen responses of the embankment system to hydraulic loading. In the proposed decision support framework, instead, the output of the quasi-Monte Carlo analysis allows for assessing the robustness of strategies under each possible way hydraulic interactions can take place. Robustness can be assessed through various metrics, in this thesis the applied metrics include e.g. regret-based metrics (as in Chapter 2 and 4), metrics related to the capability to retain Pareto optimality (as in Chapter 2) and the Hurwicz criterion (Chapter 5). Subsequently, assumptions about deep uncertainties are then made such that probabilistic information or beliefs and confidence about the occurrence of each possible way hydraulic interaction can take place are *a posteriori* evaluated and the way the performance of strategies changes is assessed accordingly. This is for instance carried out in Chapter 4 and Chapter 5.

Rank Strategies

Typically, as the evaluation of expected performances of flood risk management strategies is carried out focusing on local objectives under well-characterized uncertainty, one single performance is attributed to each strategy, i.e. the expected performance at the site of interest, and thus ranking these strategies is trivial. Should either the distribution of the deeply uncertain factors change or interests of off-site communities be taken into account, however, the ranking of strategies would change. Thus, when dealing with multiple conflicting objectives and deep uncertainties, not a single ranking exists, and the usual approach fails to acknowledge this. As an alternative, the proposed decision support method acknowledges a diverse set of objectives and uncertainty about the probability distribution of deeply uncertain factors, leading to multiple rankings, each related to a preference ordering about the decision objectives and an assumption about the distributions of deeply uncertain factors. As a consequence, no single best-performing strategy exists and the best course of action can only be identified after a careful evaluation of the performance of each strategy across the various assumptions.

Overall, the proposed approach aims at more explicitly acknowledging conflicts across flood-protected areas in terms of risk reduction (Chapter 2), trade-offs between diverse objectives such as efficiency in risk reduction and equity in risk distribution across flood-protected areas (Chapter 3 and 5), and ignorance in the characterization of deeply uncertain factors (Chapter 4 and 5) in the assessment of embankment stability. Although the proposed decision support method inevitably complicates the decision-making process in flood risk management, as it is discussed in section 6.2.2, it is envisioned that it also fosters dialogue across flood-protected areas, the analysts and policy makers, and ultimately provides a better understanding of the performance of flood risk management strategies and their sensitivity to assumptions.

6.1.3 Systemic flood risk management planning

The analysis carried out in the previous chapters focused on three lowland rivers, i.e. the IJssel River, the Rhine River and the Po River. By drawing on these three case studies, general considerations on systemic flood risk management planning are provided. In particular, systemic flood risk management planning should take into account hydraulic interactions because of three main reasons: (1) it increases efficiency in cost reduction, (2) it allows to more reliably quantify equity in risk-distribution across geographical areas, (3) it widens the range of viable flood risk management measures.

Taking into account hydraulic interactions increases efficiency as it allows avoiding overspending in risk-reduction downstream. This emerges from the study of both the IJssel River (Chapter 2) and the Low Rhine River (Chapter 5). Along the IJssel River, the analysis revealed that higher embankments would be built downstream than when costs are optimized accounting for hydraulic interactions. Along the Lower Rhine River, considering Dutch and German territories, the analysis revealed that neglecting hydraulic interactions leads to extra costs, especially in the Netherlands. This is due to an overestimation of downstream risk when hydraulic interactions are neglected, as the potential flood attenuation effect of upstream breaches is neglected. In Germany, being the upstream country, this effect is less evident than in the Netherlands.

Ignoring hydraulic interactions leads to a misleading quantification of equity in the distribution of risk across flood-protected areas, as discussed in Chapter 5. The flood risk management strategies identified neglecting hydraulic interactions seem to equally distribute risk, when, in fact, they lead to some of the most unequal distributions when hydraulic interactions are taken into account. This occurs because, when neglecting hydraulic interactions, downstream areas are found to be flooded as often as upstream ones, while, in fact, when hydraulic interactions are taken into account the former are flooded more rarely. This leads to an uneven risk distribution between upstream and downstream areas, with the upstream experiencing more frequent damages.

Adopting a system perspective while accounting for hydraulic interactions also widens the range of flood risk management measures available, particularly regarding the adoption of measures like changing the discharge distribution at the bifurcation points and embankment strengthening, both of which are seldomly applied.

In Chapter 3, it is found that changing the discharge distribution at the point where the Lower Rhine bifurcates into the Nederijn and the IJssel is paramount in regulating risk levels across the system. It is found that flood risk management strategies relying on principles of efficiency in system-wide risk reduction divert substantially more water to the IJssel, and thus much less to the Nederijn, than what is currently done. When also accounting for the equity in the distribution of risk (either by simply guaranteeing that strategies do not increase risk in any flood-protected area or by explicitly striving for an equal distribution of risk), the identified strategies still divert more water to the IJssel, but to a lesser extent to avoid disproportionally risk increases along this branch. Systemic flood risk management planning should explore the viability of this type of measure more often than currently done, while paying particular attention in possible unfair shifts in flood risk across geographical areas.

Strengthening embankments is often not regarded as a viable measure due to the associated high investment costs. In Chapter 4, however, it is found that when the uncertainty about hydraulic interactions is large, the probability of regretting embankment strengthening may be lower than regretting embankment heightening. This is more and more the case as either uncertainty about hydraulic interactions increases or investment costs of embankment strengthening decreases. For example, in a situation with large uncertainty about hydraulic interactions and optimistic estimation of investment costs (with strengthening costs still order of magnitudes higher than those for heightening), strengthening is the lowest regret option. This means that, under the conditions described above, the increased investment costs for strengthening the embankment are fully outweighed by the avoided flood damage and overall total costs are lower than what would have been had the embankment be heightened. Thus, systemic flood risk management planning should more often consider this measure as a viable one, despite the huge investments initially required.

Overall, in Chapter 2 and 5 it is found that a local approach to flood risk management planning and thus neglecting hydraulic interactions lead to "better safe than sorry" strategies, which are robust in providing risk reduction at the expense of high investment costs. In Chapter 5, it is shown that such an approach is defendable only from an efficiency view-point and only under a very pessimistic assumption on how hydraulic interactions will take place. Under all other conditions, a systemic approach to flood risk management planning which accounts for hydraulic interactions is preferable. Therefore, if flood risk analysts do not account for hydraulic interactions, they are inevitably constraining the analysis to a worst-case scenario with the identified flood risk management strategies only working well in terms of overall risk reduction. This is problematic as policy makers would take decisions relying on assumptions of which they are potentially unaware. Instead, for policy makers to properly make flood risk management decisions, it is crucial that hydraulic interactions are taken into account, trade-offs between equity about risk distribution across geographical areas and overall risk reduction are quantified, and different degrees of uncertainty are explored.

6.2 Discussion

The present research is motivated by the need to adopt a system perspective in flood risk management, as advocated by the scientific community (Klijn et al. 2012; Mens et al., 2015; Olson and Morton 2012; Vis et al. 2003, Vorogushyn et al., 2017) and as implicitly required by the EU Flood Directive (Directive 2007/60/EC, 2007). Previous research has focused on a system approach in flood risk analysis (Apel et al., 2009; Courage et al., 2013; De Bruijn et al., 2014), but this thesis is the first attempt to apply a comprehensive system approach in support of flood risk management and policy making. This requires accounting for the fact that flood-protected areas located along the same river are hydraulically connected in such a way that risk management measures for one area affect the risk in other areas. This brings about two challenges: quantifying risk-distribution between geographical areas, and designing measures based on the principle of robustness in order to account for the fact that hydraulic interactions are deeply uncertain. The next two sections discuss the implications of tackling these two challenges for flood risk research as well as for policy makers. The final section highlights limitations of the research and provides recommendations for future research.

6.2.1 Implications for flood risk research

How should flood risk analysts adapt their traditional approaches to risk analysis in order to adopt the proposed framework? Looking at Figure 6.1, two fundamental differences between the current and proposed approach stand out: a local optimization approach versus a system-wide optimization approach, and the assumption of well-characterised uncertainties versus assuming deep uncertainties. All other differences follow from these two.

A system-wide optimization approach can be accomplished through many techniques and algorithms, available as both open source and as commercial products. The analyses developed in this thesis were carried out using Many-Objective Evolutionary Algorithms, the use of which is not expected to be a challenge for risk analysts, as these algorithms are used (and often by the same analysts) in fields related to flood risk management like hydrology and water resources management (Reed et al., 2013).

As for treating uncertainties as deep rather than well-characterised, a shift in mindset is required. This is thus expected to be a greater challenge. The analysis should no longer focus on identifying the best performing measure under the most likely scenario but, rather, on identifying the most robust measure while exploring alternative assumptions about the likelihood of scenarios. In order words, the analysis should shift from an approach where uncertainties are resolved *a priori* to one which *a posteriori* explores several plausible hypotheses about these uncertainties. From the technical-side, however, this does not imply any major changes. It primarily requires not to use Monte Carlo integration to assess expected values but, instead, to use space-filling experimental design approaches (like quasi-Monte Carlo) to generate a full range of possible strategies performances and then evaluate the robustness of these strategies in retaining acceptable performances. Finally, as shown in this thesis, a post-attribution of assumptions about uncertainties can be accomplished using established approaches such as importance sampling or the Hurwicz criterion.

6.2.2 Implications for policy making

How would the proposed decision support framework affect the policy making process? Policy making would be affected primarily because the proposed decision support framework demands the consideration of (1) possible trade-offs in terms of risk reduction objectives between flood-protected areas, as flood risk management strategies may reduce risk on-site but transfer it off-site, and (2) uncertainties and possible disagreement about the likelihood of embankment failure, as this phenomenon dictates the way a given flood event will impact the system as whole. In order to do so, the policy making process is required to take into account:

- *Diverging preferences across stakeholders (e.g. upstream versus downstream flood-protected areas)*. This implies that a risk management measure, previously evaluated only based on its on-site risk-reduction benefits, it should now be thoroughly evaluated also based on its off-site effects because of the geographical trade-offs.

- *Diverse objectives in the realm of risk management (e.g. efficiency versus equity)*. This implies that, if aiming for efficiency only was not previously questioned, it should now be balanced with respect to equity of risk-distribution across areas, where balancing these two objectives is a choice of the policy makers.

- *Uncertainty about the likelihood of scenarios of hydraulic interactions.* This implies that *a posteriori* expert elicitation is needed to address uncertainty and disagreements about the likelihood of deep uncertainties and to then accordingly assess how the performance of flood risk management measures changes.

Policy making, therefore, should shift from an approach where experts and analysts provide single-best solutions to a flood risk management problem, to one where many solutions are on the table and where defining the most preferable one is ultimately a policy choice, depending on which stakeholders are valued more, which objectives are deemed more important and on whether measure are deemed to perform satisfactorily in light of uncertainties.

6.2.3 Limitations and future research

This thesis proposed a decision-making framework to adopt a system perspective in flood risk management. As such, however, the presented research has two major limitations which are both worth exploring further in future research.

The first limitation is due to the simplified modelling of the flood risk system which was adopted throughout the thesis with the partial exception of Chapter 4. This choice was mainly dictated by computational limitations. More complex and accurate models, e.g. coupled 1D-2D hydraulic models, would provide a better representation of phenomena like hydraulic routing, flow through the embankment breach, and assessment of water levels. As such, outcomes from these models could not just serve the scope of fostering understanding about the system (as the model used in the present thesis also does) but also provide support for the actual design of protection measures. In the short term, future research may apply the proposed decision support framework with the use of these more complex hydraulic models to e.g. identify the degree of model complexity up to which the proposed framework can reasonably be applied using the computational power normally available to flood risk analysts and managers. In the longer term, however, given the described benefits of adopting the proposed framework in terms of e.g. increasing efficiency or better quantifying equity, it might be desirable not being *penny wise, pound foolish* and thus directing more resources to reduce computational constrains allowing the proposed framework to be applied with the most advanced flood risk simulation models available.

The second limitation relates to the short-term view taken. Indeed, uncertainties about socio-economic and climatic change are neglected in this thesis. Accounting for these uncertainties would require developing dynamic adaptable plans, which anticipate foreseeable changes while at the same time allowing to cope with unforeseeable changes in exogenous and endogenous factors (Klijn et al., 2015). Taking a longer-term perspective will require to not only choose which strategies to implement but, also, when to do so. In addition, risk-distribution shall not only address intragenerational aspects (i.e. across flood-protected areas) but, also, intergenerational ones (i.e. of the same flood-protected area across generations).

Finally, the work introduced in this thesis represents an important first step in achieving a system approach to support flood risk management planning. Results indicate that a system approach would require a fundamental change to e.g. what flood risk management measures are implemented, where they are implemented and how much should be invested in implementing these measures. As such, more research and attention from the scientific community should be devoted to this topic as this is expected to bring major benefits to communities living in large flood-prone areas.

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About the author

Alessio Ciullo was born and raised in the South-Est of Italy, in the Apulia region. He graduated in Environmental Engineering from Politecnico di Milano in 2013 and the University of Bologna in 2016. He was a visiting student at the Vienna University of Technology in 2015 and Uppsala University in 2016. From September 2016 until October 2019, he was an early stage researcher at Deltares, Department of Flood Risk Management. Since October 2016, he is a PhD candidate at the Delft University of Technology, Faculty of Technology Policy and Management. Since November 2019, he is a researcher in the Climate Impact Research group at the Institute of Geography of the University of Bern.

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