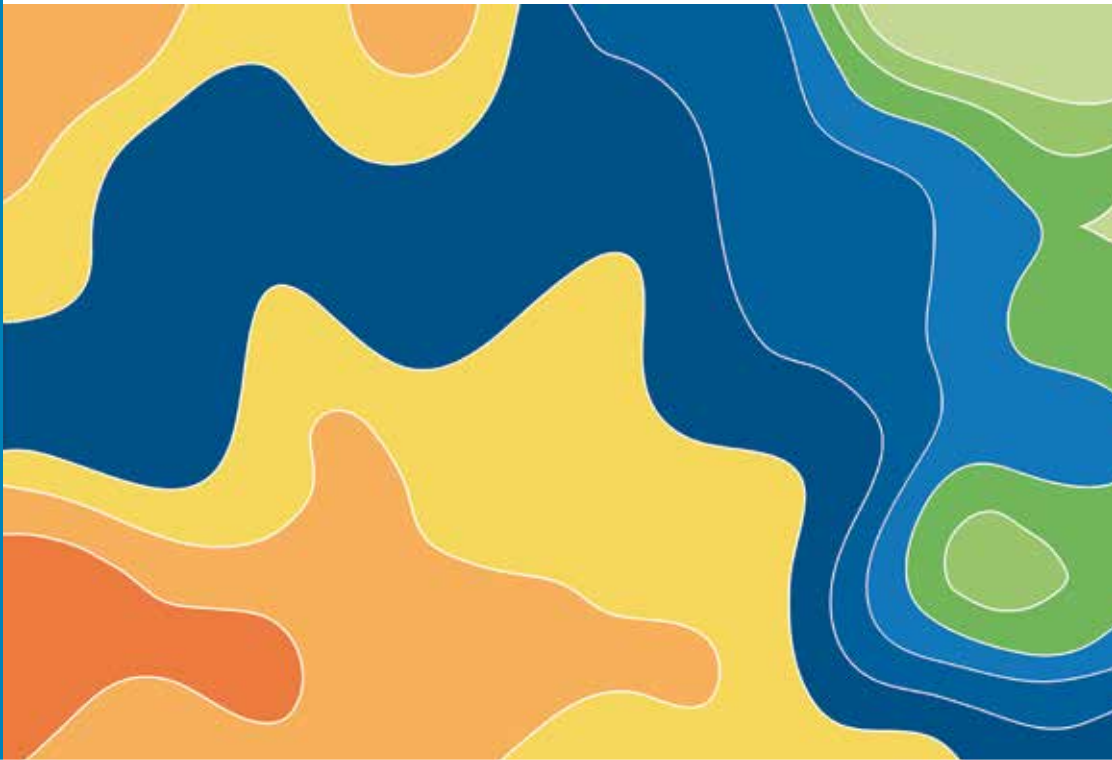


Deltares

Enabling Delta Life



System Robustness Analysis in Support of Flood and Drought Risk Management



Marjolein J.P. Mens

System Robustness Analysis

in Support of

Flood and Drought Risk Management

Marjolein J.P. Mens

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SYSTEM ROBUSTNESS ANALYSIS
IN SUPPORT OF
FLOOD AND DROUGHT RISK MANAGEMENT

PROEFSCHRIFT

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Summary

Flood and drought impacts are increasing

Floods and droughts cause increasingly large impacts on societies worldwide. The probability of these extreme events is also expected to increase due to climate change. Water management primarily tries to protect against floods and droughts, for example by building flood protection infrastructure and reservoirs. Despite structural measures to prevent flooding and water shortage, 100% protection can never be provided. Therefore, over the past decades, water management has shifted to a risk-based approach. This means that policies do not only aim at reducing the probability of occurrence of floods and droughts, but also include actions to limit the consequences of potential flooding or water shortage. Both types of measures may aid to reduce flood and drought risk to an acceptable level.

Limitations of a risk approach

Even if the risk is reduced to an acceptable level, extremely large impacts are not avoided, as demonstrated by recent floods and droughts events with devastating impact. A risk approach considers ten casualties per year in 100 years equal to 1000 casualties at once during the same period. However, the latter have a much larger societal impact. Large impacts occurring at once are considered unacceptable when it is difficult to recover from them. Hence, not only the risk but also the potential impacts should be reduced to an acceptable level. There is a need for decision support methods that help avoiding unacceptably large impacts from floods and droughts.

Another reason why risk may not suffice as decision-criterion is that it is uncertain, under both current and future conditions. Estimating current risk requires assumptions on return periods of events that do not occur in measured data. Furthermore, it is uncertain how risks develop into the future, because of uncertain future climate (and climate variability) and socio-economic developments. It is therefore difficult to decide on the most cost-effective strategy in terms of the effect on risk. This further underpins the need for additional decision criteria that take uncertainty into account.

Robustness: a new perspective on dealing with extreme events

The concept of robustness seems useful for dealing with extreme events. Robustness is known from other areas such as engineering and biology, where networks or systems have to maintain their functionality even when some components fail. Areas prone to floods or droughts can be understood as systems. When these systems can remain functioning during flood and drought events, it is likely that unmanageable impacts (i.e., disasters) are avoided. In this thesis, the concept of robustness is made operational by proposing quantifiable criteria. These criteria were tested in two flood cases and two drought cases. The cases have demonstrated the applicability of the framework and have provided insight into the characteristics that influence system robustness. Furthermore, the case studies demonstrated that assessing system robustness may change the preference ordering of management strategies.

Robustness = resistance + resilience

In this thesis, system robustness is defined as *the ability of a system to remain functioning under a large range of disturbance magnitudes*. Disturbances in this thesis are flood waves in river valleys that may cause flooding, and droughts (resulting from precipitation deficit or streamflow deficit) that may cause water shortage. 'To remain functioning' means either no impact from the disturbance or limited impact and quick recovery. System robustness is a function of two other characteristics: resistance and resilience. Disturbances that cause no impact are in the resistance range; larger disturbances that cause limited impact from which the area can recover are in the resilience range. Robustness analysis aims to identify these ranges for a specific system.

Three criteria to quantify robustness

To obtain insight into robustness, this thesis proposes three criteria to describe a system's response to disturbances,

1. The *resistance threshold* is the point where the impact becomes greater than zero;
2. The *proportionality* refers to the graduality of the response increases with increasing disturbance magnitudes;

3. The *manageability* is the ability to keep the response below a level from which recovery is difficult or impossible.

The first criterion refers to the smallest disturbance magnitude causing significant impacts and is strongly related to the system's design standard (e.g., protection against floods or reservoir capacity to prevent water shortage).

The second criterion originates from the flood risk literature; sudden floods are considered undesirable because people have too little time to prepare, leading to large impacts. Sudden events should thus be avoided in a robust system.

The third criterion compares the impact with a critical recovery threshold. This threshold represents the physical and socio-economic capacity to recover from the impacts of floods and droughts. When impacts exceed the critical threshold, it is assumed that the recovery time is long and that long-term impacts will be unacceptably high.

A robustness perspective may change decisions

In flood risk management, measures are often prioritized based on risk (a metric that combines flood probabilities and corresponding impact), in comparison to the investment costs. Both flood cases showed that a variety of measures may reduce the risk, but not all of those measures enhance system robustness. This means that different measures may be preferred when their effect on system robustness is also taken into account.

In drought risk management, measures are often assessed on the resulting water supply reliability (i.e., the probability of meeting water demand). The drought cases have demonstrated that not all measures that increase the supply reliability also reduce the drought impacts over the full range of plausible drought events. Thus, different measures may be preferred when their effect on system robustness is also taken into account.

What characterizes a robust flood risk system?

Systems with high protection levels for the entire river valley have high resistance against flood waves. However, when protection levels are equal everywhere, sudden

floods can still occur and affect a large and/or vulnerable area. Such a system is not considered robust to flood waves. Robustness of a system with a high resistance threshold can be increased by differentiating protection levels, so that least-vulnerable areas will flood first and more-vulnerable areas are relieved. Another option is to build virtually unbreachable embankments. This prevents sudden flooding and limits the inundation and thus the impact. A combination of unbreachable embankments that are also differentiated in height will further increase robustness to extreme floods. Finally, measures aimed at impact reduction increase robustness when they reduce the impacts below the recovery threshold.

What characterizes a robust drought risk system?

Drought risk systems have a high resistance threshold when their storage capacity is large compared to the demand, for example systems with large reservoirs. The resistance threshold is related to the supply reliability. A variety of supply sources will increase the supply reliability and the resistance threshold. When the objective is to reduce impacts from extreme drought events, demand reduction and temporary measures are more effective than increasing supply on a structural basis. In agricultural drought risk systems, crop diversity and having alternative sources of supply will enhance robustness to drought.

Conclusion

In conclusion, this thesis contributed to decision making in flood and drought risk management, by developing and testing an additional decision criterion. A robustness analysis method supports the assessment of impacts from extreme events, and is applicable on flood and drought risk systems. A robustness perspective supports decision makers in exploring low-probability/high-impact events and considering whether these impacts are societally acceptable. Quantifying robustness inspires the development of strategies that reduce flood and drought risk in a way that disasters are avoided.

Samenvatting

De maatschappelijke gevolgen van overstromingen en droogte nemen toe

Overstromingen en droogte hebben wereldwijd steeds grotere maatschappelijke gevolgen. Ook neemt de kans op deze gebeurtenissen waarschijnlijk toe door klimaatverandering. Waterbeleid richtte zich tot op heden op het voorkómen van overstromingen of droogte, door bijvoorbeeld dijken te bouwen of reservoirs aan te leggen. Het is echter praktisch onmogelijk om 100% bescherming te bieden. Dit besef heeft in de afgelopen decennia geleid tot een risicobenadering. Dit houdt in dat beleid zich niet alleen richt op het beschermen van extreme gebeurtenissen, maar ook op het beperken van de gevolgen, om zo overstromingsrisico en droogterisico te beperken.

Risicobenadering heeft beperkingen

Met de risicobenadering worden extreem grote gevolgen niet voorkomen, ook al is de gemiddelde jaarlijkse schade (= het risico) gereduceerd tot een acceptabel niveau. In termen van risico is tien jaar lang 100 slachtoffers per jaar vergelijkbaar met eenmalig 1000 slachtoffers in dezelfde periode. Dit laatste heeft alleen een grotere maatschappelijke impact. Extreem grote gevolgen die in één keer optreden worden onacceptabel gevonden als herstel hiervan heel moeilijk of zelfs onmogelijk is. Dit betekent dat niet alleen het risico maar ook de potentiële gevolgen van extreme gebeurtenissen gereduceerd moeten worden tot een acceptabel niveau. Dit geldt voor gevolgen van zowel overstromingen als droogte. Het ontbreekt echter aan methodes om het voorkomen van extreme gevolgen van overstromingen en droogte (rampen) mee te nemen in beleidsvorming.

Een andere beperking van risico als beleids criterium is dat het aannames vraagt over herhalingstijden van hoogwaters en droogte, omdat deze onzeker zijn. Herhalingstijden worden bepaald met meetreeksen van bijvoorbeeld waterstanden of neerslag en met statistische technieken. De meetreeks is meestal niet lang genoeg om de herhalingstijd van kleine-kans-gebeurtenissen met zekerheid te bepalen. Hoe risico's zich ontwikkelen in de toekomst is nog onzekerder, omdat niet exact te voorspellen is hoe het klimaat en

de economie zich ontwikkelen. Door al die onzekerheden is het dus ook onzeker of een voorgestelde maatregel het gewenste effect op het risico zal hebben. Dit is nog een reden om aanvullende beleidscriteria die beter met onzekerheid kunnen omgaan te verkennen.

Robuustheid als nieuw perspectief voor het omgaan met extreme gebeurtenissen

Het begrip *robustheid* lijkt een bruikbaar begrip voor het omgaan met extreme gebeurtenissen. Dit begrip is bekend uit andere vakgebieden, waar het wordt gebruikt in relatie tot systemen en netwerken, bijvoorbeeld verkeersnetwerken, electriciteitsnetwerken of computers. Als deze systemen robuust zijn blijven ze functioneren in geval van een ongeluk of storing. Een gebied dat is blootgesteld aan overstromingen of droogte is ook een systeem. Als een gebied robuust is voor overstromingen en/of droogte, dan kan het blijven functioneren ondanks dat het is ondergelopen of ondanks langdurige droogte. Als een gebied kan blijven functioneren is het waarschijnlijk dat gevolgen beheersbaar blijven en echte rampen worden voorkomen. In dit proefschrift is het begrip (systeem)robustheid toepasbaar gemaakt voor overstromingen en droogte door middel van robuustheidscriteria, die zijn getest in vier casestudies. Uit deze casestudies is gebleken dat het meenemen van robuustheidscriteria tot andere beleidskeuzes kan leiden. Het biedt daarmee een nieuw perspectief voor het omgaan met extreem hoogwater en langdurige droogte.

Robuustheid = weerstand + veerkracht

In dit proefschrift is systeemrobustheid gedefinieerd als *het vermogen van een systeem om te blijven functioneren tijdens verschillende mate van verstoring*. Overstroming en droogte worden gezien als verstoringen op een systeem (gebied). 'Blijven functioneren' betekent dat er geen schade optreedt of dat de schade beperkt blijft en het gebied weer snel herstelt. Het vermogen van een systeem om schade te voorkomen wordt weerstand genoemd. Het vermogen om te herstellen van schade wordt veerkracht genoemd. Robuustheid is het resultaat van deze twee eigenschappen. Door het analyseren van robuustheid wordt duidelijk onder welke omstandigheden gevolgen gaan optreden en onder welke omstandigheden gevolgen niet meer herstelbaar zijn.

Drie criteria om robuustheid te kwantificeren

Robuustheid kan nu geanalyseerd worden door middel van drie robuustheidscriteria. De volgende criteria helpen de reactie van een systeem op een verstoring te beschrijven:

1. Weerstand: de 'reactiedrempel' van het systeem;
2. Proportionaliteit: de mate waarin gevolgen geleidelijk optreden;
3. Beheersbaarheid: de mate waarin de gevolgen onder een kritische herstelgrens blijven.

Het eerste criterium verwijst naar de kleinste verstoring die tot significante schade leidt. Bij overstromingen is dit bijvoorbeeld de laagste afvoer die schade veroorzaakt. Dit wordt vooral bepaald door het beschermingsniveau tegen overstromingen. Bij droogte is de verstoring bijvoorbeeld neerslagtekort. Weerstand kan dan uitgedrukt worden in de kleinste hoeveelheid neerslagtekort die schade veroorzaakt.

Het tweede criterium komt voort uit het plotselinge karakter van een overstroming, bijvoorbeeld als een dijk doorbreekt. Een kleine toename van de afvoer leidt dan ineens tot een grote overstroming met grote gevolgen. Het uitgangspunt is dat plotselinge gebeurtenissen meer impact hebben, omdat mensen zich daar niet op voor kunnen bereiden. In een robuust systeem moeten plotselinge overstromingen en droogte dus vermeden worden.

Het derde criterium vergelijkt de gevolgen met een kritische herstelgrens. Deze herstelgrens verwijst naar de fysieke en sociaaleconomische capaciteit van een gebied om zich te herstellen van de gevolgen van een overstroming of droogte. Als de gevolgen groot zijn ten opzichte van de herstelcapaciteit dan zal het lang duren voordat een gebied weer kan functioneren zoals voor de overstroming of droogte. Hoe langer de hersteltijd hoe groter de gevolgen op de lange termijn. Door een kritische grens te trekken wordt het mogelijk om te beoordelen onder welke omstandigheden deze kritische grens wordt overschreden.

Beleidsvoorkeuren veranderen door robuustheidsperspectief

Bij het maken van beleid over overstromingsrisico's is het gebruikelijk om maatregelen te beoordelen op hun effect op overstromingsrisico in relatie tot hun investeringskosten (als onderdeel van een maatschappelijke kosten-batenanalyse).

Overstromingsrisico wordt dan uitgedrukt als verwachtingswaarde van de schade. Ten opzichte van dit risicocriterium hebben de robuustheidscriteria een meerwaarde, omdat niet alle maatregelen die het risico verlagen ook de robuustheid vergroten. Met andere woorden: sommige maatregelen veranderen het systeem zodanig dat het beter kan omgaan met grote overstromingen. Dit is aangetoond in twee casestudies over overstromingen vanuit de IJssel en de Maas. Robuustheidscriteria kunnen dus tot andere beleidsvoorkeuren leiden.

Bij het maken van beleid over zoetwatervoorziening is het gebruikelijk om maatregelen te beoordelen op hun effect op leveringszekerheid van water. Leveringszekerheid als criterium is echter beperkt omdat het alleen iets zegt over de kans dat watertekort optreedt en niets over de maatschappelijke gevolgen hiervan. De robuustheidscriteria hebben dan een meerwaarde, omdat de maatregelen ook beoordeeld worden op de gevolgen van een eventueel watertekort, en of deze gevolgen nog acceptabel zijn. Ook de twee casestudies over droogte hebben aangetoond dat een beoordeling op basis van robuustheid tot andere beleidsvoorkeuren kan leiden.

Hoe ziet een systeem eruit dat robuust is voor overstromingen?

Systemen met een hoog beschermingsniveau dat overal gelijk is (zoals in het Nederlandse rivierengebied) hebben een grote weerstand tegen afvoeren. Ze zijn daarmee alleen niet automatisch robuust voor extreme afvoeren, omdat deze afvoeren plotselinge overstromingen kunnen veroorzaken met veel schade in een groot gebied. Een manier om een dergelijk systeem robuuster te maken is door de beschermingsniveaus te differentiëren. Hierdoor lopen minder kwetsbare gebieden als eerste onder en neemt de dreiging bij kwetsbaardere gebieden af. Een andere manier is door de dijken praktisch doorbraakvrij te maken. Plotselinge overstromingen worden hiermee vermeden en de gevolgen zijn kleiner, omdat er veel minder water tegelijk het gebied instroomt. Een combinatie van doorbraakvrije dijken met verschillende hoogtes is ook mogelijk en zal de robuustheid nog verder vergroten. Tot slot zijn maatregelen die de gevolgen beperken aan te bevelen voor een robuuster systeem, maar ze moeten dan wel de schade reduceren tot onder de herstelgrens.

Hoe ziet een robuuste zoetwatervoorziening eruit?

Systemen hebben een hoge weerstand tegen droogte als hun bergingscapaciteit groot is in verhouding tot de watervraag, bijvoorbeeld systemen met een groot waterreservoir. Een grote bergingscapaciteit betekent meestal ook een grote leveringszekerheid. Gevolgen van droogte hangen vooral samen met de absolute vraag. Als de vraag onder normale omstandigheden heel groot is, dan veroorzaakt een droogte veel schade. Robuustheid kan vergroot worden door de vraag structureel te verminderen en door kortetermijnmaatregelen of noodmaatregelen te plannen, zoals prioriteren tussen watervragers en tijdelijke aanvoer van water uit andere bronnen. Systemen waar landbouw veel water vraagt zijn gebaat bij diversiteit in gewassen.

Conclusie

Dit proefschrift heeft het begrip robuustheid toepasbaar gemaakt voor beleidsvorming op het gebied van overstromingen en droogte. Het biedt hiermee een nieuw perspectief voor het omgaan met extreme hoogwaters en langdurige droogte. Het robuustheidsperspectief ondersteunt beleidsmakers in het verkennen van kleine-kans-gebeurtenissen en het overwegen of de gevolgen hiervan nog acceptabel zijn. Het kwantificeren van robuustheidscriteria is een middel om inzicht te krijgen in systeemeigenschappen die ervoor zorgen dat gevolgen beperkt blijven zodat onbeheersbare situaties worden voorkomen.

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1 Introduction

1.1 Flood and drought risk

Floods and droughts cause major economic losses and large numbers of casualties worldwide (EM-DAT 2009, IPCC 2012). Floods and droughts are inherent and temporary features of our climate, resulting from natural variability in precipitation, streamflow and groundwater levels. Mankind has developed many ways to deal with this variability, for example by building flood protection or reservoirs. Flood protection reduces the probability of flooding and allows economic development in river valleys and coastal areas, utilizing the many benefits of water (agriculture, navigation, recreation, industry). Similarly, reservoirs store excess water in wet seasons making it available for use in dry seasons, for example for irrigation and public water supply. These structures are usually dimensioned based on design conditions, for example the 1:100 year flood or drought.

However, design standards can be exceeded. Flood disasters continue to show that flood protection cannot provide 100% safety, for example the Japan tsunami in 2011, the flooding of Queensland (Australia) in 2011, the flooding of Bangkok (Thailand) in 2011, and the river flooding of Central and Eastern Europe in 2013. Likewise, recent droughts have shown that even with storage facilities available water is not always sufficient to meet all needs. For example, the ongoing drought in the West of the United States has resulted in low levels in reservoirs, streams and rivers, and declining groundwater levels. Other examples are Brazil, currently facing the worst drought in decades, India in 2013, and East-Africa in 2011. These events demonstrate the often devastating impact of beyond-design events.

Worldwide, the frequency and severity of flood and drought events is expected to increase due to changes in frequency, intensity, spatial extent, duration and timing of

extreme weather (IPCC, 2007; UNISDR, 2009). Climate change not only affects the probability of flood and drought events, but also the uncertainty about these probabilities. This means it is more difficult to estimate future return periods of flood and drought events. To be able to derive design standards, for example for flood protection, it is traditionally assumed that the frequency distribution does not change in time ('stationarity'). It is argued that under climate change this stationarity assumption is not valid anymore and new methods should be developed to deal with non-stationarity in risk analysis (e.g., Salas and Obeysekera 2014, Olsen et al. 2010, Milly et al. 2008).

Simultaneously, the impact of flood and drought events is already increasing due to population growth and economic developments in flood-prone and drought-prone areas (Bouwer et al. 2007). Given projections on population growth and economic development in flood-prone areas, Jongman et al. (2012) estimated a factor 3 increase in global economic flood exposure between 2010 and 2050. Thus, the likelihood of floods and droughts with catastrophic impact is increasing. This is a challenge for decision makers responsible for keeping flood and drought risk at an acceptable level.

1.2 Risk-based decision making

There is a move towards risk-based decision making in water management (OECD 2013). Risk is understood as a combination of the probability of harmful events and their associated consequences. Risk-based decision-making (RBDM) is a process to achieve an acceptable level of risk against acceptable costs, by analysing and assessing the current risk and, if needed, analysing and assessing interventions on their costs and benefits. In this process, benefits can be expressed in terms of risk reduction. Risk analysis involves considering the full range of conditions to which a system might be exposed, including those that exceed the system's design standard (Hall and Borgomeo 2013). Risk assessment involves a discussion on risk acceptability, taking into account risk perception and societal preferences (Gouldby and Samuels 2005). If the risk is considered unacceptable, risk-reducing interventions can be proposed, which will then be analysed and assessed as well.

In the context of floods, there has been a move from flood control towards flood risk management over the last decades (Hooijer et al. 2004, Klijn et al. 2008, Merz et al. 2010). Flood control aims at protecting against a particular design flood. Flood risk management, instead, aims at achieving an acceptable level of risk against acceptable cost and prescribes equal consideration of probability-reduction measures as well as consequence-reduction measures.

In the context of droughts, risk-based decision making also receives increased attention. Many countries slowly move from a crisis management approach towards a risk-based approach to drought management (Wilhite et al. 2000, Rossi and Cancelliere 2012, UNISDR 2009). This involves developing plans for drought prevention, drought mitigation and drought preparedness, including monitoring and forecasting systems. Similar to flood risk, drought risk is a combination of probabilities and consequences.

Risk is often represented by a single-value metric: the expected value of economic and/or societal losses. The use of a single risk estimate as decision criterion has been criticised for a number of reasons:

- It may not meet the decision needs of all stakeholders (Downton et al. 2005);
- It assumes risk neutrality, while the public is generally risk averse (Merz et al. 2009, Slovic et al. 1977);
- It is uncertain (De Moel et al. 2012, Hall and Solomatine 2008, Klinke and Renn 2011);
- It does not distinguish between high-probability/low-consequence and low-probability/high-consequence risks (Merz et al. 2009).

This last point implies that potential consequences may grow unlimitedly, as long as the flood probability is reduced. Whether the consequences of low-probability events are still acceptable is seldom questioned. Other criteria are thus needed to assess the possibility of large consequences. This is sometimes called 'possibilistic thinking' instead of 'probabilistic thinking' (Downton et al. 2005) and requires taking into account 'what if design conditions are exceeded'.

1.3 Robust systems

Climate variability may result in events with unacceptable consequences to the social, economic and environmental system. Unacceptable impacts, or disasters, must be avoided. IPCC (2012) consider an event a disaster when the capacity to cope with impacts is exceeded such that normal activities are severely disrupted. This is often related to the large-scale and irreversible nature of the impacts.

The desire to design systems in such a way that the potential consequences of failure are still acceptable is not new. In engineering, robustness is an important design criterion, referring to the ability to maintain essential system characteristics when subjected to disturbances (Carlson and Doyle 2002). This means that some components may fail, but propagation of damage is prevented through feedback mechanisms so that the system as a whole remains functioning. For example, airplanes are robust to large atmospheric disturbances and tall buildings are robust when storm or fire damage does not propagate into total building collapse.

Robust systems are also known as fail-safe systems. Failure of a fail-safe system does not lead to catastrophic consequences, whereas a safe-fail system minimizes the probability of failure. Hashimoto et al. (1982b) discussed this idea in the context of water management and stated that instead of trying to eliminate the possibility of reservoir failure, measures should be taken to make the consequences of failure acceptable.

Thus, to avoid disasters, systems will need to be managed in such a way that the consequences of failure are societally acceptable. In this thesis, such systems are called *robust*. It is unclear how system robustness can be operationalized in a decision making context in order to compare alternative intervention options on their effect on system robustness.

1.4 Objective and research questions

The aim of this research is to make the concept of system robustness operational in the fields of flood and drought risk management. To that end, a conceptual framework for system robustness analysis, including quantifiable criteria, is developed and tested. The

proposed system robustness criteria should aid in choosing measures that reduce the risk in such a way that unacceptable consequences are avoided.

The main research question is: how can system robustness be meaningfully defined and assessed in the context of flood and drought risk management?

The following sub-questions are addressed:

1. How can system robustness be defined for flood and drought risk systems?
2. Which criteria and indicators can be used to quantify robustness of flood and drought risk systems?
3. What is the added value of system robustness analysis for flood and drought risk management?
4. What characterizes a robust flood risk system?
5. What characterizes a robust drought risk system?

1.5 Research approach

This thesis comprises two main parts: the conceptual framework for system robustness analysis and the application of the framework in four case studies. The conceptual framework has been developed and refined by applying it on the case studies. Therefore, Chapter 2 is the result of a process in which the concept of robustness was defined and the robustness criteria were tested, discussed and refined based on the results of the case studies. Since the results of the case studies are either published in or submitted to scientific journals, they must be understood as part of the process that led to the framework described in Chapter 2.

To develop the conceptual framework, relevant literature on the concept of dealing with extreme events was studied, including literature on resilience, robustness, flood risk management and water resources management. This led to a 'systems approach': the area of interest is considered a system with physical, socio-economic and environmental aspects, and this system is disturbed by an external stressor resulting from climate variability. This conceptualisation of a system is, in principle, applicable to any system exposed to external stressors. Based on the literature and the case studies,

criteria and indicators are proposed to score systems on their degree of robustness for the chosen disturbance (research question 1 and 2).

Different versions of the analysis framework were tested in four case studies, two in the context of flood risk management and two in the context of drought risk management. The four case studies helped developing the framework in the following way:

- IJssel River valley (the Netherlands): different measures were compared on the basis of both risk and robustness, providing input for the comparison of robustness with risk (research question 3). Furthermore, quantification of the criteria was supported with data on recent flood events in Europe and the United States (research question 2).
- Meuse River valley (the Netherlands): different measures were compared on their robustness, making use of a realistic dataset. Comparing these results with those of the IJssel River case provided input for a discussion on what characterizes a robust flood risk system (research question 4).
- Streamflow drought case inspired by the Oologah water supply reservoir (United States): the conceptual framework was operationalized for droughts, including the quantification of the robustness criteria (research question 1 and 2).
- Agricultural drought case in the Netherlands: the conceptual framework was further operationalized for agricultural droughts. Comparing these results with those of the Oologah case provided input for a discussion on what characterizes a robust drought risk system (research question 5).

1.6 Outline of this thesis

A schematic overview of this thesis is provided in Figure 1. **Chapter 2** introduces the conceptual framework for system robustness analysis, as developed and tested in the subsequent case studies, described in Chapter 3-6. **Chapter 3** develops the robustness analysis method for floods and discusses the recovery threshold, based on a river valley in the Netherlands: IJssel case. **Chapter 4** discusses the added value of robustness analysis in practice, based on two river valleys in the Netherlands: IJssel case and

Meuse case. In both cases, different types of measures to influence the system robustness were tested. **Chapter 5** is a first step towards robustness analysis for droughts, illustrated with a hypothetical case including a water supply reservoir. **Chapter 6** further develops the robustness analysis for agricultural drought risk management based on a case with coastal polder areas in the Netherlands. In **Chapter 7** the results of the cases studies are discussed and the research questions are answered. This chapter finalizes with recommendations for flood and drought risk management as well as recommendations for further research.

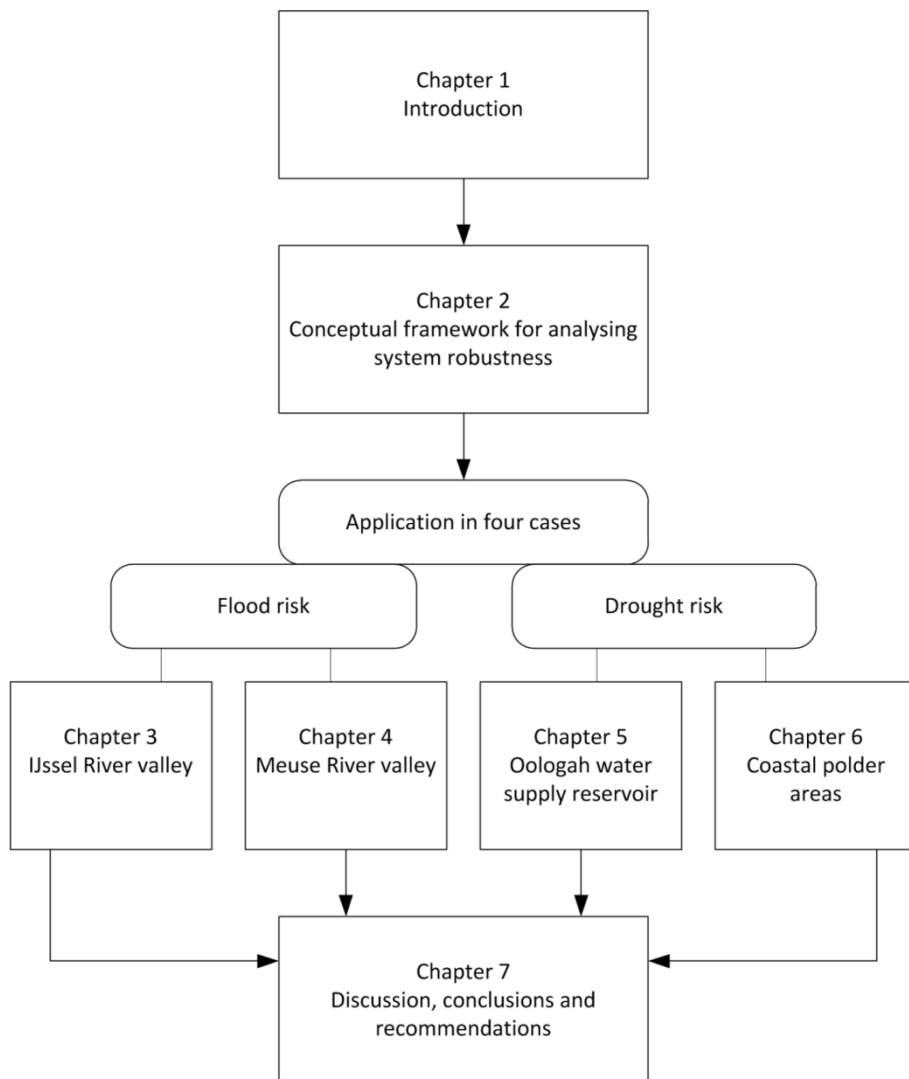


Figure 1 Outline of this thesis

2 Conceptual framework for analysing system robustness¹

2.1 Defining system robustness

2.1.1 ...in general

The term robust originates from the Latin *robustus*, meaning ‘strong’ or ‘hardy’. According to the Merriam-Webster dictionary, robust means having strength, being strongly constructed, or performing without failure under a wide range of conditions. In daily life, robustness is seen as a desirable characteristic, for instance of electricity networks that will remain functioning under high demand. Products or buildings that are designed in a robust way can survive all kinds of external forces without failing or collapsing. Robustness is thus associated with strength and durability.

In engineering, robustness refers to the ability of systems to maintain desired characteristics when subjected to disturbances (Carlson and Doyle 2002, Jen 2003). For example, airplanes are robust to large atmospheric disturbances. In biology, robustness is considered a key property of living systems, in which cells collectively reduce the impact of environmental perturbations (Stelling et al. 2004). In the transport sector, robustness is defined as the degree to which a road network can maintain its function under predefined circumstances such as short term variations in supply caused by incidents (Snelder et al. 2012). Here, robustness is seen as a characteristic of the road

¹ Parts of this chapter have been published as: Mens, M. J. P., Klijn, F., De Bruijn, K. M. and Van Beek, E. 2011. The meaning of system robustness for flood risk management. *Environmental Science & Policy*, 14(8), 1121-1131.

network and how it is managed. It means that road congestion due to incidents is prevented, and if congestion does occur, the impact on the functioning of the road network is limited, as alternative routes are available and measures and procedures are in place to enable quick recovery from the incident.

Thus, robustness as a system characteristic refers to the ability to withstand disturbances as well as the ability to recover quickly from the response to a disturbance, thereby limiting the impact from these disturbances.

2.1.2 ...in this thesis

In this thesis, system robustness is defined as *the ability of a system to remain functioning under a large range of disturbance magnitudes*. Because the focus of this thesis is on flood and drought risk management, robustness is seen as characteristic of a coupled physical and socio-economic system. System robustness has similarities with the concept of resilience and the concept of fail-safe systems.

A robust system can be considered fail-safe. Failure of a fail-safe system does not lead to catastrophic consequences, whereas a safe-fail system minimizes the probability of failure – i.e., this system has a high reliability, but consequences of failure may be large. Citing Holling (1978), Hashimoto et al. (1982b) explained the concept as follows:

“Even when it is possible to raise levees high enough or make water supply reservoirs large enough that failure is hard to imagine, it is often not economical to do so. After a point, effort is better expended making the consequences of failure less severe and more acceptable than in trying to eliminate the possibility of failure altogether.”

Merz et al. (2010) discussed the idea of fail-safe systems in the context of flood risk management and suggested the possibility of controlled flooding, by for example elevating roads in the flood-prone area, which will influence the spatial extent of the flood inundation and thereby reduce damage. In the Netherlands, a comparable effect is obtained by splitting up dike-ring areas – or ‘compartmentalization’, a strategy tested for the Netherlands by Klijn et al. (2009).

The fail-safe concept is also proposed in drought risk management: limiting the consequences of severe failure is acknowledged as an important criterion in water

supply system design (Preziosi et al. 2013, Stakhiv and Stewart 2010, Hashimoto et al. 1982b). However, the consequences of failure are often expressed in terms of the expected value of the amount of water shortage (Hashimoto et al. 1982b), which is limited to the physical water system. This may be a too narrow system definition in the context of drought risk management, because it lacks the impact of water shortage on the socio-economic system. In this thesis, robust or fail-safe means that the *socio-economic* consequences of system failure are still manageable.

Robust systems are comparable to resilient systems in ecological and socio-ecological literature. Holling (1973) introduced 'resilience' in ecosystem management and defined it as the ability to absorb disturbances without shifting into a different regime or state. Disturbances are for example fires, storms, floods and droughts. A regime shift occurs when the response to a disturbance is so large that the system characteristics significantly change (Scheffer and Carpenter 2003, Carpenter et al. 2001, Scheffer et al. 2001). An example of a regime shift is one from a clear-water lake to an algae-dominated lake. More examples can be found in the database of the Resilience Alliance (Walker and Meyers 2004, ResilienceAlliance 2011). Studying regime shifts is considered important for the management of systems, because if it is understood under which conditions a regime shift may occur, and what processes drive it, a system can be managed to persist in the desirable regime (Walker and Salt 2006).

Resilience has evolved into a broader concept of 'socio-ecological resilience' that is now used in many disciplines. The Resilience Alliance (ResilienceAlliance 2011, Folke 2006) defines it as "the capacity to absorb disturbance and re-organize while undergoing change as to still retain essentially the same function, structure, identity and feedbacks". This broader concept of resilience has been adopted by the climate change adaptation community as a way to deal with disturbing *events* (resulting from climate variability) as well as disturbing *trends* (resulting from climate change, e.g. sea level rise) (Wardekker et al. 2010, Linkov et al. 2014). This broad definition of resilience, including the ability to adapt to changes, is not identical to system robustness in this thesis, which is limited to the ability to deal with disturbing events resulting from climate variability.

A more narrow definition of resilience, the ability to recover from a disturbance (Begon et al. 1996), has been applied in flood risk management by De Bruijn (2004). She distinguished between resistance and resilience as two system characteristics that determine a system's response to disturbances. She defined resistance as the ability to withstand disturbances without responding at all, and resilience as the ability to recover from the response to disturbances. This narrow definition of resilience, also known as 'engineering resilience' (Holling 1996), stays close to its Latin origin *resilire*: to jump back. System robustness can be understood as a combination of resistance and (engineering) resilience.

Analysing concepts such as resilience and robustness requires specifying *of what* system and *to what* type of disturbance (see also Carpenter et al. 2001). Because this thesis focuses on water management, the disturbance refers to a temporary event, resulting from climate variability, for example a flood or drought event. The system of which robustness is analysed is defined in the next two sections. How the disturbance impacts the system is called the system response. A response curve describes the relationship between disturbance magnitude and system response.

2.1.3 ...of flood risk systems

A flood risk system is defined as a geographic area, along the coast or along a river, prone to flooding. The system comprises physical and socio-economic components. The physical subsystem is characterised by the elevation of the flood-prone area, the physical elements that control floods (e.g., embankments and structures), and the land cover. The socio-economic subsystem represents the people that live in the flood-prone area, among other things characterized by their age, health, education and social networks, as well as the economic value of land uses, the financial situation of the area, and economic connections to other areas.

Flood risk systems can be disturbed by intensive rainfall, flood waves in river catchments, and storm surges at sea, which may lead to flooding of areas that are otherwise dry. Rainfall, river discharges and sea water levels vary naturally in time and normally do not cause significant damage. However, extreme events may cause loss of

life/injury, and damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources (IPCC 2012).

Flood risk system robustness can be defined as the ability of a river valley or coastal plain to remain functioning under a range of flood waves or storm surges. Robust flood risk systems have some degree of resistance and some degree of resilience: the system can withstand some floods (no response), and for other (larger) floods impacts are limited and the system can recover quickly from the flood impact (response and recovery).

Figure 2 shows the response curves of two hypothetical river valleys. In this case, the river discharge is the disturbance and flood impact is the response. System A represents a river valley with very high embankments and a densely populated flood-prone area behind these embankments. This system can withstand a large range of flood magnitudes, but when the discharge exceeds the embankment height, the valley suddenly floods leading to a large impact. In contrast, system B is a natural river valley with a less-densely populated floodplain. This system's response starts at smaller disturbance magnitudes and then increases gradually. System A has a high degree of resistance and system B has a high degree of resilience.

The Mississippi river valley (United States) can be considered a good example of a robust flood risk system. During the extreme flood event in 2011, levees were intentionally blown up to inundate a rural area so as to lower river levels and avoid flooding in more densely populated area. As Park et al. (2013) note: "By intentionally selecting the mode of levee failure, and by planning for management of the failure event and reconstruction, the USACE [United States Army Corps of Engineers – the flood risk manager] was able to minimize the adverse consequences of the 2011 flood, and prevent a more devastating catastrophe." In this example, the management of the system, including planned actions at predefined triggers and clear assignment of responsibilities, is considered part of the flood risk system.

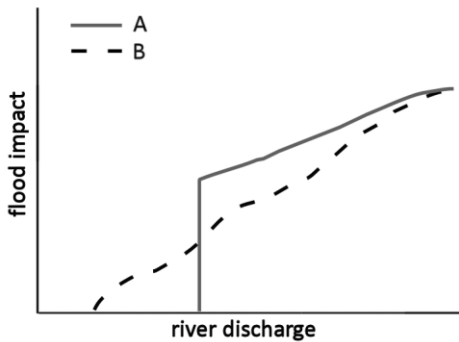


Figure 2 Response curves of two hypothetical river valleys disturbed by flood waves

2.1.4 ...of drought risk systems

A drought risk system is defined as a geographic area exposed to droughts. The system comprises physical as well as socio-economic components. The physical subsystem includes soil type, land cover and water management infrastructure (e.g., canals and irrigation installations). The socio-economic subsystem includes water users and their activities as well as plans and responsibilities to manage the water system.

Drought risk systems can be disturbed by meteorological drought (precipitation deficit) and/or hydrological drought (streamflow deficit). Precipitation, evaporation and streamflow vary naturally in time and normally do not cause impact on the system. However, periods of low precipitation and/or low streamflow may cause water shortage potentially harming the area's functions such as drinking water supply, industry, agriculture, power generation and environmental flows.

The concepts of resistance and resilience of flood risk systems can also be applied to drought risk systems. A system has resistance to droughts as long as water shortage does not occur. The resistance of a drought risk system determines the water supply reliability, the probability that water demands can be met. Supply reliability is a common criterion to assess the performance of water supply systems (Hashimoto et al. 1982b). In the water resources management literature, resilience is often measured as the probability of meeting water demand again after water shortage occurred or as the maximum duration of water shortage (Moy et al. 1986, Kjeldsen and Rosbjerg 2004).

However, this metric only includes water supply and demand and lacks the socio-economic context. Failure to meet water demand is not always a good representation of socio-economic consequences of water shortage. Thus, analogous to flood resilience, drought resilience is defined as the ability to limit drought impacts and quickly recover from these impacts.

An example of a robust drought risk system can be found in the Netherlands. During dry summers, available water is insufficient to meet all needs. To avoid irreversible damage, management rules have been formulated that determine which water user receives priority. Because of this priority setting and because it is clear who is responsible for taking decisions during a drought, drought impacts are usually limited. Other reasons to consider this drought risk system robust are discussed in Chapter 6.

2.2 Analysing system robustness

2.2.1 Response curve

Analysing the robustness of a system requires insight into the response curve: the relationship between disturbance and system response (Figure 3). Along the range of disturbance magnitudes, three kinds of system response can be distinguished. The response is zero for a first range of disturbance magnitudes, until a certain resistance threshold. In the second range, the response increases with increasing disturbance magnitudes until another threshold is reached: the recovery threshold. As long as the response is below the recovery threshold, recovery from the response is still possible. The third range is the range beyond the recovery threshold. A robust system is one where the response to a disturbance remains below this threshold over a large range of disturbance magnitudes.

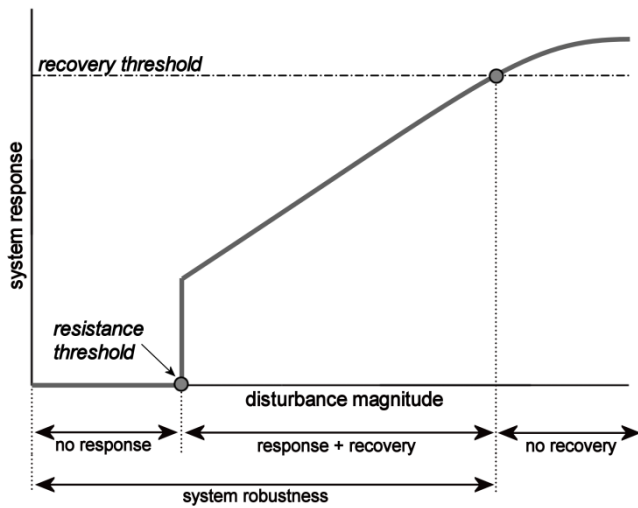


Figure 3 Theoretic response curve with three response levels associated with a range of disturbance magnitudes

The analysis of system robustness requires a definition of the system, the disturbance, the response and the recovery threshold. How these elements fit together is visualized in Figure 4. The disturbance of interest results from a naturally variable phenomenon such as river discharge or precipitation. In case of river discharge, the disturbance could be a discharge wave. In case of precipitation the disturbance could be a period with little precipitation. Whether this disturbance leads to a physical response in the system depends on the protection level against floods or the capacity to store water. Physical response can be flood inundation or declining water levels, for example in reservoirs, canals or the subsurface. The extent to which the physical response causes socio-economic impacts is determined by the exposure and vulnerability of the system to this disturbance. Exposure refers to the people, assets and activities affected by a hazard or disturbance; vulnerability is the potential to be harmed, as a function of their susceptibility and value (Gouldby and Samuels 2005).

Whether an impact becomes a disaster depends on the social and economic capacity of the region to recover from the impacts (coping capacity). A disaster may be defined as a serious disruption of the functioning of a community or a society. This involves

widespread human, material, economic or environmental losses and impacts, which exceed the coping capacity of the affected community or society (UNISDR, 2009). Recovery is the process of returning to a normal situation after an event. Recovery from floods involves pumping out water, cleaning the flooded area, reconstructing houses and other buildings, repairing infrastructure, etc. Recovery from drought involves, among other things, recharging aquifers and storage basins, and replanting crops.

The long-term impact of an event depends on the time it takes to recover, which in turn depends on the recovery capacity. Recovery capacity is defined as the general socio-economic level of society, referring to system characteristics that influence the ease with which a system recovers. Recovery capacity is a function of social capital – the ability to organize repair and reconstruction, and economic capital – the ability to finance repair and reconstruction (cf. De Bruijn 2005, Marchand 2009). A high recovery capacity implies that only very large impacts exceed the recovery threshold. Recovery capacity can be represented by a recovery threshold: the level of response or impact from which recovery is difficult.

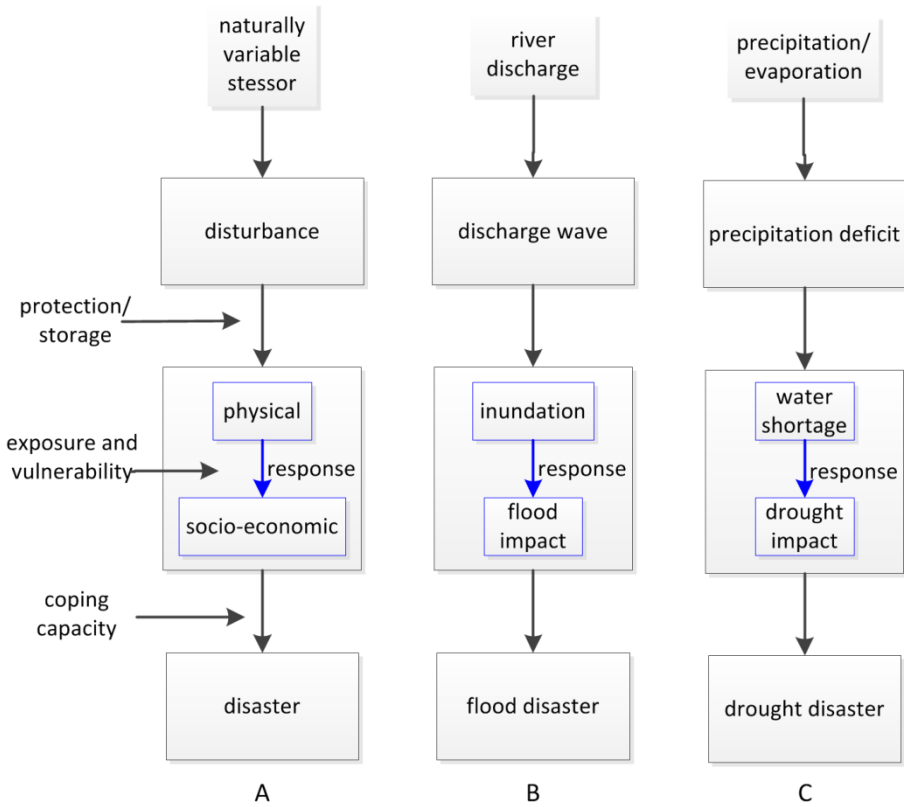


Figure 4 Relationship between disturbance, response and disaster applied on A) a conceptual system, B) a flood risk system, and C) a drought risk system

2.2.2 Characterising system robustness

The response curve can be described by the following characteristics (De Bruijn 2004):

1. a threshold that represents the resistance of the system;
2. the impact increase with increasing disturbance magnitudes;
3. the severity of the impact;
4. the recovery rate from a state where flood impacts are visible to a normal state.

The first characteristic can be called the *resistance threshold*, which is the point where the response becomes greater than zero. The resistance threshold in a flood risk

system is mainly determined by the protection level. Exceeding this level will cause inundation and most likely impact the socio-economic system. The protection level thus may be a good first indicator for the resistance threshold. In drought risk systems, the resistance threshold depends on the storage capacity within the system in relation to the demand. The water supply reliability may be a good first indicator for the drought resistance threshold.

The second characteristic can be called *proportionality*. Proportionality reflects the suddenness of the response. Some argue that a more proportional response curve is preferable, in contrast to one where the increase in response is large compared to the increase in disturbance magnitude. According to De Bruijn (2004), discontinuity of the response curve of a flood risk system may point at the possibility of a disaster, because intuitively people expect an increase in response that is proportional to the increase in discharge. Discontinuities occur, for example, when embankments breach due to overtopping.

A more proportional curve is often found in systems with a low resistance threshold. When floods or droughts occur more frequently with less severe impacts, people are expected to be better prepared and therefore a sudden increase in impact is unlikely. In contrast, systems with a high resistance threshold often also have a low proportionality, because well-protected areas attract socio-economic developments which increase their vulnerability. The flood probability may then be very small, but an extreme flood will immediately result in a high impact. Likewise, a drought risk system with high reliability (high resistance threshold) will have enough fresh water available under normal conditions, attracting water users who will get used to this situation. An extreme drought may then have a high impact.

The third and fourth characteristics are closely related. The severity of the impact refers to the short-term impact directly after the system has been disturbed. The long-term impact depends on the recovery rate, which in turn depends on the recovery capacity. This means that one region may recover more quickly from the same short-term impact than another region if its recovery capacity is larger.

When presented as an absolute value, the response severity is not an adequate indicator for whether the system can remain functioning, since the degree of disruption depends on how this damage is spread over the area and over the functions, and how it relates to what the area can cope with. The severity of the impact thus becomes more meaningful if it is compared with a recovery threshold, which was defined above as the level of impact from which recovery is difficult. It is therefore proposed to assess the severity of the impact relative to a recovery threshold, which can be called *manageability*. A faster recovery points at a larger recovery capacity and a higher recovery threshold.

Summarizing, the response curve can be described by the following criteria (Figure 5):

1. Resistance threshold
2. Proportionality
3. Manageability

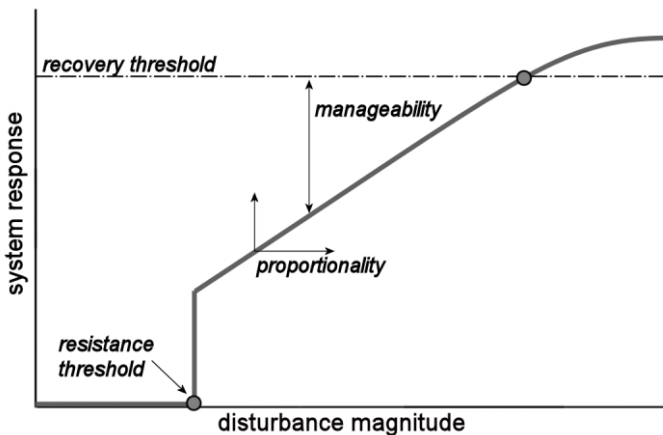


Figure 5 Response curve with robustness criteria

2.2.3 Quantifying system robustness

In order to quantify the three robustness criteria, indicators are needed. The *resistance threshold* can be quantified by the highest disturbance magnitude for which the response is negligible. For fluvial floods this can be expressed by the smallest discharge

where damage is first expected. For droughts, this can be expressed by the smallest precipitation deficit or streamflow deficit causing first impacts.

Proportionality can be quantified in different ways. De Bruijn (2004) calculated it as a value between 0 and 1, by expressing all discharges and damages in percentages of the total range considered. When the relative damage increase is exactly proportionate to the relative discharge increase over the entire response curve, proportionality scores 1. It scores close to 0 when the relative damage increase is much larger than the relative discharge increase somewhere along the curve.

In this thesis a similar approach is applied, based on the slopes of sections of the curve (Eq.1). The proportionality is 1 minus the maximum slope of the sections divided by the largest damage of all configurations. The resulting value represents the additional relative response that is caused by a standard increase in disturbance magnitude.

$$Proportionality = 1 - \frac{\max_{i=2}^N \frac{R_i - R_{i-1}}{D_i - D_{i-1}}}{D_{max}} \quad (1)$$

where:

- D = disturbance magnitude
- R = system response
- i = section indicator
- N = number of sections
- D_{max} = maximum impact of all configurations

Manageability refers to how close the response is to the recovery threshold. Quantifying this threshold requires defining when an impact becomes an unmanageable situation or disaster. When this threshold is set, manageability can be quantified by giving a score between 0 and 1 depending on at which point the curve crosses the recovery threshold. If the curve does not cross the threshold at all over the

full range of studied disturbance magnitudes, manageability is high. If the curve crosses the threshold as soon as the resistance threshold is exceeded, manageability is low.

2.3 Response curve in comparison to a risk curve

To understand the differences and similarities between risk and robustness, the concept of risk and risk curves has to be understood first. Risk is often defined as the probability of an event times the consequences of that event. Kaplan and Garrick (1981) suggest expressing risk as the relationship between probabilities and consequences. Likewise, Gouldby and Samuels (2005) acknowledge that risk is not just a multiplication of probability and consequence, but rather a function of the two elements:

$$\text{risk} = \text{function}(\text{probability}, \text{consequence})$$

Flood risk is built up from a set of 'scenarios' (events) that could happen, each having a probability and corresponding consequence. Various flood events in an area may have different consequences, not only because 1:100 year events cause less impact than 1:1000 year events, but also because an area may be flooded from different directions. When estimating flood risk, it is important to understand how the flood consequences are distributed over the probabilities. Therefore, risk is often shown as the cumulative probability distribution of the flood impact, also known as a 'risk curve' (Kaplan and Garrick, 1981). A single-value risk estimate, which is used in many flood risk studies (e.g., Meyer et al. 2009), equals the area under the risk curve: the expected annual flood damage (see Figure 6).

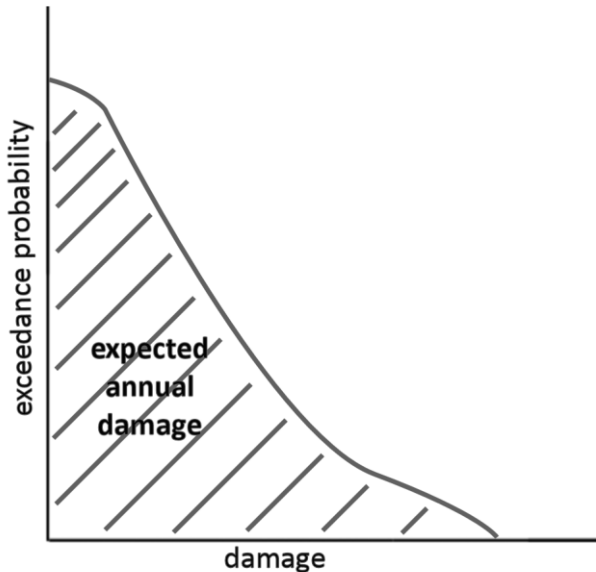


Figure 6 Risk curve: probability distribution of flood damage

The response curve, showing the impact as a function of a range of disturbances, can be easily converted to a risk curve, and vice versa. The x-axis of the response curve is a physical quantity, for example river discharge. When this x-axis is replaced by the corresponding exceedance probability, a risk curve is obtained (see example in Figure 7). In this example, an area is protected against a river discharge of $2000 \text{ m}^3\text{s}^{-1}$ with a return period of 100 years. An extremely high discharge of $3500 \text{ m}^3\text{s}^{-1}$ with an average return period of 1000 year (exceedance probability of $1/1000$ per year) causes flood damage of 10 million euro. The response curve on the left shows that the flood damage increases with increasing discharge, and that damage is zero for discharges smaller than $2000 \text{ m}^3\text{s}^{-1}$: the resistance threshold. In the curve on the right, the discharges are replaced by the corresponding exceedance probability. Thus, the order of the values is reversed; low probability corresponds to high flood damage. The expected annual damage is equal to the area under the right curve and equals 100.000 euro per year.

Thus, to obtain a response curve, the same underlying data is used as for obtaining a risk curve. The main difference is that a response curve does not need assumptions

about return periods of river discharges, because the x-axis is a physical quantity instead of an exceedance probability. In the example, the risk curve is a probability distribution of flood damages whereas a response curve is a relationship between discharges and flood damages. The effect is that a response curve puts more emphasis on the damages that correspond to the (uncertain) tail of the discharge distribution.

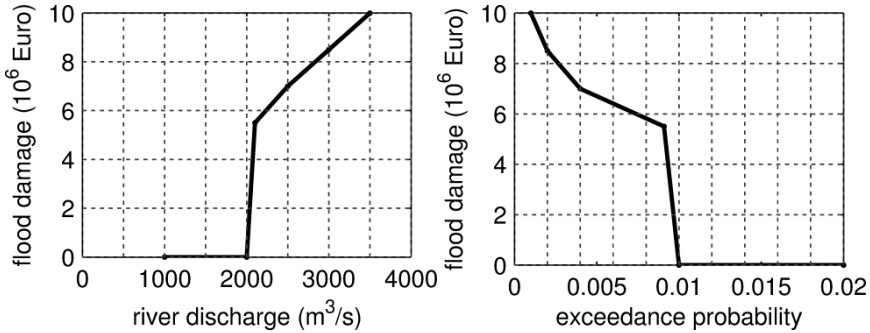


Figure 7 Comparison between a response curve (left) and a risk curve (right) for a system disturbed by river floods

2.4 System robustness versus decision robustness

Decision robustness – a characteristic of policy decisions – is a commonly used concept in policy analysis, and is used as a criterion for making decisions under uncertainty (Rosenhead et al. 1972, Lempert et al. 2003). It refers to how sensitive a particular decision is to uncertainty about how the future develops. In other words, a decision or policy is considered robust when it performs well under a range of future conditions. The RAND Corporation developed this concept further into a systematic approach for developing management strategies that are robust to uncertainty about the future, called Robust Decision Making (RDM). Decision robustness has been discussed for use in the field of flood risk management (Hall and Solomatine 2008, Merz et al. 2010), and has, for example, been applied in a flood risk management study for Ho Chi Minh City, Vietnam (Lempert et al. 2013).

Decision robustness is also known from the water resources management literature (Hashimoto et al. 1982a), where it is defined in a comparable way. Groves et al. (2013) applied RDM in a water supply and demand study for the Colorado River Basin, United States. They showed under which future conditions (in climate and socio-economy) the water supply from the river basin is not sufficiently reliable, and in how many future scenarios different intervention options increased the reliability. Decision robustness was then quantified as the percentage of scenarios in which water supply reliability was still acceptable. This shows that whether a decision is considered robust depends on the chosen performance criteria. The water supply reliability does not inform about the consequences should failure occur. Thus, in this example, a robust decision does not automatically lead to a system that can cope with the consequences of extreme droughts.

Haasnoot et al. (2013) developed a method to support the development of robust strategies for water management: dynamic adaptive policy pathways (DAPP). With this method, policymakers can explore possible actions based on their effect under a range of possible future developments over time. Compared to other robust decision making methods, DAPP takes into account that policies may be adapted in response to events or changes. Thus, the method allows adapting decisions over time. Adapting a policy over time requires defining triggers and signposts to indicate when corrective actions

need to be taken. This works well with gradual changes that are easy to detect such as sea level rise and population changes.

Although system robustness and decision robustness both refer to the insensitivity to fluctuations or changes, they differ in the following ways:

- | | |
|----------------|---|
| Object: | Decision robustness is a characteristic of a strategy, whereas system robustness is a characteristic of a system; |
| Time scale: | Decision robustness is typically focused on consequences of decisions under uncertain conditions in the long term (50-100 years ahead), whereas system robustness is analysed for a short period. |
| Disturbance: | Decision robustness focuses on the impact of long-term gradual change, whereas system robustness focuses on the impact of temporary events, resulting from variability. |
| Uncertainties: | Decision robustness typically relates to different types of uncertainty (e.g., climate change, economic development, and how processes are modelled), whereas system robustness narrows down to one specific type of uncertainty: the natural variability of the relevant external disturbance. |

Summarizing, both RDM and system robustness analysis support the development of strategies, taking uncertainty into account. They differ in time scale, type of disturbance and type of uncertainty. This thesis focuses on system robustness to temporary events resulting from climate variability.

3 The added value of system robustness analysis for flood risk management²

Abstract

Decision makers in fluvial flood risk management increasingly acknowledge that they have to prepare for extreme events. Flood risk is the most common basis on which to compare flood risk-reducing strategies. To take uncertainties into account the criteria of robustness and flexibility are advocated as well. This paper discusses the added value of robustness as additional decision criterion compared to single-value flood risk only. We do so by quantifying flood risk and system robustness for alternative system configurations of the IJssel River valley in the Netherlands. We found that robustness analysis has added value in three respects: (1) it does not require assumptions on current and future flood probabilities, since flood consequences are shown as a function of discharge, (2) it shows the sensitivity of the system to varying discharges and (3) it supports a discussion on the acceptability of flood damage. We conclude that robustness analysis is a valuable addition to flood risk analysis in support of long-term decision-making on flood risk management.

² This chapter has been published as: Mens, M. J. P. and Klijn, F. 2014. The added value of system robustness analysis for flood risk management. *Nat. Hazards Earth Syst. Sci. Discuss.*, 2, 2913-2945.

3.1 Introduction

Flood disasters continue to show that flood protection cannot provide a 100% safety. The Japan tsunami flood levels, following the 8.9-magnitude earthquake in March 2011, far exceeded the design heights of the flood walls. Other examples include the flooding of Queensland, Australia in January 2011, and the flooding of Bangkok, Thailand in October 2011. These disasters emphasize the inherent variability of hazards, and the often devastating impact of beyond-design events. The question is how decision-makers and planners should deal with this natural variability in the management of their system.

The traditional way to deal with climate variability is risk-based decision-making. Also in flood risk management, flood risk is the key criterion for decision-making, which is often balanced with the investment cost of the strategy. However, there are two reasons why flood risk may not suffice.

The first reason is that flood risk does not shed light on the acceptability of flood consequences. Flood risk is usually expressed as a single number, for example as the expected annual damage, which does not distinguish between high-probability/low-consequence and low-probability/high-consequence risks (Merz et al. 2009). This implies that potential consequences may grow unlimitedly, as long as the flood probability is reduced. Whether the consequences of low-probability events are acceptable is seldom questioned. Already 30 years ago, Kaplan and Garrick (1981) stated that a single number is not enough to communicate the idea of risk. Instead, they suggested using the full risk curve, which shows flood consequences as a function of the probability of exceedance, thereby putting emphasis on the tail of the distribution.

A different way to emphasize the low-probability/high-consequence part of flood risk is to add a risk aversion factor. Risk aversion refers to the fact that an accident with hundred fatalities is judged worse than a hundred accidents with one fatality each (a.o. Slovic et al. 1977). Different ways have been proposed to include risk aversion in risk analysis (see Jonkman et al. 2003), all resulting in higher single-value risk values. Although including this factor may increase the benefit of consequence-reducing measures, it does not provide a basis for discussing damage acceptability.

The second reason why risk may not suffice as decision-criterion is that it is uncertain how it will change over time following socio-economic developments and climate change. This paper is limited to the effects of climate change. The difficulty is in deciding upon the most cost-effective strategy, for which future flood risk needs to be quantified, while it is unknown how the climate will develop and how this affects river discharge variability. A range of equally plausible climate scenarios can be used to explore the future (Bouwer 2013, De Bruijn et al. 2008), but applying only one scenario may imply either spending too much if the future climate change is slower, or spending too little if the climate change is faster than the scenario suggests. Attempts to solve this issue are numerous, for example robust decision making (Lempert et al. 2003), tipping points analysis (Kwadijk et al. 2010) and adaptation pathways (Haasnoot et al. 2012). Although these methods can support decisions about when to implement a strategy in time, they do not solve the issue of how well a system can deal with extreme events.

An alternative way to a broader analysis of flood risk is to consider a system's robustness to a full range of river discharges. The idea is that a system that can deal better with natural variability is also better prepared for climate change. As Brown (2007) note, often climate-related risks are dominated by the present climate variability, and much can be done to reduce the vulnerability for extreme weather events. We already proposed robustness analysis as a way to incorporate uncertainty about system disturbances (Mens et al. 2011). System robustness refers to how well a system can cope with disturbances such as high river discharges, given uncertainty about the occurrence of these discharges. A robust system may have the same flood risk as its less-robust counterpart, but unexpected events are less likely to unfold in an unmanageable situation. For example, in a robust system the failure of one of the flood defences will cause minor flooding instead of major flooding that will take years to recover from.

Robustness analysis involves presenting the consequences of flooding as a function of discharge by means of a response curve. The response curve can be considered a risk curve, where probabilities are replaced by the discharge at the boundary of the system. The response curve forms the basis to quantify four robustness criteria: resistance

threshold, response severity, response proportionality, and point of no recovery. The resistance threshold refers to the smallest discharge that will cause flood damage. Severity is the impact of the flood, for example economic damage. Proportionality is the relative change in damage when the disturbance magnitude increases. The fourth criterion, point of no recovery, indicates the event from which recovery will be virtually impossible and/or the system will change significantly.

The aim of this paper is to discuss the added value of system robustness analysis, by applying it on several alternative flood risk system configurations, and compare the results with an analysis of flood risk. For this we performed a case study of the IJssel River valley in the Netherlands. The IJssel River is a branch of the Rhine River.

Case introduction

The flood risk system under study is the IJssel River valley in the Netherlands, a natural river valley with embankments on both sides of the river. The flood-prone area is divided into 6 dike-ring areas, which are areas surrounded by a closed ring of flood defences and higher grounds (Figure 8). The defences are designed to withstand river flood levels that occur on average once in 1250 years. As a consequence of climate change, the future Rhine design discharge may be raised from $16,000 \text{ m}^3\text{s}^{-1}$ to $18,000 \text{ m}^3\text{s}^{-1}$. This practically means that embankments must be raised in the future to withstand higher water levels, unless measures are taken to lower extreme flood water levels by giving more room for the river. Moreover, flood risk will increase due to socio-economic developments such as population growth, economic growth and land use changes. This was recently investigated for the Netherlands in Klijn et al. (2012a). The Delta Programme (Deltaprogramme 2011) currently explores how to deal with the increased future flood risk.

In this paper, we quantify flood risk and robustness of different system configurations. We define a system configuration is a combination of physical and socio-economic characteristics of the flood risk system, including assumptions about the stage-discharge function near the breach locations, embankment height and strength (quantified by a fragility curve), and land use. Each system configuration is a potential 'reality', in which measures such as raising embankments are implemented compared

to the current (reference) situation. For each alternative configuration we calculated flood risk and robustness. The system configurations are explained in Table 1.

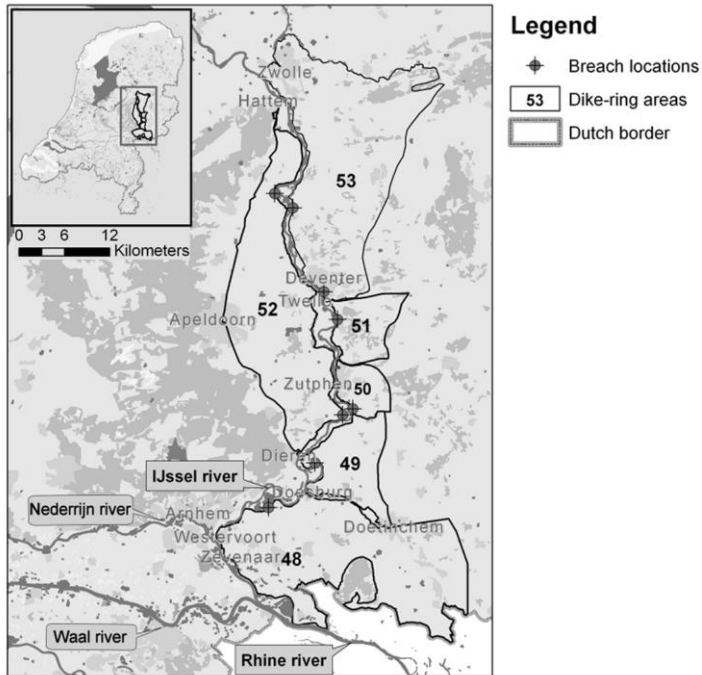


Figure 8 Case study area: IJssel River valley with delineation of dike-ring areas.

Table 1 Overview of alternative system configurations

ID	Name	Explanation
REF	Reference situation	Embankments are designed to withstand a discharge of $2560 \text{ m}^3\text{s}^{-1}$ ($T=1250$ years); the flood probability at each breach location is 1/1250 per year; land use of the year 2000.
CE	Conventional embankments	Embankments are raised with a location-dependent water level difference, which corresponds to a change in discharge from $T=1250$ to $T=5000$ years. Compared to the reference, we thus adapted the fragility curves.
RR	Making room for the river	The floodplains are lowered so that the current design water level is reached at a higher discharge. The ΔQ is about $260 \text{ m}^3\text{s}^{-1}$. This value is chosen such that the flood probability of the entire system equals that of CE.
UE1	‘unbreachable’ embankments version 1	All embankments are strengthened (not raised) so that they become ‘unbreachable’. Water may flow over the flood defence and result in flood damage.
UE2	‘unbreachable’ embankments version 2	As UE1, but embankments near cities are raised with an additional 0.5 m.

3.2 Flood risk analysis

3.2.1 Approach

We calculated the flood risk of the entire IJssel flood risk system based on flood simulations of eight different breach locations with corresponding probabilities and consequences. We simulated flooding using the two-dimensional hydrodynamic model Delft-FLS (WL|Delft Hydraulics 2001). The resulting flood depth maps were input for the *DamageScanner*, developed by De Bruijn (Klijn et al. 2007), to calculate economic damage. The damage corresponding to one breach location is considered representative for an embankment stretch. This means that any breach along this stretch will result in a similar flood pattern. For each stretch we assumed a probability

of failure that depends on the river water level. We divided large dike-ring areas into two subareas, with one breach location each.

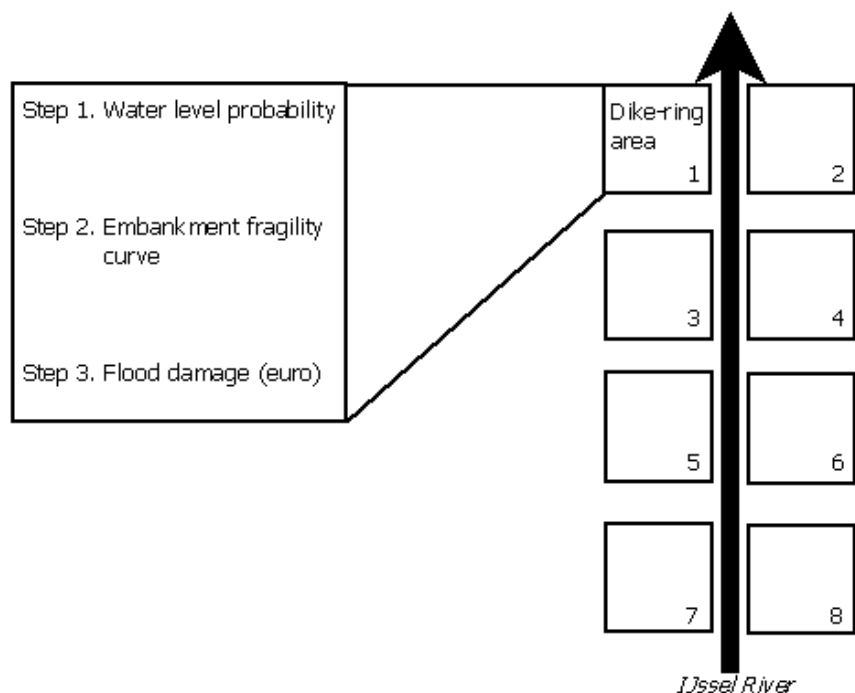
We modelled embankment breaches with a breach growth function at a predefined location. This function relates the breach width and water level difference with the inflowing discharge. The breach width increases to 220 meter in 72 hours. For flood waves that exceed the local embankment, breaches start as soon as the water level exceeds the crest level. For smaller flood waves, the breach starts at the peak of the flood wave. These breaches are assumed to be initiated by structural failure of the embankment, for example by the piping mechanism.

To estimate the flood risk for the entire IJssel system, we followed four steps (Figure 9):

1. Calculate water level probability distribution per breach location;
2. Define fragility curve at each breach location;
3. Calculate potential damage for each breach location and combinations;
4. Calculate flood probability and risk for the entire system.

The combination of the first two steps provides the embankment failure probability (=flood probability) per breach location. In the reference situation this should equal the current design standard of 1/1250 per year.

Procedure for each dike-ring area:



Procedure for entire flood risk system:

Step 4. Flood probability and flood risk

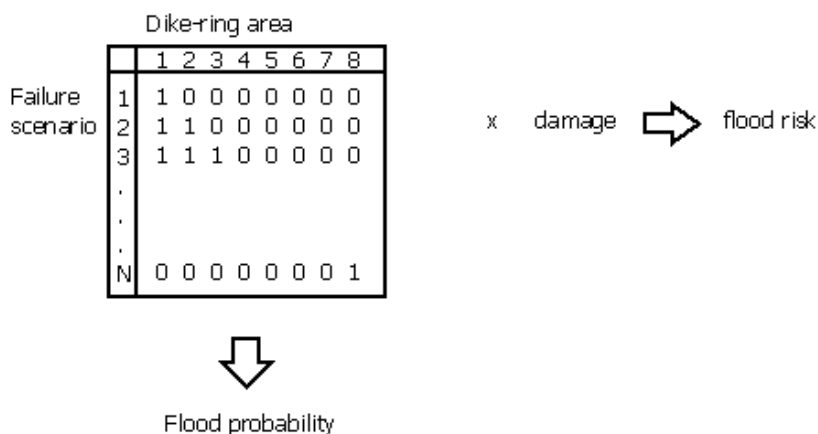


Figure 9 Steps in the flood risk analysis

3.2.2 Step 1: water level probability distribution per location

In this step we derived the IJssel discharge frequency curve from the Rhine discharge frequency curve, and then converted it to a water level exceedance curve at each breach location. The IJssel frequency curve was derived from Eq.2 (Van Velzen et al. 2007). Because it is uncertain how much water diverts into the IJssel River, we used three diversion fractions: 0.15, 0.16 and 0.18. A fraction of 0.15 means that 15% of the Rhine River discharge diverts into the IJssel River. In all studies for the Dutch government, it is presently assumed that 15.4 % of the Rhine discharge diverts to the IJssel. The parameters a and b in Eq. 2 are multiplied with the diversion fractions.

$$T = \exp\left(\frac{Q-b}{a}\right) \quad \text{for: } 25 < T < 10.000 \text{ year} \quad (2)$$

where:

Q	=	Rhine discharge ($\text{m}^3 \text{s}^{-1}$)
T	=	Return period (years)
a	=	1316
b	=	6613

To obtain a water level frequency curve, the discharge in the above equation was replaced by the corresponding water level at each breach location, based on the stage-discharge relation. Next, the water level return period at location k (T_k) was converted to a water level exceedance probability, according to:

$$1 - F_k(h) = 1 - e^{-\frac{1}{T_k(h)}} \quad (3)$$

where:

$1 - F_k(h)$	=	water level exceedance probability
$T_k(h)$	=	water level return period (year)
k	=	location index

3.2.3 Step 2: fragility curve for each location

The embankment fragility curve gives the relation between the river water level and the probability of embankment failure given that water level. Although different curves should be constructed for each failure mechanism (Van der Meer et al. 2008), we assumed one encompassing fragility curve representing all mechanisms. We approached the curve with a standard normal distribution function with $\sigma = 0.2$ and μ depending on the embankment height (Figure 10). Integrating the water level probability density function with the fragility curve gives the flood probability at a location as in Eq.4.

$$P_k = \int f_k(h) \cdot PC_k(h) \cdot dh \quad (4)$$

where:

- P_k = flood probability of location k
- $f_k(h)$ = water level probability density function
- $PC_k(h)$ = Conditional probability of embankment breaching:

$$PC_k(h) = \Phi(\mu = m; \sigma = 0.2) \quad (5)$$

For the reference situation, we chose the μ such that the flood probability per location equalled 1/1250 per year (i.e., the protection standard in the reference situation). We used the water level probability based on a diversion fraction c of 0.154. This reflects the current practice for deriving water levels for embankment design. Equation (4) was thus solved for each breach location, with $P_k = 0.0008$, and $c = 0.154$.

In the alternative system configurations we adapted the fragility curves to represent embankment reinforcements, by increasing the μ .

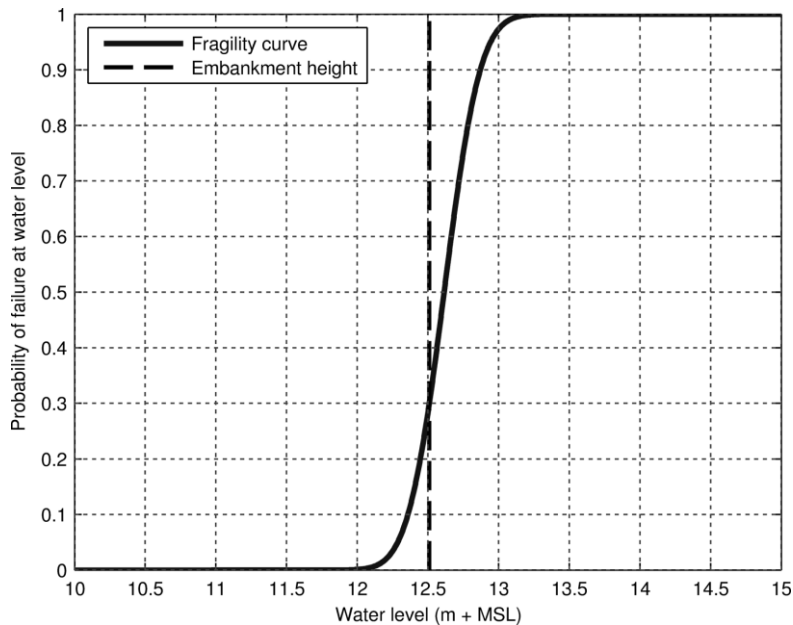


Figure 10 Fragility curve for dike-ring 48

3.2.4 Step 3: potential damage at each breach location

Potential flood damage was calculated for the eight breach locations, using the maximum flood depth maps as input for the damage model. Although the damage will increase with increasing discharge, we only used the damage figures corresponding to a flood with design discharge in the risk calculation. This will slightly underestimate the risk. However, higher damages also have a lower probability, thus contributing less to the risk.

3.2.5 Step 4: flood risk of the entire system

The flood risk calculation of the IJssel valley combines flood probabilities and consequences of eight breach locations. Because these potential flood events are correlated, we applied a Monte Carlo approach. To this end, we sampled 10,000 events from the local independent flood probabilities at each breach location. We defined the flood probability at each location with a so-called limit-state function Z , where $P(Z < 0)$ means failure (thus: flooding). Z has a normal distribution and follows from u , which

has a standard normal distribution. The relation between Z and the standard normal variable is required to be able to include correlations between different Z -functions.

The Z -function at the first breach location is described as:

$$Z_1 = \beta_1 - u \tag{6}$$

where:

- u = standard normal stochastic variable belonging to Z_1
- β_1 = reliability index of location 1

The Z -functions of the other seven locations are correlated with the first location as follows (Vrouwenvelder and Steenbergen 2003):

$$Z_k = \beta_k - \rho \cdot u - w_k \cdot \sqrt{1 - \rho^2} \tag{7}$$

where:

- ρ = correlation coefficient (0 = no correlation, 1 = full correlation)
- w_k = standard normal distributed variable for location k
- β_k = reliability index of location k

The reliability index is chosen such that $P(Z < 0)$ equals the design flood probability (1/1250 per year in the reference situation). The Monte Carlo approach generates 10,000 combinations of Z values, by drawing from u and w . The correlation coefficient represents both correlation in water levels and correlation in embankment strength. The former equals 1, since all breach locations are situated along the same river and all locations have the same protection standard. A combined correlation of 1 would imply that if one embankment fails, the other embankments will also fail. This is very unlikely, because the strength is much more variable. Therefore, the correlation coefficient is assumed to be 0.8. The flood probability of the entire system equals the number of failure scenarios (i.e., where one or more Z -values are smaller than 0) divided by the total number of scenarios.

To calculate the flood risk, the set of failure scenarios is first combined with the potential damage of the location that fails. If more than one location fails, the damages are added up. This approach thus does not take into account positive hydraulic system behaviour (Van Mierlo et al. 2007): the effect that downstream water levels will drop when breaches occur upstream. The result is a set of 10,000 scenarios of flood damage, from which a risk curve or loss-exceedance curve can be constructed. Flood risk is defined as the area under this curve:

$$\text{Flood risk} = E(D) = \int P(D) \cdot D \cdot dD = \int F(D) \cdot dD \quad (8)$$

where:

D	=	Flood damage (euro)
$F(D)$	=	Probability density of the damage
$P(D)$	=	Probability of one damage scenario
$E(D)$	=	Expected value of the damage (euro/year)

For ‘unbreachable’ embankments we used a slightly different approach. Since we assumed that such embankments are strong enough to withstand extreme water levels, even those that exceed the crest level, fragility curves do not apply in the calculation of risk. Whether and where the embankments are overtopped is completely determined by the flood simulation itself (i.e., we did not define overtopping locations beforehand). In practice, this means that upstream embankments will overtop first, if all flood defences have the same design standard. For the alternative systems with ‘unbreachable’ embankments, additional flood simulations were carried out to obtain damage figures for a range of discharge waves. The risk curve is now obtained by combining the IJssel discharge frequency curve with the response curve (damage as a function of discharge). The flood risk then equals the area under this curve.

3.2.6 Results

The estimated flood probability and flood risk are given in Figure 11 and Figure 12. The uncertainty band reflects the different possible discharge diversion fractions. For

comparison, the diamond shows the flood risk for this area according to a recent policy study (Kind 2014).

The reference system has the largest flood risk. From the alternative systems, ‘unbreachable’ embankments reduce the risk most. The system with raised embankments (CE) has a lower risk than the reference system, because the flood probability is reduced. The room for the river alternative (RR) also has a lower flood probability, but in this case because the measures affect the stage-discharge relationships and, as a consequence, the water level frequency. Therefore, higher discharges are required to cause critical water levels. Additionally, CE increases the flood damage, because critical water levels are higher, causing a higher volume of flood water flowing through the breach. This is not the case for RR. The ‘unbreachable’ embankment alternatives (UE1 and UE2) reduce the flood risk, because the probability of breaching is reduced to practically zero, and once the water overtops the defences, less water flows into the area compared to when the embankments would breach.

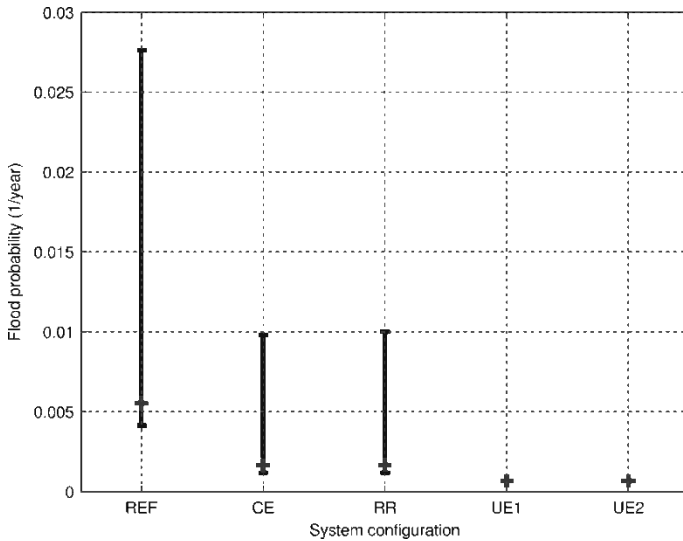


Figure 11 Flood probability of reference system and alternative configurations with uncertainty bounds reflecting the different diversion fractions

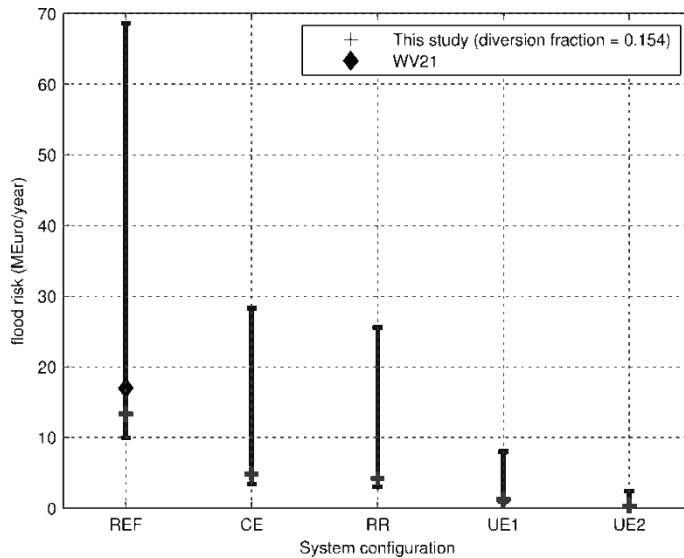


Figure 12 Flood risk of reference system and alternative configurations with uncertainty bounds reflecting the different diversion fractions

3.3 System robustness analysis

3.3.1 Approach

Robustness analysis involves presenting the consequences of flooding as a function of discharge by means of a response curve, and using this curve to obtain scores on four robustness criteria: resistance threshold, response severity, response proportionality and recovery threshold (Mens et al. 2011). In this paper, we suggest to combine response severity and recovery threshold into one measure of manageability: to which degree will the consequences of flooding still be manageable? Response severity refers to the absolute consequences of flooding, and can be indicated for instance by the economic damage. The recovery threshold refers to the maximum consequences (economic damage, affected persons or casualties) from which a society can still recover. We suggest that response severity becomes a more meaningful criterion when it is compared to a recovery threshold. When presented as an absolute value, the response severity (or the flood damage) is not an adequate indicator for whether the

system can remain functioning, since the degree of disruption depends on how this damage is spread over the area and over the functions, and how it relates to what the area can deal with. Instead, manageability better reflects whether the flood damage, if it occurs, exceeds the recovery threshold.

For the analysis of robustness we used the same models and data as for the risk analysis, but we performed additional flood simulations for discharge waves that are below and above the design discharge for the following reasons. Firstly, the fraction of the discharge that diverts from the Rhine River to its IJssel branch is uncertain and may be higher than expected; A fraction of 18% would cause a design discharge of $2880 \text{ m}^3 \text{ s}^{-1}$ for the IJssel, compared to the current $2560 \text{ m}^3 \text{ s}^{-1}$. Secondly, the projected climate change could lead to higher design discharges (Bruggeman et al. 2011), although it is found difficult to discover a trend in discharge data for the Rhine, even if climate change has an effect (Diermanse et al. 2010). Also, it is expected that the Rhine discharge entering the Netherlands reaches its physical maximum at $18,000 \text{ m}^3 \text{ s}^{-1}$ (Pelt and Swart 2011). Assuming that the Rhine design discharge will increase to $18,000 \text{ m}^3 \text{ s}^{-1}$ in 2100, the IJssel design discharge could increase to $(0.18 * 18,000 =) 3240 \text{ m}^3 \text{ s}^{-1}$. We rounded this off to $3300 \text{ m}^3/\text{s}$, as the maximum discharge to prepare for. Finally, the reason to also perform flood simulations for flood waves with lower peaks than the design level is that conventional embankments may fail before the design water level is reached, due to failure mechanisms related to insufficient strength (e.g., piping and macro-stability).

By applying the Monte Carlo approach, as explained in Section 3, we obtained a probability distribution of damage for each discharge wave. The median of this distribution is used for the response curve. Whereas we used one damage estimate per breach location for the calculation of risk, we used the full relation between discharge and damage for the robustness analysis.

Resistance threshold

The resistance threshold, (i.e., the discharge where damage is first to be expected) was quantified in two ways. The first one is based on the design discharge. The reference system has a design discharge of $2560 \text{ m}^3 \text{ s}^{-1}$ ($T=1250$ years), just as UE1 and UE2. The configurations CE and RR have a higher design discharge of $2560 + 260 \text{ m}^3 \text{ s}^{-1}$ ($T=5000$

years). However, because the embankment strength is uncertain in three of five alternative systems, embankments may breach before the design discharge is reached. This means that the lowest discharge that may cause damage may be significantly lower than the design discharge. Therefore, the second indicator for the resistance threshold is the discharge at which the probability of flooding is >10% in at least one of the breach locations. For each breach location we first selected the water level corresponding to the 10% conditional breach probability from the fragility curve. Next, the lowest discharge for all breach locations was selected. This is visualized in Figure 13 for the reference situation. The diamond indicates the resistance threshold according to the first approach.

For UE1 and UE2, the resistance threshold only depends on the height of the embankments, because it was assumed that the embankments cannot breach. The effect is that both indicators coincide.

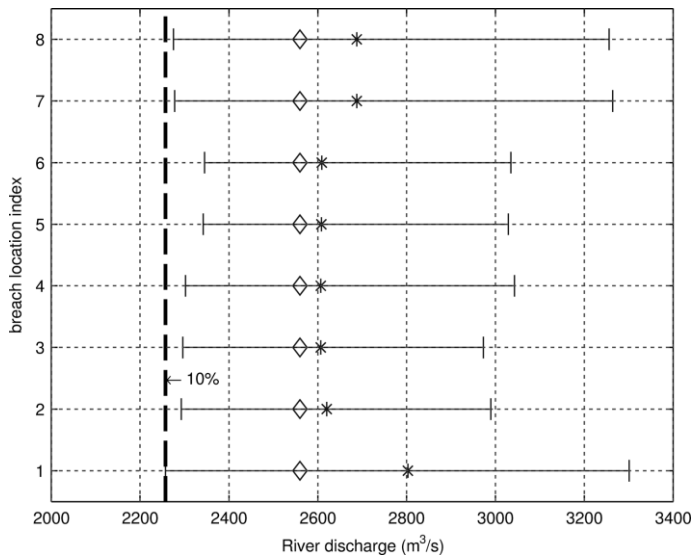


Figure 13 Determination of the resistance threshold for the reference situation, based on the fragility curves of 8 breach locations (0.1, 0.5 and 0.9 values). Vertical dashed line indicates the system resistance threshold as the lowest 10%-value of all locations. The diamond indicates the resistance threshold when it would be assumed equal to the design discharge.

Proportionality

We measure the proportionality by the maximum slope of the response curve. The resulting value represents the additional damage that is caused by increasing the discharge peak by a standard volume increase ($1 \text{ m}^3 \text{ s}^{-1}$). To obtain a score between 0 and 1, this value is divided by the largest damage of all configurations. In formula:

$$Proportionality_i = 1 - \frac{Smax_i}{\max(D_i)} \tag{9}$$

where:

- $Smax_i$ = maximum slope of response curve of configuration i (euro/ m^3)
- $\max(D_i)$ = maximum damage over all configurations (euro)

Manageability

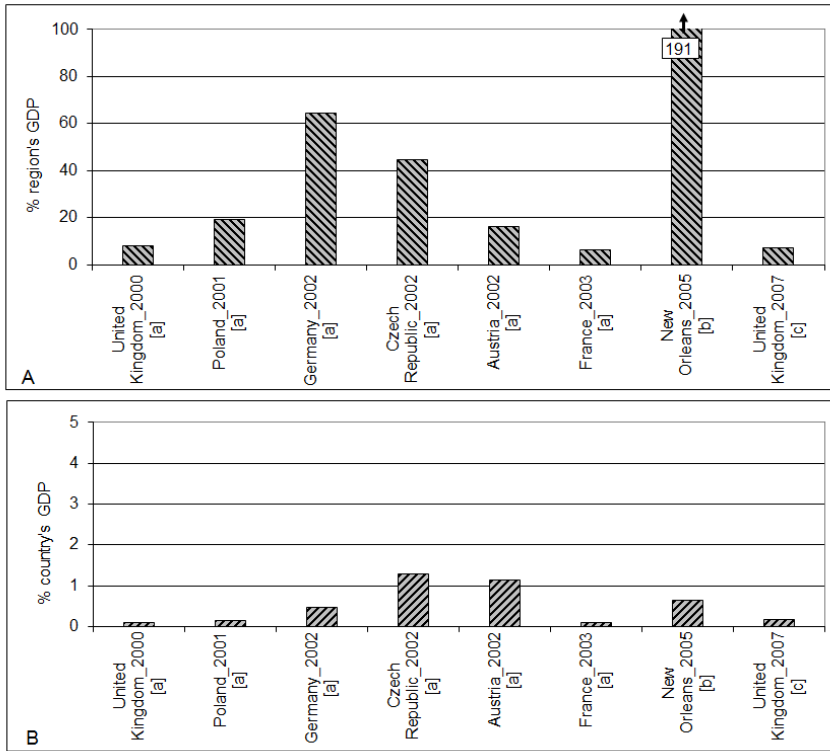
As a measure of manageability, we distinguish three zones of recovery: easy recovery, difficult recovery and no recovery/regime shift. Two thresholds indicate the transition from one zone to the other, expressed in terms of flood damage. Defining the thresholds requires a discussion on when a flood event is considered an unmanageable situation or disaster.

As noted by Barredo (2007), it is difficult to find a quantified threshold for classifying an event as major natural disaster or catastrophe. The IPCC (2012) considers a flood ‘devastating’ if the number of fatalities exceeds 500 and/or the overall loss exceeds US\$ 650 million (in 2010 values). Reinsurance company Munich RE uses a relative threshold to classify a flood event’s impact as ‘great catastrophe’ (for developed countries): overall losses x GDP per capita x $5\% \times 10^6$ (Bouwer et al. 2007). We consider this a better indicator for the no-recovery-threshold, since it relates the losses to a country’s economic capacity. It is unknown to the authors how this threshold is underpinned. We interpret it as 5% of the regional GDP, assuming the number of inhabitants in the flooded region equals 1.10^6 . We could turn this around and calculate the number of people that are needed to finance the flood recovery, assuming that

they all contribute 5% of per capita GDP. Comparing this number with the number of inhabitants shows whether a flood impact exceeds regional or national administrative boundaries. This gives an indication of the severity and the manageability of the flood event.

Based on the above, we assume that when flood damage exceeds 5% of the regional GDP, this region is unable to recover without financial aid from other regions (national scale for small countries). Likewise, if the damage exceeds 5% of the national GDP, international aid is needed. The first recovery threshold equals the regional 5% level, and the second recovery threshold the national 5% level. Figure 14 shows the economic damage of some recent flood events as a percentage of the regional and national GDP, where the regional GDP is calculated as per capita GDP $\times 10^6$. All flood events exceed the first threshold, but do not exceed the second one, indicating that it has not been easy to recover from the floods, but international assistance was not needed.

Applying these thresholds to the IJssel case, with reference year 2000, results in the following two thresholds: €3.4 billion (=5% of GDP of the provinces of Gelderland and Overijssel) and €21 billion (5% of Netherlands GDP) (Statline, 2013).



^a Barredo (2007)

^b Knabb et al. (2006)

^c EM-DAT (2013)

Figure 14 Economic damage in US Dollar for some major flood events as percentage of region's GDP (A) and country's GDP (B). Region's GDP is assumed equal to GDP per capita x 10⁶. Source of GDP data: United Nations (2013)

3.3.2 Results

Figure 15 shows the response curves of the reference situation and the alternative system configurations. These curves already reveal that all alternatives increase the ability to remain functioning, compared to the reference situation. The alternative with 'unbreachable' embankments (version 2) increases the robustness most, because it takes a discharge of 3200 m³ s⁻¹ before the system reaches the zone of 'difficult

recovery'. This is the highest discharge of all systems. Table 2 summarizes the scores on the robustness criteria, which will be further explained next.

The reference system has the lowest resistance threshold: a discharge of $2500 \text{ m}^3 \text{ s}^{-1}$. This means that when this discharge occurs there is at least a 10% probability that an embankment will fail. This threshold level arises from the uncertainty in embankment strength. By raising the embankments in a conventional manner (CE), the resistance threshold rises. Making room for the river (RR) also raises the resistance threshold, but in this case because the stage-discharge relation is adapted. This means that in both alternatives a higher discharge is needed to reach a critical water level. In the alternatives with 'unbreachable' embankments (UE1 and UE2), the uncertainty about strength is assumed to be virtually eliminated, and the threshold equals the current design discharge of $2560 \text{ m}^3 \text{ s}^{-1}$.

The proportionality decreases when embankments are being raised, because the maximum change in damage is increased. Making room for the river does not change the proportionality, whereas 'unbreachable' embankments significantly reduce it. Because in the second version of 'unbreachable' embankments the crest levels are varied, the increase in damage is smaller than in the first version.

The manageability scores best in the second version of 'unbreachable' embankments, and second best in the first version of 'unbreachable' embankments. In UE2 the zone of difficult recovery is reached at a discharge of about $3200 \text{ m}^3 \text{ s}^{-1}$, whereas in UE1 this zone is reached earlier at a discharge of about $2800 \text{ m}^3 \text{ s}^{-1}$. The other configurations reach the difficult recovery zone immediately as soon as the resistance threshold is exceeded. The zone of no recovery is never reached in either of the configurations.

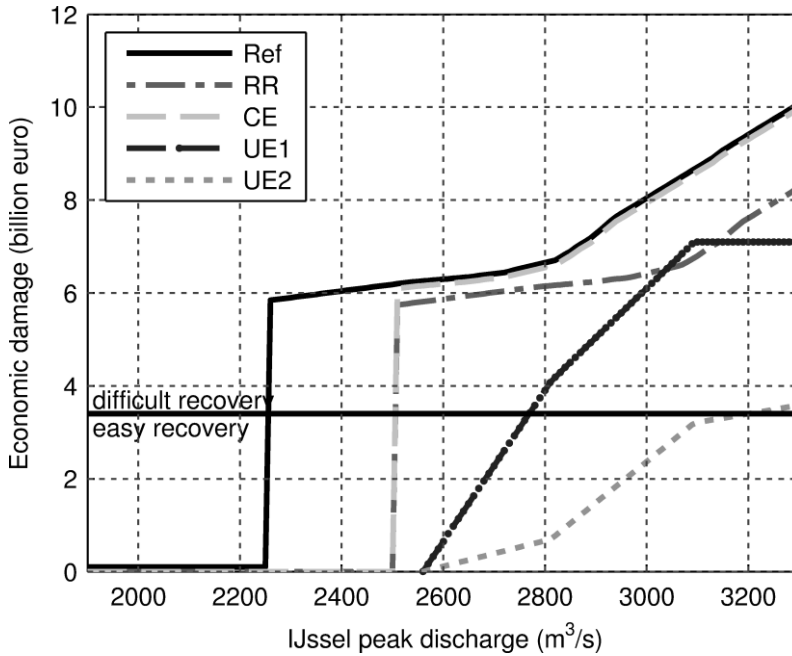


Figure 15 Response curves for reference system and alternative configurations

Table 2 Overview of scores on the robustness criteria. REF = Reference; CE = Conventional Embankments; RR = making Room for the River; UE1 = Unbreachable Embankments; UE2 = Unbreachable Embankments differentiated in height

Robustness criterion	Indicator	REF	CE	RR	UE1	UE2
Resistance threshold	^a	0.7	0.8	0.8	0.8	0.8
Proportionality	^b	0.4	0.4	0.4	1	1
Manageability	^c	0.5	0.5	0.5	0.7	1

^a Discharge where conditional flood probability > 0.1, relative to maximum discharge [3300 m³ s⁻¹ = 1]

^b Largest change in damage for discharge increase of 10 m³ s⁻¹, relative to maximum damage

^c Recovery zone (no recovery = 0, difficult recovery = 0.5, easy recovery = 1)

3.4 Discussion of system robustness criteria

The main purpose of this paper was to explore the added value of robustness criteria compared to single-value flood risk, when evaluating alternative flood risk system

configurations. We found that flood risk is reduced in all configurations, but robustness is only enhanced in the configurations with 'unbreachable' embankments. This means that if the risk reduction would have been equal in all configurations, a strategy with 'unbreachable' embankments would have been preferred. Each robustness criterion is discussed next and compared with flood probability or flood risk.

Resistance threshold

Obviously, the higher the flood defence the higher the resistance threshold and the lower the flood probability. However, the resistance threshold is expressed in terms of discharge, a physical parameter, whereas the flood probability is 'likelihood'. The flood probability needs assumptions on discharge variability and discharge diversion and will thus change when new information becomes available and when the climate changes. In contrast, the resistance threshold remains unchanged when assumptions about the natural discharge variability are adapted. Only when embankments are raised or strengthened, or when knowledge about the failure mechanisms increases, both resistance threshold and flood probability are affected. Thus, the resistance threshold depends less on assumptions about discharge variability and climate change. This is considered of additional value to flood risk.

Response proportionality

The second robustness criterion, response proportionality, is another additional element compared to flood risk. It values a low sensitivity of damage to a change in discharge. A proportional response curve means that a slightly higher or lower discharge than expected would not result in substantially different damage. Thus, in systems with 'unbreachable' embankments (like UE1 and UE2), which score high on proportionality, an accurate prediction of the discharge is less critical; if the discharge is slightly higher than anticipated, the effect on flood damage will be minimal.

Manageability

The third robustness criterion, manageability, has additional value to flood risk by introducing a reflection on the flood consequences compared to what is considered acceptable. In contrast, the risk approach implies that as long as the probability is small enough, the absolute damage is irrelevant. In this paper, we proposed three recovery

zones as indication of manageability. In practice, these thresholds would be the result of a societal discussion among decision makers and other stakeholders.

3.5 Conclusion

This paper discussed the added value of robustness analysis for flood risk management by comparing five alternative configurations of the IJssel flood risk system. The system with ‘unbreachable’ embankments that differ in height has the lowest flood risk. If the implementation cost would be known, the most cost-effective measure could be chosen. However, the flood risk and thus the cost-effectiveness depend on uncertain flood probabilities and discharge diversion fractions. Because of these uncertainties it is considered important to obtain insight into how well the system can deal with extremely high discharges. The robustness criteria show that the systems with ‘unbreachable’ embankments are best able to cope with extreme events. This is because the damage increases proportionally with an increase in discharge. When ‘unbreachable’ embankments are built with different heights, the ability to cope with extreme events increases even more, because the absolute damage is smaller.

To summarize, the robustness analysis gave us the following insights:

- Whereas the flood probability reduction differs between all system configurations, the resistance threshold hardly distinguishes between the systems. This means that although the flood probability is reduced, the resistance threshold (i.e., the discharge where a flood event has a likelihood of at least 10%) is similar in all configurations. Because quantifying the resistance threshold does not require assumptions about current and future discharge return periods, the score does not change with climate change;
- The proportionality criterion is a valuable addition to flood risk, because it shows how flood consequences vary with the river discharge. This indicates how sensitive the system is for uncertainties about or changes in the design discharge;
- Scoring on manageability adds to flood risk, because it allows an explicit discussion of damage acceptability. In contrast, the risk approach implies that as long as the probability is small enough, the absolute damage is irrelevant;

More in general, drawing a full response curve is considered to provide more insight into system functioning, compared to single-value flood risk only, because:

- It makes explicit how a measure influences different constituents of flood risk. Some measures reduce the flood-probability by changing the stage-discharge relationship and others by affecting the fragility curve of the defence. Some also reduce the inflow volume or the maximum flood depths and hence the flood consequences. The response curve shows these differences.
- It supports a discussion on flood damage acceptability, by triggering questions like: ‘what if the design standard is exceeded?’ The risk may be considered acceptable, but the potential flood damage may not.
- It moves the discussion away from uncertain design standards and uncertain flood probabilities, towards how the system functions and what can be done to manage the entire flood risk system under a range of plausible discharges. It poses the question: which discharge range do we want to be prepared for and how?

A robustness perspective challenges the idea of economically optimal protection standards for individual subsystems (or dike-ring areas) within a river valley. Flood risk can be better managed when the entire river valley is viewed as one system. For example, intentional flooding upstream can be used to protect downstream cities when extremely high discharges occur. Thus, the flood risk of the entire river valley can be reduced to an acceptable level while at the same time the proportionality is high. This calls for an analysis of a range of low-probability discharges, and questioning what can be done to limit the flood consequences. It is possible to both reduce the risk and enhance the robustness by differentiation of protection standards within the river valley. After all, flood risk management is not only about meeting the legal protection standards, but also about manageability of events when these standards are exceeded.

Acknowledgements

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4 Enhancing flood risk system robustness in practice: insights from two river valleys³

Abstract

Decisions about flood risk management are usually based on the reduction in flood risk compared to the cost of the strategy. It is common practice to express this flood risk (the combination of flood probabilities and potential flood damages) into a single number. The downside of this approach is that explicit information about how the system responds to the whole range of possible water levels or river discharges is lacking. This type of information is relevant when a robust system is desired. We consider robust (fluvial) flood risk systems to have the ability to remain functioning under a range of possible river discharges. This paper analyses system robustness for different system configurations of two embanked river valleys in the Netherlands: the IJssel River Valley and the Meuse River valley. Comparing the results of these cases provides us with clues about how to enhance a flood risk system's robustness. The IJssel case shows that a system with embankments that will not breach when overflowed scores best on overall system robustness. The Meuse case shows that systems with differentiation in protection levels along the river score best on overall robustness. Furthermore, we found that in systems with high protection standards, the most effective way to increase system robustness is by increasing the system's

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response proportionality. This means that the consequences of flooding increase proportionally to an increase in river discharge. These findings confirm that a system robustness perspective may help to develop strategies that reduce the flood risks without increasing the vulnerability to beyond-design floods.

4.1 Introduction

Increased policy focus on vulnerability, as one of the components of flood risk, was triggered by recent disasters in for example New Orleans in 2005 and Japan in 2011, both unexpected events that exceeded the protection standards. Despite these events and the fact that risks increase due to population growth and economic development in flood-prone areas (Jongman et al. 2012, IPCC 2012, Klijn et al. 2012a), many countries organize flood risk management primarily around flood defences and protection standards.

Flood risk in terms of expected annual damage, quantified by the combined probabilities and consequences of all possible flood events in a region, is an effective decision criterion to compare different types of measures, from strengthening embankments to land use planning. However, the use of a single risk estimate as decision criterion has also been criticized for a number of reasons (see also Mens and Klijn 2014):

- It may not meet the decision needs of all stakeholders (Downton et al. 2005);
- It assumes risk neutrality, while the public is generally risk averse (Merz et al. 2009);
- Risk is uncertain, since many assumptions are needed to calculate risk, especially for systems with an extremely high protection standard (as in the Netherlands)(De Moel et al. 2012);
- It does not distinguish between low-probability/high-consequence and high-probability/low-consequence risks (Kaplan and Garrick 1981, Merz et al. 2009).

The main concern with using risk analysis in decision-support is how to deal with uncertainty. Downton et al. (2005) argue that practitioners should communicate better about uncertainties in estimates and how they are handled in developing strategic alternatives, whereas others focus on developing quantitative uncertainty analysis methods in support of flood risk management (Hall and Solomatine 2008). Uncertainty may be a reason to consider additional decision criteria besides the single-value flood risk estimate, for example the severity, duration and controllability of the risk (Stirling 1998). In addition, some authors propose taking into account worst-case scenarios

(Merz et al. 2010) or start so-called ‘possibilistic thinking’ instead of ‘probabilistic thinking’ (Clarke 2005). Thus, in addition to the traditional comparison of flood risk and costs, it is recommended to analyse the ‘what if design conditions are exceeded’ scenario.

In literature on socio-ecological systems, the proposed way to deal with uncertainties is to aim for a robust or resilient system, instead of trying to control external disturbances (Folke 2006). Among other things, control means that the variability of the system is reduced to make its behaviour better predictable: floods hardly happen. However, the downside of too much control is that unanticipated events may cause surprise and crisis (Holling 1996): when a flood does happen it may turn into a disaster. The idea of steering on system persistence (thereby allowing disturbances) instead of system stability was first introduced by Holling (1973) for ecosystem management, and later extended to the management of socio-ecological systems (Carpenter et al. 2001, Walker and Salt 2006). This type of management is often called ‘resilient’. In the field of flood risk management, however, the term resilience is associated with the ability to recover from the response to a disturbance (De Bruijn 2005), which is a narrower interpretation than that of the ecological and socio-ecological literature. To avoid confusion, we use the term system robustness when we mean the ability to remain functioning under a range of possible disturbance magnitudes (Mens et al. 2011).

The idea of using system robustness as decision criterion in addition to damage risk, fatality risk and costs, was already tried out in De Bruijn et al. (2008) and Klijn et al. (2012a), but only in a qualitative manner. A quantitative method for system robustness analysis was introduced by Mens et al. (2011) and improved by Mens and Klijn (2014). The following criteria together provide an indication of system robustness (see Figure 16):

1. Resistance threshold, or the smallest river discharge that will cause substantial economic damage;
2. Response proportionality, or the insensitivity of the response to changes in discharge;
3. Manageability, or how easy the system can recover from the flood consequences.

The last criterion relates to some critical level of damage from which recovery will be very difficult.

In this paper, we compare system robustness to discharge waves of two embanked river valleys: the IJssel River valley and the Meuse River valley. The analyses provide insight into the system response to a range of river discharge waves, including the extreme ones. We compare the results of both cases and draw some generic conclusions about how to enhance the system robustness of embanked river valleys.

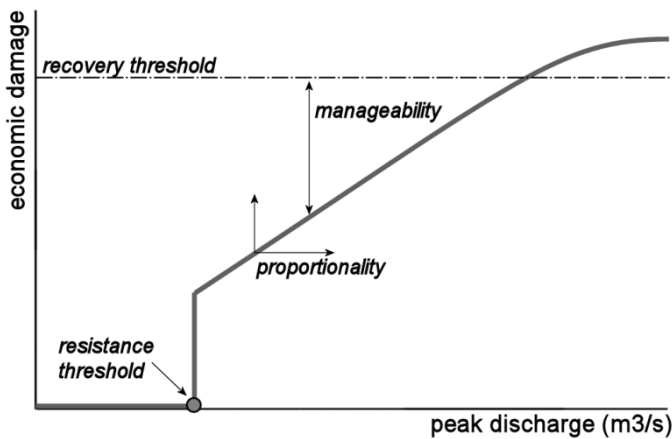


Figure 16 Theoretic response curve of a flood risk system (adapted from Mens et al., 2011)

4.2 Method: Quantification of system robustness

4.2.1 Response curve

Quantifying system robustness starts by constructing a so-called response curve: the relationship between peak discharge and flood damage, from which the system robustness criteria can be derived (Mens et al. 2011). The response curve can be obtained from the following information, which typically underlies a flood risk analysis:

- River discharge-frequency curve;
- Water level frequency curve at each breach location;
- Relationship between river water level and flood damage;

- Critical water levels at each breach location, which initiate flooding.

To obtain a response curve for an entire river valley, damages of all possible breach locations have to be combined. However, because of the uncertainty about embankment strength, it is unknown which embankment will breach first. Many combinations are possible, each with a unique damage sum. It is very unlikely in embanked river valleys, if not hydraulically impossible, to have all breaches occurring within one flood event, simply because there is not enough water to flood the entire system. Therefore, we developed a method to obtain a damage estimate corresponding to each discharge wave. First, for a given discharge wave, the damages of each breach location are collected. We take into account that, depending on the protection standards, some locations will have zero damage at the chosen discharge, because the critical water level is not yet exceeded. The critical water level equals the design water level when only the failure mechanism overflow is taken into account. In other cases, a critical water level has to be selected based on fragility curves. Second, the damage estimates are added up in all possible combinations, but with a maximum of four dike-ring areas. With that we assumed that at a given river discharge, each combination of breach locations has an equal probability of occurrence. Finally, we calculate the median of the damage. The procedure is repeated for a range of river discharges.

4.2.2 System robustness criteria

The system robustness criteria are derived from the response curves of each alternative system configuration. The first criterion, resistance threshold (the lowest discharge causing damage), may be lower than the design discharge, due to uncertainty about the embankment strength. If fragility curves are available, it can be quantified as the discharge where the conditional probability of flooding is greater than 0.1 for one or more breach locations. This approach was followed for the IJssel case. For the Meuse case, fragility curves were not yet available. Therefore, the resistance threshold was estimated as the discharge corresponding to $T = 250$ year (Asselman et al. in prep.). At this return period, the discharge is $500 \text{ m}^3 \text{ s}^{-1}$ lower than the design discharge and the water levels are 0.5 to 0.6 m lower than the dike height. This is a very rough estimate, but it does not influence the conclusions of the paper.

The second criterion, proportionality (the sensitivity of the damage for changes in discharge), is measured by the maximum slope of the response curve. The resulting value represents the additional damage that is caused by increasing the discharge peak by a volume increase of $1 \text{ m}^3 \text{ s}^{-1}$. To obtain a score between 0 and 1, this value is divided by the largest damage of all configurations. In formula:

$$Proportionality_i = 1 - \frac{Smax_i}{\max(D_i)} \quad (10)$$

where:

$Smax_i$ = maximum slope of response curve of configuration i (euro/m³)
 $\max(D_i)$ = maximum damage over all configurations (euro)

The third criterion, manageability, is scored on a scale of 0 (no recovery) to 1 (easy recovery). In Mens and Klijn (submitted) we assumed that recovery is difficult when the flood damage exceeds 5% of the regional GDP. If the damage exceeds 5% of the national GDP, the zone of no recovery is reached. We give a score based on the height of the damage when the resistance threshold is exceeded compared to the two recovery thresholds. If the damage passes the first recovery threshold zone immediately, then it receives a score of 0.5. If the damage reaches the first recovery threshold at the maximum discharge, it receives a score of 1. When the damage increases proportionally, it will first stay below the recovery threshold and at higher discharges it will cross the recovery threshold. In that case, the recovery zone is not clear and the score will be between 0.5 and 1. We assume that the longer it stays below the threshold, the higher the score.

4.3 Introduction to the cases

4.3.1 IJssel case

The IJssel River is one of three branches of the Rhine River. The IJssel River Valley consists of 6 dike-ring areas (see Figure 17). Each dike-ring area is protected from

flooding by a ring of flood defences and adjacent high grounds, which are designed to withstand river discharge waves that occur on average once in 1250 years.

The future IJssel River discharges are uncertain, because of natural variability, uncertain climate change and unknown distribution of water over the three Rhine River branches. Therefore, it is relevant to evaluate proposed strategies on how the adapted system will deal with a range of discharges, instead of optimizing the strategy for just one design discharge. As a result of the mentioned uncertainties, the discharge frequencies are uncertain. Instead of trying to calculate the frequencies, we analyse the flood impacts for a range of discharges for which the system should be prepared.

The IJssel case builds on available data from Mens and Klijn (2014), in which flood risk and system robustness was calculated for several alternative system configurations. We reused this data to discuss what enhances the system's robustness. The IJssel design discharge was estimated at $2560 \text{ m}^3 \text{ s}^{-1}$. For the flood damage calculations in that study, it was assumed that embankments breach when the local water level reaches its peak (for discharge waves with $Q_{peak} < 2560 \text{ m}^3 \text{ s}^{-1}$), or when the local design water level is exceeded (for discharge waves with $Q_{peak} > 2560 \text{ m}^3 \text{ s}^{-1}$).

The system robustness analysis requires a choice on the maximum river discharge for which consequences are calculated. One option is to use the future design discharge according to the worst case climate change projection. According to the Dutch Delta Programme (DeltaProgramme 2013), the Netherlands should prepare for a design discharge of the Rhine River of $18,000 \text{ m}^3 \text{ s}^{-1}$ in the coming 50-100 years. However, the maximum discharge of the IJssel River also depends on how the Rhine discharge is distributed over the Rhine Branches. In Mens and Klijn (2014) the percentage of the discharge that diverts from the Rhine River to the IJssel River was varied between 15 and 18%. Assuming a maximum fraction of 18%, the worst case discharge for the IJssel yields $3250 \text{ m}^3 \text{ s}^{-1}$. This was rounded off to $3300 \text{ m}^3 \text{ s}^{-1}$.

Following Asselman et al. (in prep.), the reference system is as close as possible to the projected situation of 2015, when projects currently being implemented will be finalised. It is assumed that at that time each dike-ring area will meet the required flood probability.

We compared the following alternative configurations with the reference system, where a configuration is the combination of river geometry, embankment location and strength, and land use:

- IJssel_CE Conventional Embankments: embankments are raised by Δh (location-dependent) that corresponds to a change in discharge from $T=1250$ years to $T=5000$ years;
- IJssel_RR Room for the River: the floodplains are lowered such that the water level at the current design discharge is reached at a higher discharge. The ΔQ is about $260 \text{ m}^3\text{s}^{-1}$, which corresponds to the change in discharge in CE;
- IJssel_UE1 ‘Unbreachable’ Embankments, version 1: all embankments are strengthened (not raised) such that they become practically ‘unbreachable’. Water may, hence, flow over the flood defence and still cause flood damage;
- IJssel_UE2 ‘Unbreachable’ Embankments, version 2: like UE1, but embankments near cities are raised by 0.5 m.

To implement CE (conventional embankments) into the model, the fragility curves were adjusted, whereas for RR (‘room for the river’) the stage-discharge relationship was adjusted, For UE (‘unbreachable’ embankments), the fragility curves for mechanisms other than overflow were removed, so flooding would only start when the design water level is exceeded (without breaching). In UE2 the fragility curves near large cities were adjusted such that they represent 0.5 m higher embankments.

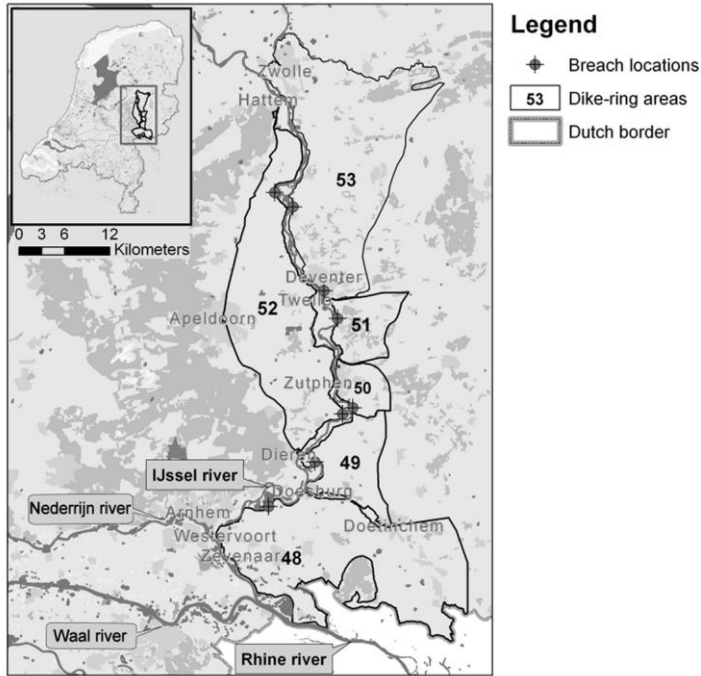


Figure 17 IJssel River valley with dike-ring areas and breach locations indicated (Mens and Klijn, 2014)

4.3.2 Meuse case

The Meuse River has a larger capacity than the IJssel River with a design discharge of $3800 \text{ m}^3 \text{ s}^{-1}$ ($T=1250$ years). The part of the Meuse River valley that we focus on also consists of 6 dike-ring areas (Figure 18). In contrast to the IJssel River valley, not all dike-ring areas are valley-shaped. The ones north of the river are entirely surrounded by embankments, whereas the other ones have higher grounds in the south. In the western (downstream) part of the river, water levels are also influenced by the sea level and storm surges. The embankments in this part are designed to withstand water levels that are exceeded on average once in 2000 years. This water level may be caused by different combinations of sea water level and river discharge. However, for the purpose of this paper we assume that the design water levels for the western part also correspond to a discharge of $3800 \text{ m}^3 \text{ s}^{-1}$.

The data for this case was obtained from a recent policy study (Asselman et al. in prep.), where flood risks were calculated for different system configurations. Flood simulations and corresponding damage were available for all dike-ring areas and for different river discharges.

We analysed the system robustness for discharges up to $4600 \text{ m}^3 \text{ s}^{-1}$, because the design discharge is expected to increase to $4600 \text{ m}^3 \text{ s}^{-1}$ according to the most extreme climate change scenario for the year 2100 (Asselman et al. in prep.). Higher discharges are deemed physically impossible, due to extensive flooding further upstream where protection standards are lower.

In the reference configuration, floods may occur at a lower discharge than the design discharge, because embankments are currently not designed to resist the failure mechanism *piping*. We assumed that piping may start to occur at a discharge of about $3300 \text{ m}^3 \text{ s}^{-1}$, which has a return period of 250 years. This corresponds to 0.5 to 0.6 m lower water levels depending on the location.

We compared the following alternative configurations for the Meuse River valley:

- Meuse_CE Conventional embankments: embankments are raised to withstand a discharge of $4200 \text{ m}^3 \text{ s}^{-1}$. However, embankments may still fail due to piping, thus floods may occur at a lower discharge of $3700 \text{ m}^3 \text{ s}^{-1}$;
- Meuse_RR Room for the river: measures are taken to adapt the stage-discharge relationships. The design water levels will thus be lowered, but not at all locations. For areas where this measure has no effect, floods may still occur at a discharge of $3300 \text{ m}^3 \text{ s}^{-1}$ (as in the reference) but the total flood damage will be much smaller;
- Meuse_CE/RR A combination of raising embankments and giving room to the river. Floods may occur at a discharge of $3700 \text{ m}^3 \text{ s}^{-1}$. Due to the water level lowering at some locations, the damage at higher discharges will be smaller than in the reference.

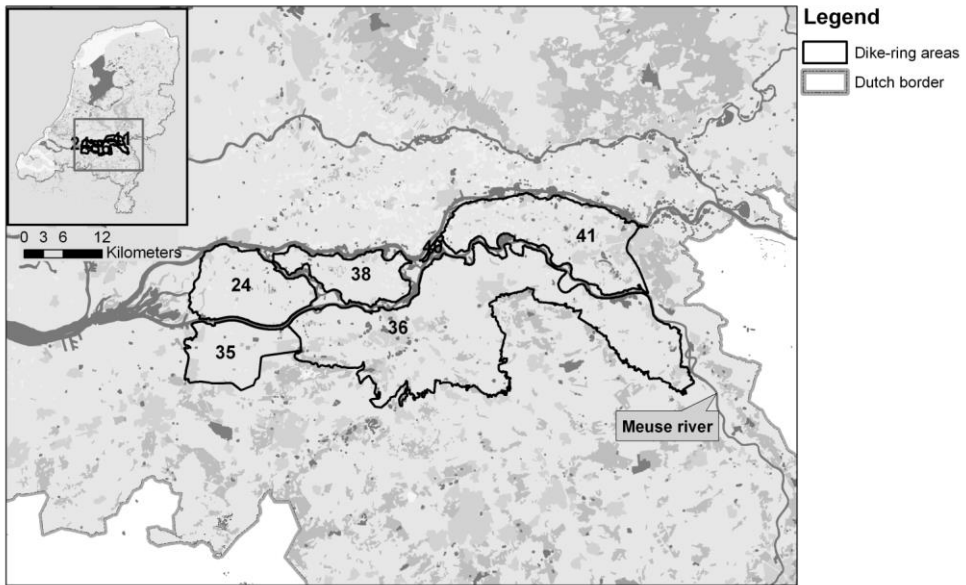


Figure 18 Meuse River valley with dike-ring areas indicated

4.4 Results

4.4.1 IJssel River valley

The response curve and the robustness scores of the IJssel case are given in Figure 19 and Table 3. The two recovery thresholds are taken from Mens and Klijn (2014): $3.4 \cdot 10^9$ euro (=5% of GDP of the provinces of Gelderland and Overijssel in the year 2000) and $21 \cdot 10^9$ euro (5% of Netherlands GDP in the year 2000). The second threshold is not visible in Figure 19, which means that it is unlikely that flooding in the IJssel River valley will result in an unmanageable situation without recovery. The resistance threshold is increased in all configurations, whereas the proportionality and the manageability are only enhanced in the configurations with 'unbreachable' embankments.

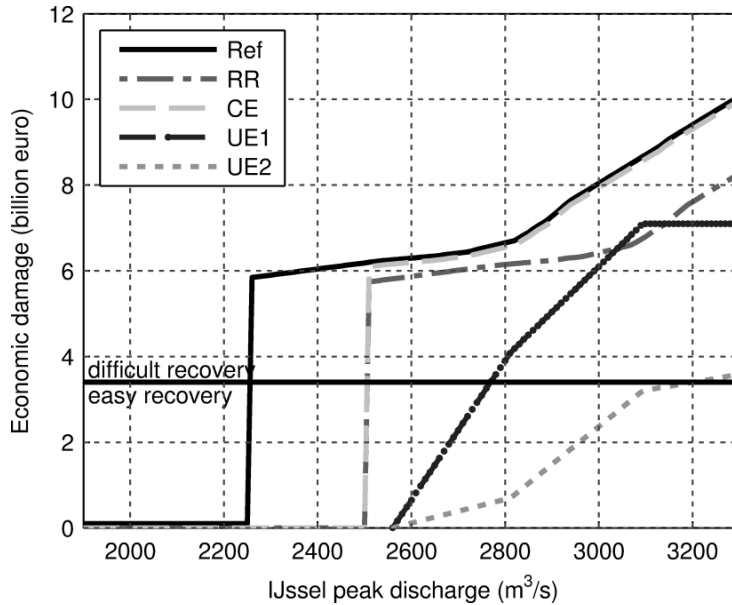


Figure 19 Response curves of the IJssel system configurations (Mens and Klijn, 2014)

Table 3 Overview of system robustness scores of the IJssel River valley (Mens and Klijn, 2014). Grey tones indicate an increase compared to the reference. IJssel_REF = Reference; IJssel_CE = Conventional embankments; IJssel_RR = Making room for the river; IJssel_UE1 = ‘unbreachable’ embankments; IJssel_UE2 = ‘unbreachable’ embankments differentiated in height

System robustness criterion	Indicator	IJssel_REF	IJssel_CE	IJssel_RR	IJssel_UE1	IJssel_UE2
Resistance threshold	a	0.7	0.8	0.8	0.8	0.8
Proportionality	b	0.4	0.4	0.4	1	1
Manageability	c	0.5	0.5	0.5	0.7	1

^a Discharge where conditional flood probability > 0.1, relative to maximum discharge [$3300 \text{ m}^3 \text{ s}^{-1}=1$]

^b Largest change in damage for discharge increase of $1 \text{ m}^3 \text{ s}^{-1}$, relative to maximum damage

^c Recovery zone (no recovery = 0, difficult recovery = 0.5, easy recovery = 1)

4.4.2 Meuse River valley

The response curve and the robustness scores of the Meuse case are given in Figure 20 and Table 4. The two recovery thresholds are $5.3 \cdot 10^9$ euro (=5% of GDP of the provinces

of Noord-Brabant and Gelderland in the year 2000; CBS (2013)) and $21 \cdot 10^9$ euro (5% of the Netherlands GDP in the year 2000). Here, the second threshold is also too high to be shown in the figure. The resistance threshold is only higher in the configurations where embankments are raised. In contrast to IJssel_RR, the resistance threshold of Meuse_RR is similar to the reference situation. The proportionality is enhanced in all configurations except Meuse_CE (raising embankments). The manageability is enhanced in Meuse_RR and Meuse_RR/CE.

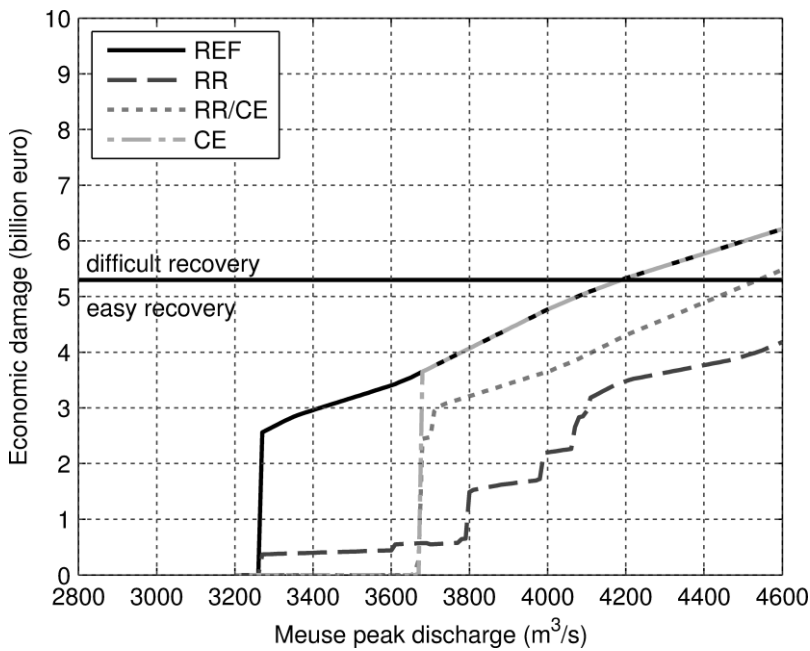


Figure 20 Response curves of the Meuse system configurations

Table 4 Overview of system robustness scores of the Meuse River valley. Grey tones indicate for each criterion a decrease (dark grey) or an increase (light grey) compared to the reference. Meuse_REF = Reference; Meuse_CE = Conventional Embankment raising; Meuse_RR = making Room for the River; Meuse_RR/CE = combination of Meuse_CE and Meuse_RR.

System robustness criterion	Indicator	Meuse_REF	Meuse_CE	Meuse_RR	Meuse_RR/CE
Resistance threshold	^a	0.7	0.8	0.7	0.8
Proportionality	^b	0.7	0.6	0.9	0.8
Manageability	^c	0.8	0.8	1.0	0.9

^a Discharge where critical water level is exceeded, relative to maximum discharge [$4600 \text{ m}^3 \text{ s}^{-1}=1$]

^b Largest change in damage for discharge increase of $1 \text{ m}^3 \text{ s}^{-1}$, relative to maximum damage

^c Recovery zone (no recovery = 0, difficult recovery = 0.5, easy recovery = 1)

4.5 Discussion

4.5.1 What enhances system robustness?

From the two example river valleys, we learned that two types of measures have a strong effect on system robustness: the ‘unbreachable’ embankments in the IJssel case and making room for the river in the Meuse case. In both cases, the resistance threshold was not adapted, but instead the damage was reduced. More importantly, in these alternative system configurations, the damage increases more proportional with a discharge increase. However, making room for the river in the IJssel case (IJssel_RR) has a minor effect on proportionality. This can be explained as follows.

The IJssel case was a theoretic study in which we could lower the water levels in the model homogeneously along the entire river (IJssel_RR). This resulted in a new protection level that was equal for each dike-ring area. The Meuse case is more realistic in the sense that sets of measures were chosen by stakeholders. As a consequence, the water level lowering in Meuse_RR varied for the dike-ring areas and therefore some embankments are relatively higher than others. This means that when the system’s resistance threshold is exceeded, not all dike-ring areas will be flooded simultaneously. This resulted in a differentiation in protection levels for the Meuse. It is this

differentiation that has a strong effect on proportionality. We found a similar effect with IJssel_UE2, where ‘unbreachable’ embankments heights were differentiated and proportionality scores well.

Also without differentiation, ‘unbreachable’ embankments have a strong effect on proportionality and robustness. This is because less water is flowing into the dike-ring area, since the embankments will only overflow and not breach. This automatically causes a more proportional increase of the damage with increasing discharge. Furthermore it reduces the flood extent and flood depths, which has a positive effect on manageability, since the damage stays further away from the recovery threshold. Making room for the river, even if protection levels are not differentiated (IJssel_RR), does reduce flood extent and flood depths and therefore has a positive effect on robustness. However, in the IJssel case this effect was minor, partly because the chosen water level reduction was only 10-20 cm.

Robustness is less positively influenced by conventional embankment raising, which is supported by both cases (Meuse_CE and IJssel_CE): the resistance threshold is higher, but the proportionality is lower than the reference. This means that it seems to be safer, because higher discharges are needed to cause flooding, but once the embankments fail the damage approaches the recovery threshold immediately. In the IJssel case the damage exceeds the recovery threshold, whereas in the Meuse case the damage stays below this threshold. In the Meuse, not only the flood damage is smaller, but also the recovery threshold is higher. Apparently, this region is economically better able to recover.

4.5.2 How realistic are ‘unbreachable’ embankments?

We assume that ‘unbreachable’ embankments will never fail. In practice, it may be difficult or at least expensive to construct an embankment of which the probability of structural failure and thus breaching can be neglected. We use ‘neglected’, because a zero failure probability is geotechnically impossible. Currently, design criteria for conventional embankments in the Netherlands require the failure probability due to ‘other’ failure mechanisms than overtopping (such as piping) to be less than 10% of the design standard (Rijkswaterstaat 2007). ‘Unbreachable’ embankments can be defined

as embankments for which these design criteria are a factor 10 stricter, thus less than 1% of the design standard (see also De Bruijn et al. 2012). This means, for dike-ring areas with a design standard of 1/1250 per year, that the probability of embankment failure due to 'other failure mechanisms' is smaller than 1/125,000 per year. Additionally, 'unbreachable' embankments could be designed such that the probability of breaching due to overtopping is also less than 1% of the design standard. If this is implemented, we feel that the probability of failure (in the sense of breaching) may be neglected. However, further research is needed to explore the technical feasibility and costs of changing a conventional embankment into an unbreachable one.

4.6 Conclusion

A risk approach is key to modern flood risk management, but for deciding about the most desirable system configuration in view of uncertain discharges, a robustness perspective may be of additional value. We analysed the flood consequences of the IJssel River valley and Meuse River valley in terms of economic damage for four alternative system configurations. Based on the results, we conclude that the following types of measures increase robustness in river valleys:

- Differentiation in protection standards;
- Limit flood extent and flood water depths. This can be achieved by ensuring a limited difference between design water levels and the elevation of the protected area, for example by building 'unbreachable' embankments or giving room to the river.
- Of all studied alternative configurations of the IJssel River valley, the one with 'unbreachable' embankments (version 2) increases the system's robustness most. This alternative combines both types of measures as described above. However, there are practical limitations to construct 'unbreachable' embankments, such as costs and available space.
- Of all studied configurations of the Meuse River valley, the one that gives more room for the river at specific locations increase the system's robustness most. Similar to the most robust IJssel configuration, this is mainly caused by

differentiating the protection standards and thereby significantly increasing the proportionality of the flood damage.

We feel that these conclusions apply to all embanked river valleys with a natural relief, and with hydraulic system behaviour. Hydraulic system behaviour ensures that, when water flows over the embankments at one location, water levels elsewhere will be lowered. Measures that reduce the water level (like giving room to the river) will be extra effective in areas where the stage-discharge relation is steep, thus where an increase in discharge causes a large increase in water level. This is regularly the case near large cities. Although space may be limited to relocate the embankments, a bypass or widening the floodplain across the river may be effective. ‘Unbreachable’ embankments will have a limited effect on system robustness in small polder areas that will fill up very quickly, causing large water depths and thus casualties and damage.

We conclude that a system robustness perspective makes explicit what happens if protection standards are exceeded. It thus helps in developing strategies that reduce the flood risks without increasing the vulnerability to beyond-design floods.

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5 Developing system robustness analysis for drought risk management: an application to a water supply reservoir⁴

Abstract

Droughts will likely become more frequent, of greater magnitude and of longer duration in the future due to climate change. Already in the present climate, a variety of drought events may occur with different exceedance frequencies. These frequencies are becoming more uncertain due to climate change. Many methods in support of drought risk management focus on providing insight into changing drought frequencies, and use water supply reliability as key decision criterion. In contrast, robustness analysis focuses on providing insight into the full range of drought events and their impact on a system's functioning. This method has been developed for flood risk systems, but applications on drought risk systems are lacking. This paper aims to develop robustness analysis for drought risk systems, and illustrates the approach through a case study with a water supply reservoir and its users. We explore drought characterization and the assessment of a system's ability to deal with drought events, by quantifying the severity and socio-economic impact of a variety of drought events, both frequent and rare ones. Furthermore, we show the effect of three common

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drought management strategies (increasing supply, reducing demand and implementing hedging rules) on the robustness of the coupled water supply and socio-economic system. The case is inspired by Oologah Lake, a multipurpose reservoir in Oklahoma, United States. Results demonstrate that although demand reduction and supply increase may have a comparable effect on the supply reliability, demand reduction may be preferred from a robustness perspective. To prepare drought management plans for dealing with current and future droughts, it is thus recommended to test how alternative drought strategies contribute to a system's robustness rather than relying solely on water reliability as the decision criterion.

5.1 Introduction

5.1.1 Drought management under uncertainty

Droughts affect more people than any other kind of natural disaster owing to their large scale and long-lasting nature (WMO 2013). In 2012, drought losses in the US were estimated at 30 billion USD (NOAA 2013), making it the most extensive drought year since 1930. There is a possibility that droughts will intensify in the 21st century due to reduced precipitation and/or increased evapotranspiration (IPCC 2012). This means that droughts may become more frequent, of greater magnitude and/or of longer duration. Future uncertainty, combined with natural climate variability, is a challenge for long-term decision making on drought management.

In view of climate change, it is increasingly acknowledged that each country should develop and implement national drought management plans to reduce drought risk to an acceptable level (Wilhite et al. 2014, Sivakumar et al. 2014, OECD 2013). Such drought plan development can be supported by ‘stress-testing’ water supply systems on drought events that are more severe and/or longer in duration than historic droughts (e.g., Watts et al. 2012, Steinschneider and Brown 2013). However, decision making criteria are lacking to compare and rank various drought management measures.

Decision making on drought management often relies on a measure of water supply reliability (Iglesias et al. 2009, Rossi and Cancelliere 2012): the probability of meeting the water demand. Reliability can be increased by either reducing the demand (e.g. by water conservation, reuse of wastewater and reduction of distribution losses) or increasing the supply (e.g. by building new reservoirs, expanding existing reservoirs, constructing desalination plants). However, this reliability metric is based on estimates of long-term demand and supply patterns, and does not give insight into the (socio-economic) impact of water shortage once it occurs. Besides managing towards an acceptable balance between demand and supply, it is important to understand the impact of temporary situations of water shortage and the effect of short-term measures that aim to reduce these impacts, such as delivery restrictions/rationing, temporary additional sources of supply, and prioritization among users. In addition to

long-term supply reliability, decision making criteria are thus needed to provide insight into the effect of drought management measures during droughts. This paper proposes new criteria to support decision-making on drought risk management.

5.1.2 Analysing system robustness

A method to obtain insight into the impact of a range of hydro-meteorological events on a system's functioning has been proposed in Mens et al. (2011): system robustness analysis. The concept of robustness originates from the engineering literature, where it is defined as the ability of systems to maintain desired system characteristics when subjected to disturbances (Carlson and Doyle 2002). A similar concept, resilience, originates from the socio-ecological resilience community and is defined as the ability of ecosystems or socio-ecological systems to absorb disturbances without shifting into a different regime (Holling 1973, Walker and Salt 2006, Folke 2006, Scheffer et al. 2001). Robustness and socio-ecological resilience are comparable concepts (Anderies et al. 2004), but robustness is considered more suitable for systems in which some components are designed (Carpenter et al. 2001). Since we focus on water management systems (including drought risk systems), which usually contain many engineering components, we prefer the term robustness. Furthermore, resilience in water management has been defined as the ability to recover from the impact of flood events (De Bruijn 2004), which stays closest to its original (latin) meaning: 'to jump back'.

In a flood risk context, systems are disturbed by river flood waves, and they may shift into a different regime when the impact from flooding is too large to recover from (Mens et al. 2011). Resilience, in the narrow definition, can be considered one of the system characteristics that add to a system's robustness; the ability of a system to remain functioning depends on its ability to recover from the response to a disturbance. Another characteristic that adds to system robustness is *resistance*, the ability to withstand disturbances without responding at all (zero impact) (see De Bruijn 2005).

The robustness analysis method aims to provide insight into the sensitivity of a system to extreme events that result from climate variability, for example floods and droughts. Because climate change may affect the frequency of these events, robustness analysis

focuses on a range of events that are plausible both now and in the future. Understanding the relationship between extreme events and their impact on the system is believed to aid in drafting robust strategies that increase the system's ability to deal with both frequent and rare events, now as well as in the future.

The first step in a robustness analysis is to draw a relationship between drought severity and corresponding impact: the *response curve* (Figure 21). This curve visualizes the impacts that can be expected under a range of drought events. Next, the curve is described by the following robustness criteria:

1. **Resistance threshold:** under which drought conditions will socio-economic impacts first start to occur? In other words: to what extent can the system withstand droughts?
2. **Proportionality:** how gradual does the impact increase with increasing drought severity?
3. **Manageability:** under which range of drought conditions are impacts still manageable? In other words: when do impacts exceed a societally unacceptable level?

In a flood risk system, the *resistance threshold* relates to the protection standard. A *proportional* response curve of a flood risk system implies that sudden impacts are avoided, because a slight change in river discharge does not result in substantially different flood impact. Finally, flood impacts are *manageable* when they are below a critical level for a large range of flood magnitudes. The robustness analysis method has been successfully applied on two systems exposed to river flooding, where it was demonstrated that the robustness criteria have additional value compared to the more traditional decision making criteria based on single-value risk (Mens and Klijn 2014, Mens et al. 2014).

Since system robustness analysis has been developed in a flood risk management context, it is unclear whether and how it can be applied on drought risk systems. The aim of this paper is therefore to develop the robustness analysis method for drought risk systems. We illustrate the approach with a case inspired by Oologah Lake in Oklahoma (United States) and its water users.

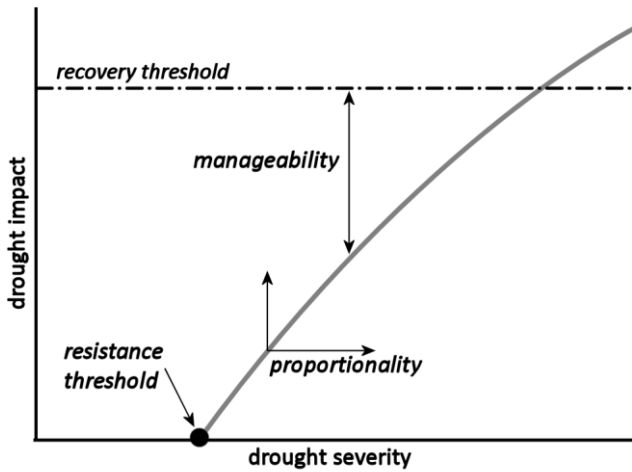


Figure 21 Example response curve: relationship between drought severity and drought impact; and robustness criteria

5.1.3 Application on a drought risk system

To explore the potential of robustness analysis in a drought management context, this paper develops the approach for a system exposed to droughts. The system includes a water supply reservoir and water users. As an illustration of the approach, we apply it on a case inspired by the Oologah reservoir in Oklahoma, United States. The data available from this reservoir was adapted to be able to show the effect of different drought management strategies (smaller demand, higher capacity, hedging rules) on the robustness.

Oologah Lake is a reservoir northeast of the city of Tulsa, Oklahoma, in the United States. This reservoir was constructed between 1950 and 1972 as one of many reservoirs aiming at flood control of the Verdigris River. The Verdigris River is a tributary of the Arkansas River, which flows into the Mississippi River. Besides flood control, the reservoir has three other functions: water supply, navigation and recreation. The reservoir is operated such that the water level is low enough to buffer high runoff events (flood control) and high enough to provide a buffer for droughts (water conservation). We focus on water supply for municipal use. According to historic

streamflow measurements, the average annual inflow sum is about $2.8 \cdot 10^9 \text{ m}^3$. The reservoir capacity is about $6.7 \cdot 10^8 \text{ m}^3$. For the purpose of the illustrative case, we reduced the reservoir capacity to $5.4 \cdot 10^8 \text{ m}^3$ (see Section 2.2). In this way, a wider range of extreme drought events is available that cause different levels of shortage in water supply.

Drought management strategies lead to new system configurations with different characteristics. We consider the following strategies:

- S1 Demand reduction Water demand is reduced on a structural basis, for example by more efficient distributing systems, motivating inhabitants to reduce domestic water use, and by rainwater harvesting (so tap water is not used for watering gardens and lawns).
- S2 Hedging Outflow is temporarily reduced when a critical reservoir level is reached; thereby accepting smaller losses now to avoid major losses later on.
- S3 Reservoir expansion The conservation storage is increased at the cost of the flood control buffer, making more water available. Demand remains the same as in the reference. No hedging rules apply.

5.2 Methods and assumptions

5.2.1 Water balance model and input data

A simple water balance model calculates storage over time as a function of inflow and outflow. The storage is the volume of water in the reservoir that is available for water supply, the inflow is the volume of water per time step flowing into the reservoir, and the outflow is the users' intake from the reservoir (also a volume of water per time step). In the reference situation no hedging rules are assumed: this means that demand is met until the reservoir is empty. Each simulation assumes a full reservoir at the start. If the conservation storage is exceeded, the model releases water accordingly.

Overview of parameters in the reference configuration:

- Reservoir capacity = $5.4e8 \text{ m}^3$
- Required outflow (demand) = $17.4 \text{ m}^3 \text{ s}^{-1}$

Parameters for the configurations with alternative drought management strategies:

- S1 Demand reduction from 17.4 to $15 \text{ m}^3 \text{ s}^{-1}$
- S2 Hedging: at 25% storage the outflow is reduced by 60%
- S3 Reservoir expansion by 20% (from $5.4e8 \text{ m}^3$ to $6.7e8 \text{ m}^3$)

Values for S1 and S3 are chosen such that their resulting water supply reliability (%time outflow > demand) is similar. Implementing hedging rules will reduce the supply reliability, but will potentially mitigate the severity of impacts over the duration of the event.

The input of the water balance model is a time series of monthly averaged streamflow. We used 60-year historic river flow measurements upstream Oologah Lake, as available from waterdata.usgs.gov (gauge *Lenapah*, Oklahoma, USGS 07171000). From a previous Oologah Lake study (Qiao et al. 2014), projected future series were available: 112 realisations of 150-year time series of reservoir inflow. These series originate from a range of climate models from which the output was used in a hydrological model of the Verdigris catchment. The hydrologic response of Oologah Lake watershed to climate change was analysed by using downscaled climate projections in the Variable Infiltration Capacity (VIC) land surface model. We used the 112 monthly hydrographs from projections of the World Climate Research Program Coupled Model Intercomparison Phase 3 (WCRP-CMIP3), including IPCC's CO₂ emission scenarios A1b, A2 and B1. We obtained this set from USBR (2012). The same dataset was used by Williams (2013) for his study on the effect of climate change on water availability from Oologah Lake.

This paper does not aim to analyse the effect of climate change on drought and drought impact. Instead, we use the historic and future inflow series to obtain a range of plausible drought events for which the impact can be simulated with the water balance model and the loss functions (described below). This will help to obtain insight

into how impacts vary with different drought magnitudes, which can be used to conduct climate risk assessments.

5.2.2 Characterising and selecting drought events

To select drought events from a long time series, different methods have been developed. Hisdal and Tallaksen (2000) give an overview of the most common methods, for example the threshold level method (TLM) and the Sequent Peak Algorithm (SPA). The threshold level method assumes a user-defined threshold (for example the long-term mean); a drought event occurs when the streamflow is below this threshold (Yevjevich 1967, Dracup et al. 1980). The downside of TLM is that for longer droughts the flow may temporarily exceed the threshold, which divides the longer droughts into smaller mutually dependent droughts (Hisdal and Tallaksen 2000). To avoid this problem, smaller drought events can be pooled. SPA can be considered a pooling method.

SPA (Loucks and Van Beek 2005, Vogel and Stedinger 1987) is an automated equivalent of the Rippl Mass Diagram Approach, one of the first methods to calculate a reservoir's storage requirement. The design storage of Oologah Lake has been determined with this method as well. We chose this method, because it is able to combine consecutive smaller drought events into one large drought event.

With SPA, the required storage K_t is calculated over a period of record of streamflow Q_t , given a required release R_t (Eq.11). The design storage equals the maximum value of K_t , see Figure 22.

$$K_t = \begin{cases} R_t - Q_t + K_{t-1} & \text{if positive} \\ 0 & \text{otherwise} \end{cases} \quad (11)$$

The onset (t_{on}) of an event is where K_t becomes positive, and the offset (t_{off}) is where K_t reaches its maximum value (Hisdal and Tallaksen 2000). The event duration is thus defined as:

$$\text{duration} = t_{off} - t_{on} \quad (12)$$

We can now calculate the drought volume:

$$\text{volume} = \sum_{t_{on}}^{t_{off}} (R_t - Q_t) = K_{t_{off}} \tag{13}$$

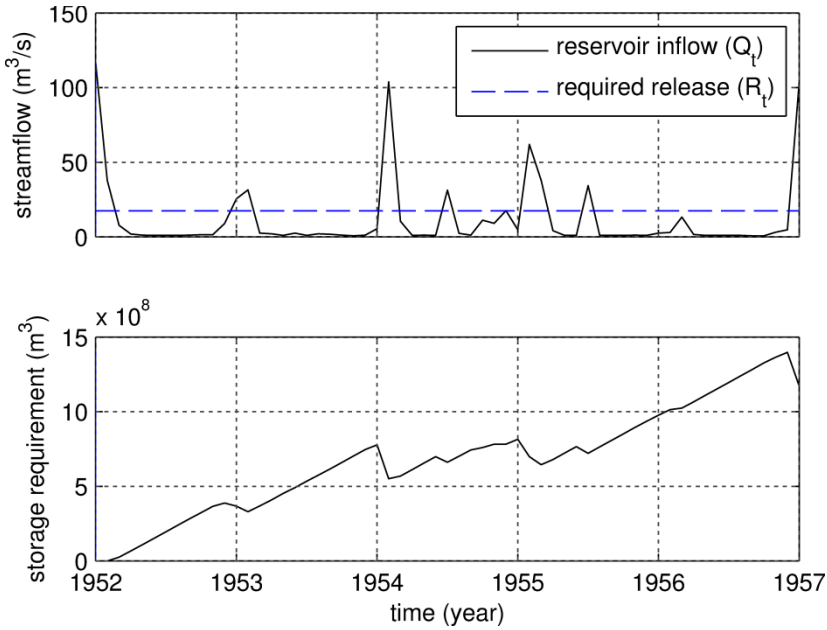


Figure 22 Example of sequent peak algorithm: (a) time series of streamflow (Q_t) and required release (R_t), and (b) corresponding storage requirement: the reservoir would be designed based on the maximum value

The SPA method was applied on each of the available inflow time series. For each of the time series, the following steps were taken:

- Selection of periods during which $K_t > 0$;
- Store start date of each period: the onset of the drought event;
- Find the date where K_t reaches its maximum value: the offset of the drought event;
- Go back to original streamflow series and select the part from onset to offset; this is the input time series for the water balance model.

Each of the 150-year streamflow timeseries yielded several drought events with different characteristics (duration and volume).

5.2.3 Water supply loss function

For municipal water use, the economic impact of drought can be expressed in terms of change in welfare. One of many ways to estimate change in welfare is through willingness-to-pay (WTP) (Dixon et al. 1996). WTP in a drought context is the sum that individuals and businesses are willing to pay to avoid the drought. WTP can be estimated as a function of the amount of available water, the baseline water use (water use when there are no shortages), water rate and price elasticity, see Eq.14 (Dixon et al. 1996).

$$WTP(Q) = P_0 \left(1 - \frac{1}{\eta}\right) (Q_0 - Q) + \frac{P_0}{2\eta Q_0} (Q_0^2 - Q^2) \quad (14)$$

where:

WTP	=	willingness-to-pay [\\$]
P_0	=	water rate [\\$ m ⁻³]
Q_0	=	baseline water use [m ³]
Q	=	water available from reservoir [m ³]
η	=	price elasticity [-]

As suggested by Brozović et al. (2007), we can assume that in case of 100% water shortage, a government would supply the basic water needs for drinking and sanitation by trucking in water from a different source (e.g. a different reservoir). An estimate for trucking cost was taken from the guidebook of the US National Cooperative Highway Research Program in 1995 (NCHRP 1995). They give an estimate of 0.0885 US\$ per ton per US mile in the year 1995, including 45% empty miles. For the year 2013 this equals 0.1309 US\$ per ton per mile (based on consumer price indices of 152.4 in 1995 and 233.4 in 2013) and 0.086 US\$ m⁻³ km⁻¹ (0.95 m³ water weights about 1 ton).

The monthly costs (C) involved with trucking in water are thus:

$$C(Q_T) = C_T \cdot x \cdot Q_T \tag{15}$$

where:

- C_T = water trucking price [$\$ \text{ m}^{-3} \text{ km}^{-1}$]
- x = trucking distance [km]
- Q_T = water volume to be trucked [m^3]

The basic water requirement BWR (m^3 per month) can be calculated by assuming that 10% of the baseline municipal water use (Q_0) is needed for drinking and sanitation. If the water supply Q from the reservoir is less than BWR , we assume that the government will truck in a water volume of $(BWR-Q)$. These are the additional cost on top of $WTP(BWR)$. The total losses associated with water supply deficit (L_{WS}) are calculated by combining Eq.14 and Eq.15:

$$L_{WS} = \begin{cases} WTP(Q) & \text{for } BWR \leq Q < Q_0 \\ C(BWR - Q) + WTP(BWR) & \text{for } Q < BWR \end{cases} \tag{16}$$

When reservoir outflow Q is smaller than BWR , the government has a cost of providing enough water to obtain BWR , and individuals have a cost of having less water than their baseline use. In practice, however, it may be technically difficult for a water authority to pump very small amounts of water through their distribution network. The resulting loss function is given in Figure 23, which shows the loss L_{WS} as a function of reservoir outflow Q .

We used the following values for the case:

- The consumer price for municipal water $P_0 = \$0.84 \text{ m}^{-3}$ ($\$0.00318$ per gallon) (Tulsa 2013);
- Average municipal water demand $Q_0 = 17.4 \text{ m}^3 \text{ s}^{-1}$ (Ref) and $Q_0 = 15 \text{ m}^3 \text{ s}^{-1}$ (S1);
- Price elasticity $\eta = -0.41$ (Dalhuisen et al. 2003);

- Trucking distance $x = 290$ km, assuming that water will be trucked in from the Kaw reservoir 145 km (90 miles) away, which is 290 km roundtrip;

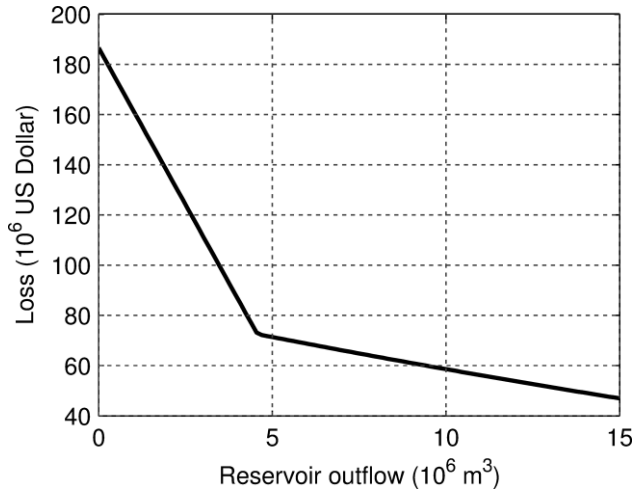


Figure 23 Loss for municipal water users as a function of reservoir outflow (for 1 month), based on reference water demand

5.2.4 Scoring the robustness criteria

To draw the response curve of the drought risk system, the disturbance was quantified by the drought volume: the cumulative difference between inflow and demand over the duration of the drought event. The drought impact (response) was quantified as the total loss in US Dollar as a result of this drought event. The response curve was then used to score the robustness criteria.

The resistance threshold was quantified as the largest drought volume that first causes drought impact. When this is divided by the largest drought volume considered, a value between 0 and 1 is obtained.

The proportionality was scored by visually detecting sudden changes in drought impact with increasing drought volume. Proportionality is scored high when no sudden changes occur, and low when the impact increases from zero to maximum impact as a result of a small increase in drought volume.

The manageability was scored by looking at the steepness of the curves. If the curve is less steep than the reference, impacts are smaller and larger drought volumes are needed to cause the same level of impact.

5.3 Results

Figure 24 shows the response curves of all configurations. Each curve is a combination of points representing a single drought event. The figure also shows linear fits through all data points of one configuration. The curves clearly differ between the configurations.

The *resistance threshold* in the reference is similar to the reservoir capacity. This was to be expected, since the reference assumed no hedging so that drought impacts only occur when the drought volume exceeds the reservoir capacity. This means that the system can withstand drought events until a drought volume of $5.4 \cdot 10^8 \text{ m}^3$. The maximum volume of all considered drought events is about $14 \cdot 10^8$, thus the system can withstand about 40% of the total drought range considered. The resistance threshold therefore scores 0.4 on a scale of 0 to 1. The water supply reliability of the reference is estimated between 0.96 and 1, depending on the climate change scenario. The supply reliability was calculated for each of the 112 streamflow series (based on projections of future climate). Some of these series did not contain any drought event with a volume exceeding the reservoir capacity. This explains the supply reliability of 1. This points at a likely wetter climate according some of the climate scenarios, but it does not mean that drought events will never occur in these futures. Because the length of each streamflow series was limited (150 years), it may be a coincidence that extreme drought events with a small occurrence probability did not occur.

The resistance threshold is increased to 0.5 ($\sim 7 \cdot 10^8 \text{ m}^3$), by either reducing demand (S1) or by increasing supply (S3). The supply reliability is increased in both alternatives to 0.98-1. The hedging option (S2) decreases the resistance threshold to 0.35 and the supply reliability to 0.94-1. Because the outflow is temporarily reduced already when there is still water available from the reservoir, impacts start to occur at smaller drought volumes.

The S1 curve is the least steep one of all the curves, pointing to the fact that a smaller demand (the amount people are used to) also cost less to replace when this amount is lacking. Demand reduction thus increases the drought *manageability*, because it takes larger droughts before a societally unacceptable level of drought impact is reached. The S3 curve is as steep as the reference, so manageability is comparable. However, because of the higher resistance threshold the total impact remains smaller than that of the reference configuration. S3 thus increases the robustness to drought events.

The S2 curve is less steep than the reference curve for small droughts and as steep for more extreme droughts. Thus, the impact is larger than in the reference between about 4 and $7 \cdot 10^8 \text{ m}^3$ drought volume. This is because the outflow is reduced before the reservoir is empty. At a volume of about $7 \cdot 10^8 \text{ m}^3$ the reservoir is empty and impact increases with the same rate as in the reference. However, impacts remain smaller than in the reference for large drought volumes. Thus, hedging is beneficial in terms of reducing impact due to extreme droughts, but the impact is increased for the more frequent droughts. In sum, the manageability is equal to the reference.

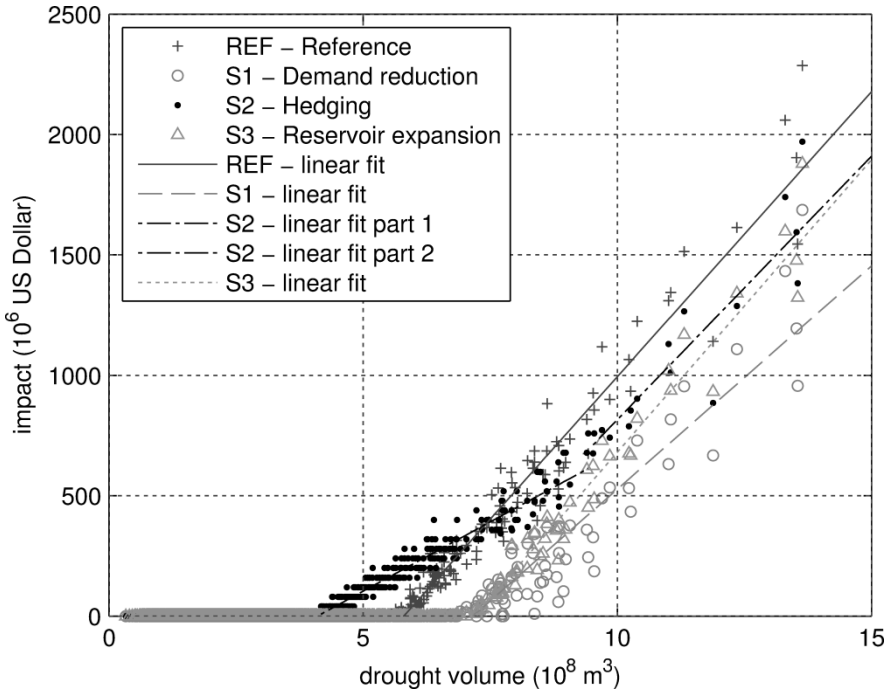


Figure 24 Response curves of reference configuration and alternative configurations with implemented strategies (S1, S2 and S3)

5.4 Discussion, conclusions and recommendations

5.4.1 Discussion and conclusions

The aim of this paper was to develop system robustness analysis for drought risk management. To that end, the existing framework for robustness analysis, originally developed for floods, was adapted for droughts and illustrated with a drought case. The results showed that different types of measures (demand reduction, supply increase and hedging) score differently on two of the three robustness criteria: resistance threshold and manageability. The third criterion, proportionality, did not distinguish between the system configurations. This could however change when different types of measures are considered.

The case clearly showed the different effect of increasing water supply and reducing water demand. If demand is smaller, impacts will start at larger droughts and impacts are lower over the entire range of drought magnitudes. Demand reduction thus scores higher on both resistance threshold and manageability, and is therefore advocated from a robustness perspective. If only the supply reliability (the traditional decision criterion) were used, both measures would have been perceived comparable. This means that the decision between these two measures would mainly depend on the cost involved (besides side-effects on sustainability criteria such as environmental impact). The robustness criteria show the additional benefit of demand reduction which may be worth the investment.

Implementing hedging rules reduced the resistance threshold: impacts will start at smaller droughts. However, these impacts do not increase as fast as in the reference and total impact from extreme drought events is lower than that of the reference. The system configuration with hedging rules thus scores higher on manageability. However, the question is whether the lower score on one robustness criterion outweighs the higher score on the other robustness criterion. Furthermore, the effect of hedging highly depends on the type of loss function and the demand reduction factor, and could thus be different for other system configurations and other systems.

Although the resistance threshold is scored on a scale between 0 and 1, this does not mean that a score of 1 should be the ultimate goal. The resistance threshold is intended to inform about which range of drought events the system can withstand (zero impact), in this case 40% of the total range considered. The score is expected to raise awareness about the possibility of larger events (the other 60% of the total range considered; the 'extreme range') that the system cannot withstand; thus for which impacts are expected. The second criterion, manageability, then informs about how well the system can cope with the impacts of drought events in the extreme range.

The total range of drought events considered is a subjective choice. In this case it was chosen to select drought events from a long time series of projected streamflow, according to several climate change scenarios. This shows how severe drought events may become, without having to judge about the likelihood of the climate scenarios. How the future will develop is uncertain, but because drought events originate from

climate variability (also in the current climate), the possibility of extreme drought events is certain. Thus, it is certain that extreme drought events will occur at some point, but it is uncertain when. Against this background it may be wise to consider a higher level of manageability, since resistance cannot eliminate the certainty of a drought event. Decision makers still have to decide on the range of drought events for which to prepare management plans and the required level of manageability. A system that is robust for the chosen range of events will most likely be robust for even more extreme events as well.

The illustrative case has demonstrated that a robustness analysis provides additional insight into how a system responds to droughts, compared to the traditional decision criterion *water supply reliability*. Because the impact of drought is expressed in economic terms, and a wide range of drought events is considered, the robustness approach fits well with the move towards risk-based drought management. Furthermore, the analysis does not depend on assumptions about how the future climate develops; instead it takes into account a wide range of possible drought events resulting from climate variability. We thus consider robustness analysis promising as part of drought risk management under climate change uncertainty.

5.4.2 Recommendations

Compared to the applications of the robustness framework on floods (Mens and Klijn 2014, Mens et al. 2014), the impacts in this case were not compared with a recovery threshold. Exceeding a recovery threshold means that impacts are unacceptable in the sense that recovery will be very difficult, costly and time-consuming. It is recommended that future drought applications compare the impacts with a recovery threshold.

For future applications it is recommended to take into account the impact on various water users, instead of only municipal water use. This makes a robustness analysis more interesting, because it allows testing different short-term drought management strategies, for example those that prioritize water supply among users during a drought.

Acknowledgements

Thanks are due to the US Army Corps of Engineers (Institute for Water Resources and Tulsa District) for their support in carrying out the research reported in this paper. The work was partially funded by the Netherlands Knowledge for Climate program.

6 Analysing the robustness of an agricultural drought risk system: a case in a coastal polder area in the Netherlands⁵

Abstract

This paper develops and tests new criteria and indicators for long-term drought risk management under climate change. Drought is a temporary phenomenon resulting from climate variability that may cause an imbalance between supply and demand. As part of drought risk management, it is important to understand how the system responds to extreme drought conditions. In this paper, we propose and apply a new method to analyse how a system deals with a wide range of drought conditions: robustness analysis. Such an analysis provides insight into which system characteristics are responsible for ‘no drought damage’ under frequent drought conditions and for ‘limited drought damage’ under rare drought conditions. In our case study, we focus on agriculture by calculating the expected crop yield deficit for low-lying polder area in the Netherlands, under a range of drought conditions. These drought conditions result from a combination of local precipitation deficit (the cumulated difference between evapotranspiration and precipitation) and external water supply deficit. Based on the results, we discuss how system robustness analysis can be used in drafting long-term drought risk management strategies.

⁵ This chapter has been submitted to the *Journal of Water Resources Management*: Mens, M., Van der Sluijs, J. P., Ter Maat, J. and Jeuken, A. submitted. Analysing the robustness of an agricultural drought risk system: a case in a coastal polder area in the Netherlands. *Water Resources Management*.

6.1 Introduction

6.1.1 Drought risk management under climate change

Drought is one of the major natural hazards (UNISDR 2009). It may cause water shortage impacting communities through affecting for instance agriculture, industry, navigation, drinking water supply and sanitation. Recent droughts have caused large impacts worldwide (WMO 2013), and these impacts increase in severity and frequency due to climate change as well as due to unsustainable use and a growing demand for water resources (Wilhite et al. 2014).

To prepare for future droughts, it is widely acknowledged that countries should move from crisis management to risk management (Wilhite 2011, Rossi and Cancelliere 2012, Xerochore 2010). Drought risk management is defined as a systematic process to prevent, mitigate and prepare for the adverse impacts of drought and the possibility of disaster (UNISDR, 2009). This approach is followed in the Netherlands' Delta Programme, the national decision making process on how to adapt to climate change (DeltaProgramme 2013). One of the policy analyses on behalf of the Delta Programme showed that the current water supply strategy in the Netherlands is not climate-proof in the long term (Klijn et al. 2012b). In the worst case climate change scenario for 2100, they estimated an increase in agricultural drought risk from $400 \cdot 10^6$ euro year⁻¹ to $1100 \cdot 10^6$ euro year⁻¹. To reduce this risk, different types of measures are considered: increasing the fresh water supply (for example by increasing the buffer capacity of the main fresh water lake), and decreasing the water demand (for example by motivating farmers to change to different crop types or by making water use more efficient).

Various methods have been developed to quantify drought risk (e.g., Giannikopoulou et al. submitted, Rossi and Cancelliere 2012), which is a prerequisite for the design of a drought risk management policy. Expected risk reduction obtained by implementing alternative management strategies can then be weighed against the investment cost in a cost-benefit analysis.

However, a single-value risk estimate does not distinguish between high-probability/low-consequence and low-probability/high-consequence risks (see also Merz et al. 2009). Furthermore, risk analysis requires estimates of drought return

periods, which are uncertain especially in a changing climate. In this paper we follow a different approach that firstly avoids assumptions on drought probabilities, and secondly provides better insight into how sensitive a system is to a variety of drought conditions: system robustness analysis. This method allows a more explicit consideration and debate about whether consequences of drought are acceptable or not, and about how and against what costs they can be reduced. Some drought impacts can be considered unacceptable, because their impact on economy and welfare is difficult to recover from. For example, the current drought in California already cost 2.2 billion US Dollar and left many agricultural workers jobless (Howitt et al. 2014).

A method for analysing system robustness to hydrological hazards has been proposed by Mens et al. (2011) and further developed for droughts in (Mens et al. accepted). This robustness analysis method quantifies the sensitivity of a system to events that result from climate variability, for example floods or droughts, which may have an impact on the socio-economic subsystem. Because climate change may affect the frequency of these events, robustness analysis focuses on a wide range of events that are plausible now as well as in the future. Understanding the relationship between drought events and their impact will aid in drafting robust strategies that increase the system's ability to cope with both frequent and rare events, now as well as in the future.

In this paper, we further develop and test the existing robustness analysis framework by a specific application on agricultural drought risk in low-lying polder areas in the Western part of the Netherlands ('West-NL'). Through this case study, we aim to answer the following questions:

- What are appropriate criteria for analysing robustness of polder areas to droughts?
- How robust are agricultural polder areas in the western part of the Netherlands for droughts?
- Which system characteristics determine such an area's robustness for droughts?
- How can this robustness be increased?
- What is the added value of robustness analysis in the context of drought risk management

6.1.2 Case study area

The West of the Netherlands is a system of low-lying polder areas. The main land use types are agriculture (potatoes, horticulture, bulbs, flowers, dairy farming), service industry, urban area, nature parks and recreation. The water supply and drainage system consists of ditches, canals, lakes, and pumps and sluices. In winter, there is an excess of water that is drained and pumped out to either the North Sea or the Hollandse IJssel. In summer, fresh water is let into the surface water system from the Hollandse IJssel (Gouda inlet), and brackish water is discharged by two pumping stations (Figure 25). The inlet water is needed for water level control, flushing for water quality management and water supply (irrigation, drinking water, industry). Water level control is important to guarantee the stability of canal embankments, and flushing is needed to reduce the salinity in the canals and ditches, caused by seepage of saline groundwater. During an average summer, the total external fresh water inlet amounts 40 to 60 10^6 m^3 . In a dry summer, this may increase to about 100 10^6 m^3 (Rijnland 2009).

Occasionally, conditions occur in which the Gouda inlet cannot be used: if Western Europe is also in a drought, river discharges may become very low, causing the intrusion of salt sea water into the Hollandse IJssel ('external salinization'). Because of strict water quality standards, the inlet at Gouda has to be temporarily closed under these conditions. This would mean that water is temporarily not available for water level control, flushing and water supply. However, to avoid irreversible damage to embankments, nature and buildings, 'contingency water supply' from further upstream has been made available ('KWA' in Figure 25), but the capacity of this supply system is limited. In practice this usually implies that irrigation is restricted in such periods, which increases the probability of crop damage.

Recent studies for the Netherlands show that the current water supply strategy is not climate-change proof in the long term (Klijn et al. 2012b). In the worst case climate change scenario for 2100, they estimate an increase in agricultural drought risk from 400 $10^6 \text{ euro year}^{-1}$ to 1100 $10^6 \text{ euro year}^{-1}$, and a decrease in nature value with 4 to 7%. Also, drinking water inlets may suffer more often from high chloride concentrations.

Therefore, a future ‘climate-proof’ fresh water supply is a national priority on the Dutch water policy agenda.

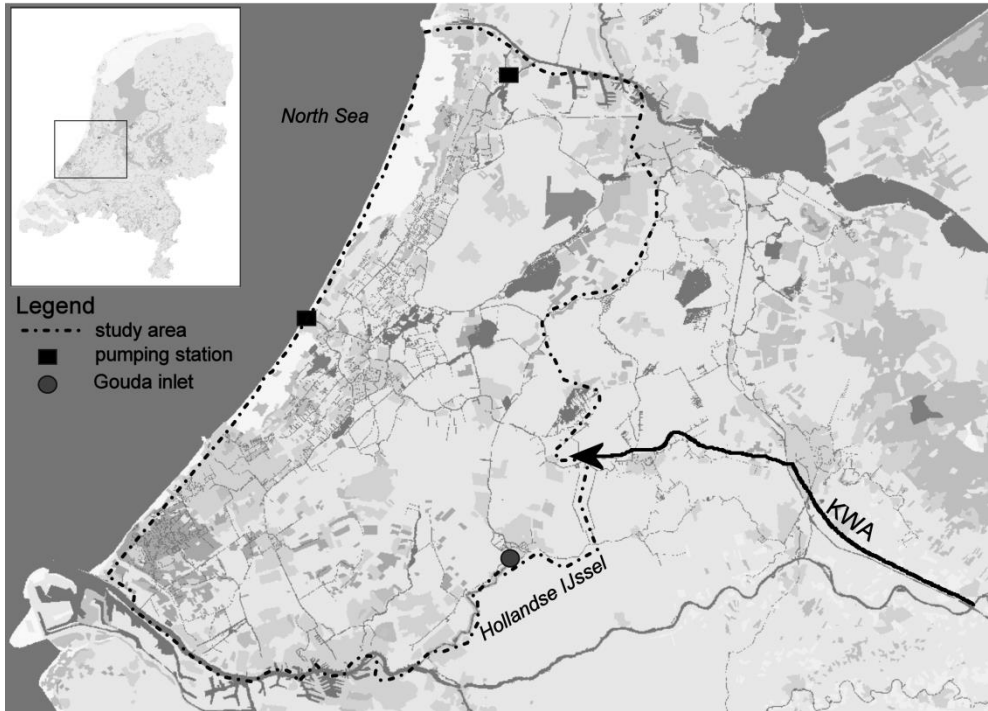


Figure 25 Case study area

6.1.3 Outline

The remainder of this paper is structured as follows. Section 2 explains the framework for robustness analysis as it was developed before, and how it was adjusted for application on agricultural drought in low-lying polder areas. Section 3 describes two models that were used as well as climate data, including historic and synthetic time series of precipitation and evapotranspiration. Section 4 discusses the results of the case study: how robust is West-NL? Section 5 discusses the added value of robustness analysis in drought risk management, by discussing the robustness criteria and how robustness can be increased. This leads to the conclusions in Section 6.

6.2 System robustness analysis framework and alternative system configurations

6.2.1 Response curve

Overview

The starting point for a system robustness analysis is a response curve, the relationship between disturbance (drought condition) and system response (drought impact), see Figure 26. Drought condition is a combination of meteorological drought (precipitation deficit) and hydrological drought (water supply availability), which may potentially lead to agricultural drought (soil moisture deficit), following the definitions of Wilhite and Glantz (1985). The (economic) impact on agricultural yields in the area can be considered the response (Figure 27). The next sections discuss in more detail how disturbance and system response can be quantified.

The time scale of the analysis depends on the climate which determines the probability of consecutive drought years. Because we focus on the Netherlands, we can assume that over-year droughts are very unlikely, since winter precipitation is sufficient to recharge the soil moisture. Furthermore, we are interested in the growing season, since we focus on agricultural drought. In the Netherlands, the growing season is from April to September. The response curve is formed by the characteristics of possible drought events. In this case a drought event covers one growing season. Each point on the response curve thus represents the combination of precipitation deficit and yield deficit over the growing season of a potential (drought) year.

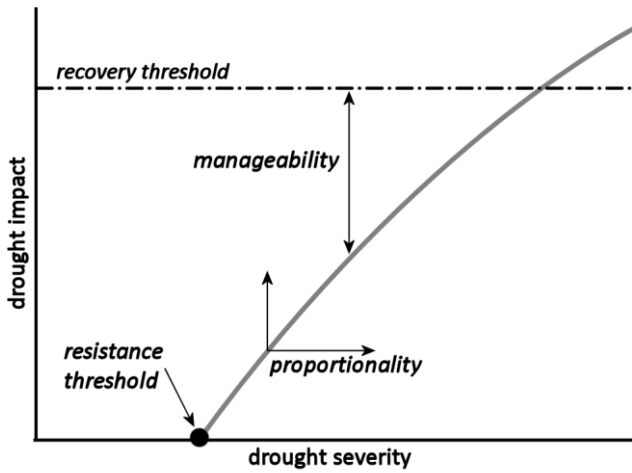


Figure 26 Theoretic response curve for droughts (Mens et al. accepted)

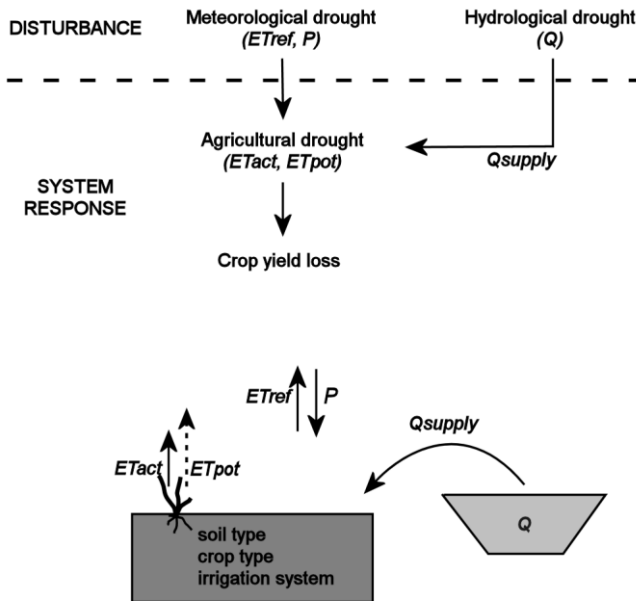


Figure 27 Relationship between disturbance and system response in the context of agricultural drought. ET_{ref} =reference evapotranspiration; ET_{act} = actual evapotranspiration; ET_{pot} =potential evapotranspiration P =precipitation, Q =river discharge

System

The system is the polder area with its soil characteristics, land-use types and water management infrastructure (including canal network and sprinkler installations). The system characteristics determine whether a disturbance will cause water shortage at any location in the system and to what extent this will translate into crop yield loss. We quantified water shortage in the soil moisture by the evaporation ratio, actual evapotranspiration divided by potential evapotranspiration ($E_{ratio} = ET_{act} / ET_{pot}$). A shortage occurs when $E_{ratio} < 1$. This ratio varies in time and is a common output variable of many (agro-)hydrological models.

Disturbance

The two disturbances, PD and WSA , can be understood as the external conditions affecting the water balance (including soil moisture) in the system. In this case, water supply refers to irrigation water which is taken in from the Hollandse IJssel. This external water supply is only relevant for the areas that are irrigated.

PD is the main disturbance to the system and will be plotted on the x-axis of the response curve. Reference evapotranspiration refers to the potential evapotranspiration on a reference surface: short grass. Because PD is independent from the system characteristics such as soil type and land use, it is considered external to the system, which means it cannot be influenced by measures.

As indicator for disturbance we propose the maximum cumulative precipitation deficit ($MCPD$), which is largest cumulative difference between reference evapotranspiration and precipitation deficit that occurs during the summer half year (Beersma and Buishand 2004), see Eqs. 17 and 18. When the cumulative sum becomes negative, it is reset to zero. The time scale of t is 'decades', assuming 36 'decades' in a year. Each month is divided into three decades, where the first two decades have a length of 10 days and the third decade covers the remaining days in that month. The summer half year is from $t=10$ to $t=27$ (April to September).

$$CPD_t = \max[0, CPD_{t-1} + ET_t - P_t] \quad \text{for } 9 < t < 28 \quad (17)$$

$$MCPD_i = \max[CPD_{10} \dots CPD_{27}] \quad (18)$$

where:

ET = reference evapotranspiration (m)

P = precipitation (m)

CPD = cumulative precipitation deficit (m)

$MCPD_i$ = maximum cumulative precipitation deficit in year i (m)

The second disturbance, water supply availability, is taken into account by performing all model simulations for a situation with 100% water availability from the Hollandse IJssel (Gouda inlet always open) and a situation with 0% water availability from the Hollandse IJssel (Gouda inlet always closed). In reality, a continuous closure throughout the growing season is unlikely. The results of these two simulations provide a bandwidth around system response (see also Section 2.2).

Response

The response of the system is the impact of the disturbances on the agricultural yield. For quantifying the response, an agricultural impact model can be used that calculates the crop growth in time as a function of the evaporation ratio. In the case study, the response is quantified as the relative difference between potential yield and actual yield (Eq.19): the crop yield deficit (YD). Potential yield (Y_{pot}) is the crop yield that would have been obtained if sufficient water had been available. Actual yield (Y_{act}) is the crop yield that is obtained given the actual soil moisture conditions.

The yield deficit is calculated for each crop type separately, but we are interested in one response value for the entire study area. Therefore, the deficits for each crop type were multiplied by their (constant) economic value. The system response is thus expressed in monetary terms. Note that this value should not be interpreted as the actual economic impact, because the actual income from crops depends on the market price of a crop, which is difficult to predict because of price elasticity.

$$YD = \frac{(Y_{pot} - Y_{act})}{Y_{pot}} \cdot 100 \quad (19)$$

6.2.2 System robustness criteria

The system robustness criteria can be derived from the response curve. Three criteria have been proposed to compare different system configurations (Mens et al. accepted, Mens and Klijn 2014):

1. Resistance threshold: under which drought conditions will damage start to occur?
2. Proportionality: how sudden does the drought impact increase with worsening drought conditions?
3. Manageability: to what extent are the drought impacts societally acceptable?

The *resistance threshold* tells us under which drought conditions damage may be expected. This is expressed in terms of *MCPD*. It can be expected that small values of *MCPD* will not cause any damage, because most soils have the capacity to retain water available for plants. Also, some damage is considered insignificant, because yields always vary due to many different factors (weather conditions, insects, diseases). To some extent, farmers are thus used to this 'business risk'. We quantify the resistance threshold as the smallest *MCPD* where $YD=5\%$.

Proportionality refers to the steepness of the response curve. This is quantified by fitting a line through the data points. Proportionality is calculated as the maximum steepness of the fitted curve. To obtain a value between 0 and 1, we divide the steepness by the maximum value of the fitted line, and subtract it from 1.

Manageability means that the yield deficit does not cross a level of unacceptable drought impact, from which recovery is expected to be difficult. This level is difficult to quantify. The 100% damage level implies that the entire yield is lost, thus the response curve will never exceed this point by definition. Furthermore, a 100% damage level in our cases study is not expected to influence the economy in an unmanageable way. In 2012, agriculture contributed about 1.6% to the Netherlands' national GDP (CBS et al. 2013). Thus, in the very unlikely event of losing the entire agricultural yield, the impact

is much smaller than a critical 5% GDP level (cf. Mens and Klijn 2014). We thus cannot imagine crossing a critical threshold in this case study area. However, even if the damage does not exceed a critical threshold, droughts are considered better manageable if the yield deficit remains small under a wide range of conditions. We quantify manageability as the relative number of cases (simulations) where yield deficit is smaller than 10%. The more cases with a yield deficit below this threshold, the higher the manageability.

For the purpose of this case study we propose an additional criterion: the insensitivity to external water supply via the Gouda inlet (*Gouda inlet insensitivity*). Low river discharges will cause the external water supply inlet to be closed. If this coincides with a dry summer, in terms of precipitation deficit, required irrigation water will not be available and the yield deficit will increase. We consider high dependence on external supply less robust than minor dependence. Gouda inlet insensitivity is quantified by the difference in YD between the situation with 100% external water supply and the situation with 0% external water supply during the entire growing season. These are the two extremes, because in most cases of low river discharge the inlet will be closed for only a part of the growing season. A large difference in YD implies a high dependence on external water supply. As a measure of Gouda inlet insensitivity we take 1 minus the largest relative difference of the entire data set. In this way, a score of 0 means sensitive, whereas a score of 1 means insensitive.

6.2.3 Alternative system configurations

An alternative system configuration is the reference system in which changes have been made, for example in land use type and water management network, because of autonomous developments and/or the implementation of measures. Analysing the robustness of alternative system configurations provides insight into effect of different types of measures and developments.

Drought risk reduction measures can be grouped according to which of the two elements of drought risk they tackle: probability and consequences. Classification depends on the definition of drought. We can hardly change the weather patterns causing evaporation and precipitation, but we can change the availability of water at a

specific location. Here, we refer to drought as water shortage for a specific function. Drought probability reduction involves increasing the availability of water at a specific location. Probability-reduction measures are for example those that increase the storage capacity (for example, local water retention basins, aquifer storage, water level management), or those that increase external water supply (including the installation of sprinklers). Measures that reduce the consequences of a drought are related to the demand for water, for example improved irrigation efficiency, crop rotation, and increased use of drought-resistant crop varieties (IPCC 2012).

Another way of grouping drought risk reduction measures is by the spatial scale on which they apply. The Netherlands Delta Programme (DeltaProgramme 2013) distinguished between regional measures and national measures, basically referring to the difference between reducing the regional demand for external water and increasing the external water supply from the main rivers and lakes towards the different water management regions in the Netherlands. Distinguishing between national supply and regional demand is typical for the Netherlands context. Regional measures aim to reduce the dependency on external water supply, for instance by increasing the storage within the regional system of lakes, canals, and aquifers. National measures aim to enhance external water supply in quantity or quality. In the Netherlands climate research programme 'Knowledge for Climate', the regional measures were further classified based on the responsible sector (Jeuken et al. 2012).

Table 5 gives an overview of measures grouped against both the responsible entity and where they have an effect (regional demand/national supply). Changing the inlet criteria refers to the Gouda closure regime based on expected chloride concentrations. This regime is considered quite strict (Van der Zee et al. submitted). Changing the criteria practically means that external water can be supplied for a longer time, reducing the probability of water shortage, but at the same time compromising the water quality. The sensitivity of crop yield to brackish irrigation water remains uncertain (Van Bakel and Stuyt 2011).

We analysed the following alternative system configurations:

GI (Grass Irrigation)	Increasing the irrigation area from 7% to 75% of the case study area, by installing sprinklers on all grass lands
CS5 (Contingency Supply)	Increasing the contingency water supply capacity by $5 \text{ m}^3 \text{ s}^{-1}$
CS10 (Contingency Supply)	Increasing the contingency water supply capacity by $10 \text{ m}^3 \text{ s}^{-1}$
GI-CS5	Combination of GI and CS5
GI-CS10	Combination of GI and CS10

Table 5 Classification of drought risk reduction measures

		effect on	
		regional demand	national supply
responsibility	water manager	enhance regional storage capacity increase water network efficiency prioritize among users	enhance national storage capacity increase contingency supply capacity loosen inlet criteria
	water user	increase water use efficiency (farm) increase crop diversity change to drought-resistant crop types increase local storage capacity	

6.2.4 Models

Overview

To model the system response to drought disturbances in terms of agricultural yield deficits, we used two different model cascades: two hydrological models (NHI and RAM) in combination with the same agro-economic model AGRICOM. The first hydrological model, NHI, is physically-based and complex with long computation times. Model results were available from the policy analysis on behalf of the Delta Programme (Klijn et al. 2012b), of which we used two 35-year time series of *Eratio* (historic and future). This yielded a total of 70 years representing a variety of drought conditions. We consider this dataset a good representation of the real system. However, a 35-year historic series may not contain all extreme drought conditions in which we are interested.

The second model is a Rapid Assessment Model (RAM) model with simplified water balance equations, and based on NHI (Haasnoot et al. 2014). It is considered less realistic in terms of predictive capacity, but it allows us to model many possible combinations of weather, water supply and system configurations. With this model we simulated two times 1000-year synthetic time series of evapotranspiration and precipitation, representing current and future climate respectively. These results give more insight into the system characteristics that explain robustness.

NHI

The National Hydrological Instrument (NHI) (De Lange et al. 2014) is the most sophisticated hydrological model of the Netherlands available. It consists of a coupled saturated/unsaturated zone model, a regional surface water model and a national water distribution model. The key inputs for NHI are evapotranspiration and precipitation grids (250 m). The calculation time step is one day. From the evaporation and precipitation grids we calculated the *MCPD*, by averaging the grids for the total study area and then applying Eq.18. This yielded one value per year (for the growing season).

RAM

The rapid assessment model (RAM) is a simple water balance model, derived from the Integrated Assessment Meta Model (IAMM) developed by Haasnoot et al. (2014). The IAMM consists of several modules of which we only used the water demand module, schematised in Figure 28. This module calculates potential and actual evapotranspiration, based on input time series of precipitation and reference evaporation, and input maps with land use and soil type. Other model variables and parameters are soil moisture characteristics (e.g. crop factor, water retention curves), initial groundwater condition, elevation, and target water levels. Most of these variables have been derived from the NHI model. The model was applied on a resolution of 250 m. The model keeps the surface water at a constant level. It is thus assumed that sufficient water is pumped in from either Gouda or elsewhere for this purpose. This reflects current practice.

For our case study, we calibrated our version of RAM based on the NHI model results of the historical period 1975-1996. To that end, we compared the relationship between yield deficit (*YD*) and maximum cumulative precipitation deficit (*MCPD*). Figure 29 shows that the shapes of the curves are comparable.

In the original IAMM, the water demand module is connected to a water distribution module, which calculates the amount of (surface) water supply from other areas. Because RAM lacks this connection, we added a 'decision rule' that determines whether the water demand can be supplied from Gouda. The connection with the contingency water supply network is modelled in a comparable way. When Gouda is closed, the model checks whether the demand exceeds the contingency supply capacity in that time step, and supplies the water accordingly.

A higher *MCPD* will increase the demand for external water. If this water can be provided by the Gouda inlet, RAM will calculate zero yield deficits for the irrigated areas. However, if Gouda is closed, the yield deficit depends on the capacity of the contingency supply. The total yield deficit is calculated over the entire area, and is thus a sum of deficits in the irrigated and non-irrigated areas.

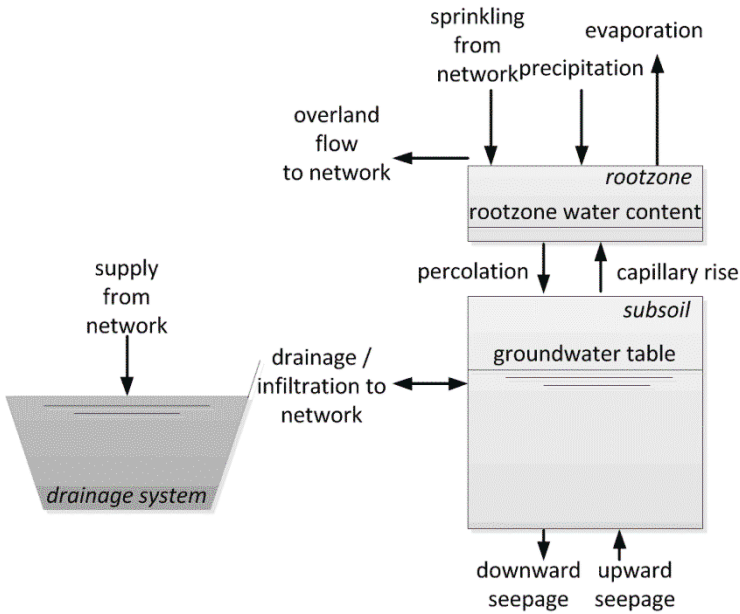


Figure 28 Rapid Assessment model (RAM), adapted from Haasnoot et al. (2014)

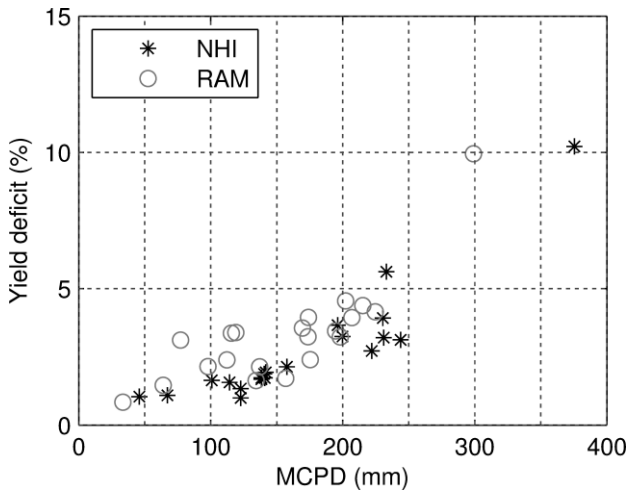


Figure 29 Result of RAM model calibration: yield deficit as a function of Maximum Cumulative Precipitation Deficit (MCPD), according to NHI and RAM, applied on West-NL, for the period 1975-1996

AGRICOM

AGRICOM (Mulder and Veldhuizen 2014) is an agro-economic model to estimate agricultural yield losses due to water shortage, saline soil moisture and water excess. We used the water shortage module. As input it requires the ratio between actual and potential evapotranspiration in time (*Eratio*), which is provided by NHI and RAM. The model uses crop-specific damage functions relating the *Eratio* with a damage fraction: the fraction of crop yield that will be lost due to drought. The damage function changes in time, taking into account the growing phases of the crop. The damage fraction of the previous time step determines the fraction of the crop that survives for the next time step. The total damage fraction at the end of the growing season is then multiplied with the expected (potential) crop yield to obtain the actual crop yield, in kg ha^{-1} . The potential crop yield may also differ from year to year, since it depends on the potential evapotranspiration.

6.2.5 Data

Precipitation and evaporation in the current climate

Both models use precipitation and reference evaporation as input time series. For the current climate, NHI uses the historical time series of P and ET_{ref} from 1961 to 1995, on a daily basis, and the spatial mean of various measuring stations. For the Delta Programme, the Netherlands institute for meteorology (KNMI) developed time-dependent input maps of 1000×1000 m for the entire Netherlands. From this set, we selected the area of West-NL and calculated the mean of P and ET_{ref} over this area, which allowed us to estimate one *MCPD* value for the entire study area.

Whereas NHI input for the current climate is based on historical time series, RAM uses a synthetic time series of P and ET_{ref} . The data was again obtained from KNMI, who used a stochastic weather generator (Brandsma and Buishand 1998) to create synthetic time series of P and ET_{ref} for several regions in the Netherlands, including our case study area (Beersma and Buishand 2007). Because this time series is much longer (1000 years) than the historic time series (35 years), it contains more extremes in both year-to-year variability and variability in timing of *PD* within the growing season.

Precipitation and evaporation in the future climate

For a representation of future climate, we used transformed time series (P and ET_{ref}) of both the historical 35-year time series and the synthetic 1000-year series. This data was also provided by KNMI, who developed a tool for the transformation of climate data (Bakker and Bessembinder, 2012). This tool transforms historical time series by applying a certain change (or “delta”) to daily values. The historical time series are adjusted in such a way that the newly generated time series for the future is consistent with one of the four KNMI’06 climate change scenarios of the Netherlands (Van den Hurk et al. 2006). It also takes care of the fact that the change in average values can differ from the change in extreme values (Bakker and Bessembinder 2012). We selected the worst-case KNMI’06 climate change scenario, $W+2100$, representing a change in average summer precipitation of -26% (coastal areas) and an average change in temperature of +4 °C (Van den Hurk et al. 2006).

6.3 Results: how robust is West-Netherlands for droughts?

6.3.1 Analysis with NHI

Figure 30 shows the response curve for West-NL as modelled with NHI. As expected, the yield deficit increases with increasing $MCPD$. However, it is difficult to draw a curve through the points in the figure, because for each $MCPD$ value a range of YD is shown. For example, at an $MCPD$ of 400 mm, the yield deficit ranges between about 5 and 10%. This range can be explained by a combination of two factors: 1) the timing of the drought within the growing season, and 2) the water supply availability. The first factor is important, because of the different crops with their differing drought vulnerability, a deficit in spring may cause more yield loss than the same deficit in august. The second factor refers to a closure of Gouda, which leads to additional yield deficit in the irrigated areas. It is unclear which of the two factors explain the observed range. Therefore, the Gouda inlet insensitivity cannot be scored.

Figure 30 shows a resistance threshold of about 250 mm $MCPD$, where the 5% YD is exceeded for the first time. Because the maximum $MCPD$ considered in the analysis is 600 mm, the resistance threshold scores 0.4 on a scale of 0 to 1. The return period of $MCPD = 250$ mm has been estimated at 10 years (Beersma and Buishand 2007) in the

current climate and 1 year in the worst-case future climate (Klijn et al. 2012b). This does not mean that in the future the crop yield deficit will exceed the 5% level almost on a yearly basis. The same *MCPD* of 250 mm could also lead to less than 5% crop yield deficit, because of the variability in drought timing.

The proportionality is estimated at 0.93 on a scale of 0 to 1. This means that at the steepest part of the fitted response curve, the yield deficit increases with 5% of the maximum deficit with a 1 mm increase in drought magnitude. The yield deficit thus increases proportionally with increased precipitation deficit;

Manageability was scored 0.95. The drought response is considered manageable, because a recovery threshold is not reached; under the most extreme condition the yield deficit is still smaller than 20%. The most extreme condition is a high precipitation deficit timed in the most sensitive period combined with a closed Gouda inlet. However, even if the *YD* stays far below a recovery threshold, we prefer low *YD* over high *YD*. Therefore, we identified a 10% *YD* level as an additional threshold. In both models, about 95% of the cases stay below the 10% damage level. Note that an individual farmer may still suffer high yield deficits, but because we summarize deficits for the entire region, this is not visible in the analysis. This reflects an implicit choice for a water manager perspective, as opposed to that of an individual farmer.

Summarizing, the system robustness criteria score as follows on a scale from 0 to 1:

Resistance threshold: 0.4 (the 5% *YD* level is reached at a *MCPD* of about 250 mm)

Proportionality: 0.93 (7% increase in *YD* for a 1 mm increase in *MCPD*)

Manageability: 0.96 (*YD* < 10% in 96% of the cases)

Gouda inlet insensitivity: n/a

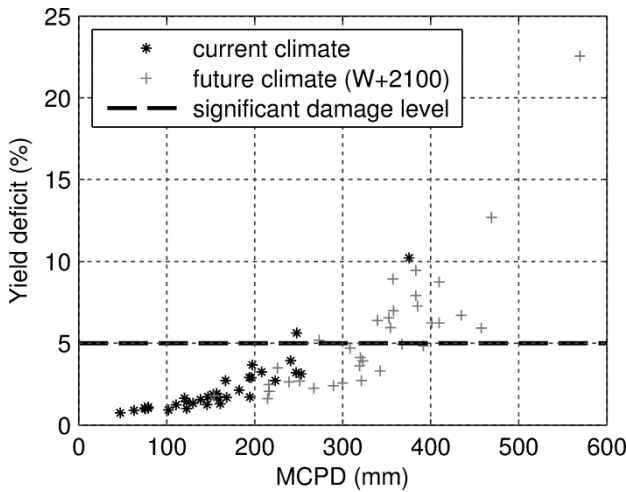


Figure 30 Agricultural yield deficit (*YD*) as a function of maximum cumulative precipitation deficit (*MCPD*), modelled with NHI for current and future climate conditions

6.3.2 Analysis with RAM

Figure 31 shows the response curves based on the calculations with the rapid assessment model (RAM). Figure 31 shows the response curve for the ‘Gouda open’ situation (100% water supply from Gouda) and the ‘Gouda closed’ situation (0% water supply from Gouda). The robustness scores of the reference and alternative configurations are shown in Table 6. Since Figure 31 (Left) is a situation where we assume 100% water supply, the bandwidth is entirely explained by the variation in timing of the precipitation deficit. It thus illustrates that the timing within a year is very important in determining the yield deficit.

The **resistance threshold** is slightly smaller than that obtained with NHI, namely 0.3 (*MCPD* = 160 mm). However, of all the cases with 160 mm *MCPD*, only 1 case exceeds the 5% *YD* level of yield deficit. Because this rare event did not occur in the time series simulated with NHI, this may explain the difference between the two resistance thresholds. The score on **proportionality** is comparable to that obtained with the NHI model: 0.95. The **Gouda inlet insensitivity** is scored at 0.67. This means that a closure of the Gouda inlet could increase the yield deficit with a maximum of 33%. This shows that the range due to drought timing is much larger than the range due to water supply

availability. This effect can be explained by the fact that only 7% of the total case study area is irrigated.

Additionally irrigating grass lands (GI) decreases the yield deficit, as reflected in the slightly higher score on manageability, but only for the cases with an open Gouda inlet. For the cases in which the inlet is closed, the total yield deficit is not affected. This causes a larger difference between 'open' and 'closed' and therefore the score on Gouda inlet insensitivity is negatively affected: from 0.67 to 0.31. Proportionality is slightly higher.

Increasing the capacity of the contingency supply has a positive effect on the Gouda inlet insensitivity; it increases from 0.67 to 0.83 (CS5) and 1 (CS10). The contingency supply capacity of $10 \text{ m}^3 \text{ s}^{-1}$ is thus sufficient to supply the largest demand of all modelled cases. It also has a small positive effect on the manageability. The capacity of CS5 is not sufficient, since the demand still exceeds the supply in 21% of the cases where Gouda is closed. However, deficits are smaller compared to the reference situation with a closed inlet, and therefore it also has a small positive effect on the manageability.

The negative effect of GI on the Gouda inlet insensitivity can be partly counteracted by also increasing the contingency supply (GI-CS5 and GI-CS10). However, these capacities are not sufficient to reach the same Gouda inlet insensitivity as in the reference, because the external water has to be shared by a larger irrigated area.

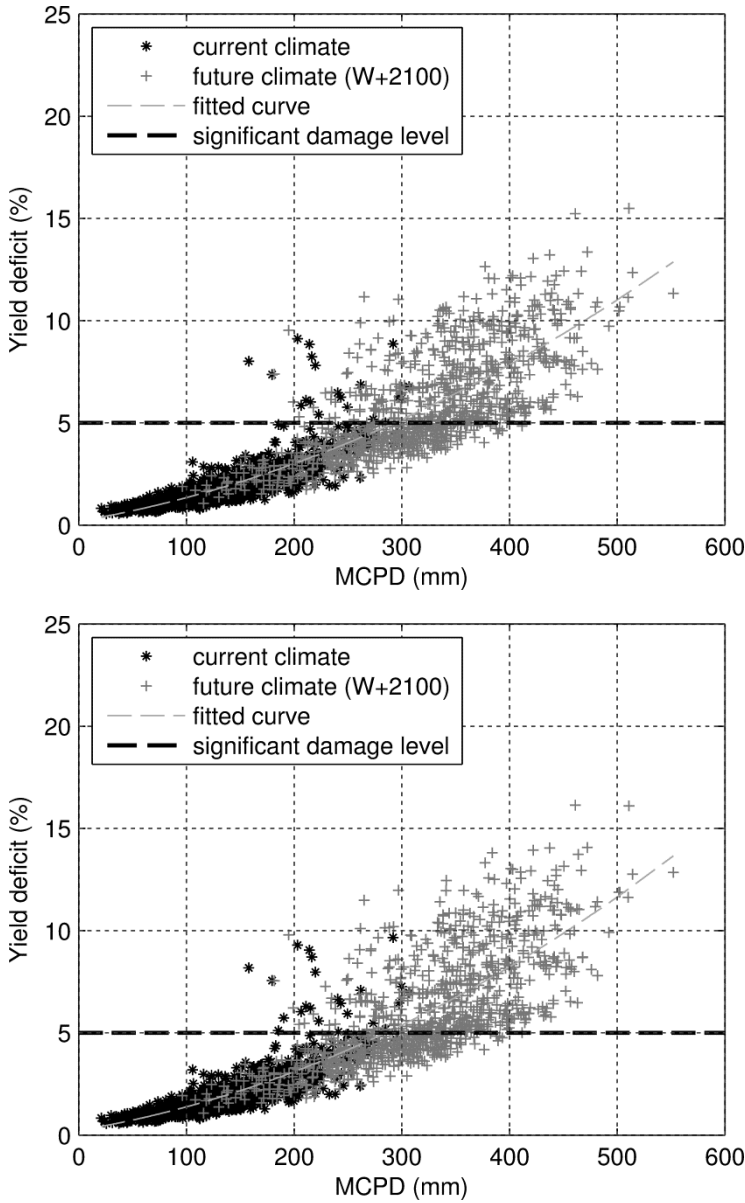


Figure 31 Agricultural yield deficit (*YD*) as a function of maximum cumulative precipitation deficit (*MCPD*), modelled with RAM for current and future climate conditions in the reference configuration. Upper: assumption of 100% water supply (Gouda open). Lower: 0% water supply (Gouda closed)

Table 6 Overview of scores on the system robustness criteria

Configuration ID ^a	Ref	GI	CS5	CS10	GI-CS5	GI-CS10
Resistance threshold	0.3	0.3	0.3	0.3	0.3	0.3
Proportionality	0.95	0.96 ^b	0.95	0.95	0.96 ^b	0.96 ^b
Manageability	0.95	0.97	0.96	0.96	0.97	0.98
Gouda inlet insensitivity	0.67	0.31	0.83	1	0.44	0.48

^a Ref = Reference configuration; GI = Grass land irrigated; CS5 = Contingency supply of $5 \text{ m}^3 \text{ s}^{-1}$; CS10 = Contingency Supply of $10 \text{ m}^3 \text{ s}^{-1}$; GI-CS5 = Grass land irrigated & Contingency Supply of $5 \text{ m}^3 \text{ s}^{-1}$; GI-CS10 = Grass land irrigated & Contingency Supply of $10 \text{ m}^3 \text{ s}^{-1}$

^b This is the average value of a range of 0.95 - 0.97, which is caused by the difference between 'Gouda closed' and 'Gouda open'

6.4 Discussion

In this discussion, we elaborate on the meaning of the robustness criteria, how the robustness scores can be explained, and how robustness can be increased. Based on that, we discuss the added value of robustness analysis in the context of drought risk management.

6.4.1 System robustness criteria

System robustness to drought was quantified by drawing a relationship between precipitation deficit and yield deficit, for two situations: a closed Gouda inlet and an open Gouda inlet throughout the season. This relationship was then used to quantify four robustness criteria: resistance threshold, proportionality, manageability, and Gouda inlet insensitivity.

The resistance threshold points at the internal storage capacity of the system and is expressed in mm MCPD (or fraction of maximum MCPD). It shows that smaller values will not cause any significant drought damage. However, larger values will not always cause significant damage, because of the variability in drought timing. The resistance

threshold thus represents a worst-case scenario; the smallest value of *MCPD* that will cause damage when timed in the most sensitive part of the season. It would be interesting to explore the effect of increasing the storage capacity on the resistance threshold.

Proportionality did not discriminate between the alternatives, because of two reasons: the choice of the indicator and the inherent proportional behaviour of the drought system. First, proportionality is meant to point at the possibility of sudden changes in damage, implying that droughts can come as a surprise. The proposed indicator does not detect sudden changes, because fitted curves are all proportional. Also, steepness is already included in manageability. Steeper curves will cross critical thresholds at smaller values of *MCPD*, resulting in a lower score on manageability. Steepness should therefore not be part of proportionality. Second, a proportional increase of drought impact seems inherent to drought risk systems. Droughts build up slowly in time and the effect on crop yield is an accumulation of consecutive periods of water shortage. Sudden changes in damage are therefore not expected. Thus, proportionality was not a relevant robustness criterion, at least for this case study.

The score on manageability depends on the chosen threshold, in this case set at 10% *YD*. In practice, this threshold should be chosen in consultation with stakeholders. In fact, several thresholds could be chosen, to show how the simulated cases are spread over different damage categories. The key question is what level of damage is still considered acceptable.

The Gouda inlet insensitivity was specific for this case study, because we identified two types of disturbances. As indicator we used a case-by-case comparison of *YD*. The result thus indicates the largest difference between two cases, even if the corresponding condition occurred just once. Alternatively, the average difference of all cases could be used. However, from a robustness perspective it is interesting to understand the effect of a potential closure of Gouda, even if this has a small probability.

6.4.2 How can system robustness be explained?

The scores on the different robustness criteria can be explained by several system characteristics. In general, the yield deficit increases with increased precipitation deficit,

but because of the timing variability high yield deficits can also occur with relatively small precipitation deficits.

The resistance threshold of 160 mm (RAM model) or 250 mm (NHI model) is a direct consequence of the storage capacity of the system. Due to the clay and peat soils in a large part of the study area, soil moisture is available for the crops for at least one month of zero rainfall. Another storage aspect is the fact that water levels in the polder canals are managed. This explains the slow decline of groundwater levels during a dry period, which adds to the storage capacity.

The manageability can be explained by the drought sensitivity of the crops in combination with the crop diversity. The drought sensitivity varies in time between crop types. Because not all crops are as sensitive to drought in the same period, only a very prolonged drought will affect all crops at the same time. In the Netherlands' climate, a drought lasting the entire growing season is very unlikely.

The Gouda inlet insensitivity is determined by the irrigated area and the value of the irrigated crops. Because only a minor part of the area is irrigated, the difference between 0 and 100% supply is small in the reference configuration.

Summarizing, the following system characteristics determine the robustness of the studied drought risk system:

- Internal storage capacity of the system
- Varying drought sensitivity of crops
- Diversity of crop types within the area
- Access to external water supply (sprinkler installations)
- Capacity of the contingency supply

Because the system (West-NL) has favourable conditions for most of these aspects, it scores high on most robustness criteria.

6.4.3 How can system robustness be increased?

Our analysis has shown that system robustness can be increased by enhancing one or more of the above-mentioned system characteristics. We only adapted the last two characteristics: giving more areas access to external water supply, and increasing the

capacity of the contingency supply. Note that irrigating grass lands is not very realistic, because it is not very cost-effective from a farmer’s point of view. It is recommended that future studies consider additional irrigation of higher-value crops.

The studied alternative configurations did not influence the resistance threshold but we can think of measures to increase the storage capacity, most likely having a positive effect on the resistance threshold. For a future study we therefore recommend to include measures that increase the storage capacity, such as soil improvement, flexible drainage, and retention basins. These are expected to increase the resistance threshold, because a larger precipitation deficit is needed to exceed the 5% yield deficit.

The manageability was hardly influenced by the studied alternatives, because it scored high already in the reference. Measures that aim at drought impact reduction, for example by changing to crop types that are less sensitive to drought, will positively affect the manageability.

Summarizing, the following measures affect different aspects of robustness:

Measure	Robustness aspect affected
Increase storage capacity	Resistance threshold
Reduce drought sensitivity of crops	Manageability
Increase diversity of crop types	Manageability
Increase irrigated area	Manageability / Gouda inlet insensitivity
Increase contingency supply capacity	Gouda inlet insensitivity

6.4.4 The added value of robustness analysis for drought risk management

Drought risk refers to the expected value of yield loss. The risk reduction achieved by implementing an alternative strategy could be compared with the investment costs of the proposed strategy. This is the basis of risk-based decision making.

A risk analysis typically combines probabilities and consequences. Drought risk can be quantified based on the results with the RAM model, since each set of 1000 model runs

(either current or future climate) represents the probability distribution of the precipitation deficit. The expected value of the simulated yield deficits can thus be considered the risk (in % per year) for current and future climate conditions. Gouda inlet closure could also be taken into account by assigning a probability of occurrence to both the open and closed situation. The yield losses could also be expressed into monetary values, allowing quantification of monetary drought risk. All proposed measures will reduce the drought risk to some extent.

In the robustness analysis, we have separated the source of a drought, precipitation deficit/water supply deficit, from the consequences of a drought, crop yield loss. In a traditional risk analysis, different measures (reducing demand/increasing supply) will reduce the risk to some extent. The robustness criteria additionally show which aspect of the risk curve is affected by the measure. For example, increasing the storage capacity and increasing the contingency supply may have a comparable effect on the balance between demand and supply, but they score differently on the robustness criteria. We suggested that the storage capacity will increase the resistance threshold, but other aspects of robustness (manageability and Gouda inlet insensitivity) may not be affected, which means that high yield deficits under rare drought conditions are still possible. From a robustness perspective, the contingency supply option may therefore be more desirable. The robustness analysis thus provides additional insight that can be used in a drought risk decision making context.

6.5 Conclusion

This paper explored how system robustness analysis can be operationalized in the context of drought risk management, by proposing and quantifying system robustness criteria for an agricultural polder area in the Netherlands. To this end, we defined water shortage as a situation in which actual evaporation is smaller than the potential evaporation needed for crop growth. Water shortage is caused by a combination of precipitation deficit and water supply shortage, the latter caused by closure of the Gouda inlet. As a measure of drought impact we chose the relative crop yield deficit. We analysed how sensitive the yield deficit is for a change in precipitation deficit as

well as for a change in water supply, and we analysed how this robustness is affected by drought reduction measures.

The robustness was quantified by drawing a relationship between precipitation deficit and yield deficit, for two situations: a closed Gouda inlet and an open Gouda inlet throughout the season. This relationship was then used to quantify the four robustness criteria: resistance threshold, proportionality, manageability, and Gouda inlet insensitivity. Proportionality could not discriminate between the alternative configurations. Therefore, it seems not a relevant criterion in a drought context.

The following system characteristics explained the high robustness scores of the studied drought risk system:

- A storage capacity of at least 160 mm
- Limited drought sensitivity of crops
- High diversity of crop types within the area in combination with a variation of drought sensitivity in time
- Small area with access to external water supply (sprinkler installations)

Furthermore, we showed that drought timing has a larger effect on the yield deficit than Gouda inlet closure. This can however change when more areas are irrigated.

Installing sprinkler installations (as in extending the irrigated area) reduces the yield deficit for many conditions, but it also increases the water demand thereby increasing the dependence on water supply from Gouda. Because the Gouda inlet is not available under some conditions, a high dependence is not desirable. This can only be (partly) counteracted by also increasing the contingency supply capacity. When this capacity is not large enough, yield deficits can still occur under some conditions. The yield deficits under these conditions could be further decreased if the supply water would be prioritized for the high-value crops. Although this was not simulated in the case study, we expect that increasing the storage capacity will increase the resistance threshold, and reducing the crop sensitivity will enhance the manageability.

Robustness analysis provides insight into the conditions under which drought impacts can be expected. The use of a Rapid Assessment Model allowed simulating a large

number of time series of precipitation and evapotranspiration, which implicitly represented a large range of drought conditions.

The robustness analysis allowed comparing alternative strategies under a range of drought conditions and helps explaining the effectiveness of these strategies. We showed that a robustness analysis provides insight into which system characteristics are responsible for 'no response' under frequent drought conditions (resistance threshold) and 'limited response' under rare drought conditions (manageability). Although the case study results are specific for the Netherlands situation, we believe that the conceptual framework for system robustness analysis could be valuable for other drought risk systems as well. We therefore conclude that robustness analysis has added value for drought risk management under climate change.

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7 Discussion, conclusions and recommendations

7.1 Thesis overview

This thesis developed and tested a framework for robustness analysis in the context of flood and drought risk management. This framework consists of a definition, the steps to take when analysing robustness, and robustness criteria to aid decision making on alternative risk management strategies. This was motivated by the view (in the literature and in the policy making domain) that the traditional risk approach, based on a single-value risk metric, is insufficient to avoid disasters. Impacts become disasters when they exceed a society's coping capacity, thus when they become unmanageable. In this thesis, unmanageable impacts were considered 'societally unacceptable'. The traditional risk approach implicitly assumes that large impacts from flood or drought events are acceptable if their probability of occurrence is low. However, even when flood or drought risk is reduced to an acceptable level, the impact of a low-probability event may still be too high to recover from. To avoid disasters, measures need to be taken not only to avoid impacts, but also to limit the impact of extreme (beyond-design) events and to enhance the recovery capacity. This is especially relevant as extreme events are uncertain and may become more frequent and/or severe in the future.

The proposed robustness analysis framework aimed to provide a quantitative method to support the assessment of risk reduction measures on their effect on the consequences of a range of flood or drought events. To test this framework, it was applied in two flood cases and two drought cases. All cases visualized the expected impacts for a range of flood or drought magnitudes, and quantified and discussed

robustness criteria for various system configurations. A system configuration is the combination of system characteristics that determines how the system responds to floods or droughts, and can be adapted by implementing measures. By comparing different system configurations, insight was obtained into the characteristics that determine a system's robustness to floods or droughts.

This chapter answers the research questions (Chapter 1) and reflects on the meaning of these answers in the broader context of flood and drought risk management. Furthermore, it provides recommendations on how to proceed with research on system robustness.

7.2 Answering the research questions

7.2.1 Research question 1: How can robustness be defined for flood and drought risk systems?

In this thesis, system robustness was defined as *the ability of a system to remain functioning under a range of disturbance magnitudes*. Disturbance refers to events that result from climate variability, for example floods and droughts. Disturbances may be quantified by, for example, flood wave peak or drought volume, and can take various magnitudes. Along the range of disturbance magnitudes, three kinds of system response were distinguished: the response is zero for a first range of disturbance magnitudes, it increases for a second range, and it exceeds a recovery threshold for a third range. A robust system is one where the response to a disturbance is below this threshold over a large range of disturbance magnitudes.

The proposed robustness definition was found applicable and useful in the context of flood and drought risk management. A fluvial flood risk system is considered robust when socio-economic impacts of river flooding do not exceed a societally unacceptable level ('recovery threshold') for a wide range of flood waves. Likewise, a drought risk system is considered robust when socio-economic impacts of drought do not exceed societally unacceptable levels for a wide range of drought magnitudes.

7.2.2 Research question 2: Which criteria and indicators can be used to quantify robustness of flood and drought risk systems?

System robustness can be quantified by drawing a relationship between disturbance and response. Robustness criteria aim to characterise this curve, and indicators allow to quantify the criteria in order to assess alternative system configurations.

The following three robustness criteria were proposed:

1. The *resistance threshold* is the point where the impact becomes greater than zero, i.e., the smallest disturbance magnitude causing significant impacts;
2. The *response proportionality* is the suddenness of the response increase with increasing disturbance magnitudes;
3. The *manageability* is the ability to keep the response below a level from which recovery is difficult or impossible.

The criteria and indicators are elaborate on De Bruijn's work (De Bruijn 2004, De Bruijn 2005) on resistance and resilience of flood risk systems. She also proposed to quantify the resistance threshold and the proportionality of the response. Her other criteria were related to the severity of the response and the rate of recovery. This thesis adds the concept of a recovery threshold to be able to assess when flood impacts turn into a disaster. It is considered more meaningful to assess the severity of the response relative to a maximum value instead of assessing the severity alone. This maximum value is the recovery threshold: the impact from which society can just recover. The criterion 'manageability' thus combines De Bruijn's severity and recovery rate. Although the choice of the recovery threshold is arbitrary and should result from a societal discussion, this threshold is required to assess robustness.

How the criteria are quantified is case-dependent. Quantifying the **resistance threshold** is straightforward, because it is defined as the smallest disturbance magnitude causing significant impacts. It is thus expressed in terms of the disturbance magnitude, for example flood wave peak or drought volume.

Proportionality was quantified as the maximum slope of the response curve, which indicates how much of the increase in response occurs at once. The resulting value was divided by the maximum response of all configurations. The results from the flood

cases give the following reasons to reconsider this indicator: 1) it is case-dependent, because it is divided by the maximum response of all configurations; 2) it is not a dimensionless unit, which makes it difficult to communicate; and 3) the proportionality changes with the severity of the response, which seems to overlap with manageability. Therefore, it is recommended to reconsider this indicator.

In the drought cases, proportionality hardly discriminated between different configurations, as no sudden jumps in drought impact were detected. This can be explained by the fact that the studied droughts built up slowly in time and with each increase in drought magnitude, a larger amount of water had to be replaced (agricultural drought case) or a higher percentage of crop yield was lost (streamflow drought case). However, in other drought risk systems with other characteristics the effect may be different.

Quantifying **manageability** requires a choice on what level of impact is considered 'societally unacceptable' or difficult to recover from. This also depends on how the system response is quantified. In the flood cases the response was quantified as monetary flood impact and this was compared with a threshold in terms of Gross Domestic Product (GDP), as an indication of economic capacity. A different possibility to quantify system response to floods is by the number of affected people or casualties, which can then be compared with a critical number (e.g., Mens et al. 2011).

7.2.3 Research question 3: What is the added value of system robustness analysis for flood and drought risk management?

A risk approach to decision making involves maintaining or reducing risk to an acceptable level against acceptable societal costs. Risk analysis aims to identify and quantify probabilities and consequences of adverse events. A risk curve, the probability distribution of the consequences, is a good way to visualize risk. However, when risk analysis is used in a cost-benefit analysis or multi-criteria analysis, metrics are required to summarize the risk curve, for example by the expected value of the consequences.

In flood risk management, risk is often represented by the expected annual damage, the area under the risk curve. Such a single-value metric implies that as long as the probability is low enough, high absolute consequences are always accepted. Thus,

when decision makers aim to prevent societally unacceptable consequences, a single-value metric does not suffice. Both flood cases showed that a variety of measures may reduce the single-value risk, but not all measures increase the ability to cope with extreme discharges. This means that different measures may be preferred when their effect on system robustness is taken into account. In flood risk systems in which the potential flood consequences of low-probability events are unacceptably high, the robustness criteria aid to prioritize risk-reduction measures. Thus the added value of system robustness is that the system is then not only assessed on the acceptability of single-value risk, but also on the acceptability of flood impacts under a wide range of event magnitudes.

In drought risk management, risk is often represented by the reliability of water supply systems, or the probability of meeting water demand. Although this allows comparing different measures that decrease demand or increase supply, this indicator does not take into account socio-economic consequences of water shortage. Reliability is thus not an appropriate indicator for risk (defined as the combination of probabilities and consequences). The streamflow drought case showed that not all measures that increase the supply reliability also reduce the drought impacts over the full range of plausible drought events. The robustness criteria thus aid in the choice for measures that reduce the impact of droughts when demands cannot be met. Measures that reduce impact score well on robustness.

7.2.4 Research question 4: What characterizes a robust flood risk system?

The flood cases (Chapter 3 and 4) have shown how different system configurations score on the robustness criteria. This gave insight into what enhances a flood risk system's robustness.

Systems with a high protection level have a high resistance threshold. However, a high resistance threshold often causes a low proportionality and a low manageability, because it attracts socio-economic developments in the flood-prone area. High protection levels alone are thus not sufficient to obtain a robust system. Furthermore, the actual discharge that causes flooding is uncertain, because embankments may breach before the design water level is reached. Because the resistance threshold

represents the lowest discharge that may cause flood impact, large uncertainty about the design water level means that the resistance threshold is smaller than the protection level. Thus, at some point, further increasing the protection level (and reducing the flood probability) does not affect the resistance threshold (see Chapter 3).

Manageability is high when flood impacts are low over the full range of flood magnitudes. This can be achieved by for instance a small difference between design water levels and the elevation of the protected area (i.e., a wide river with low embankments), land use zoning, compartmentalization, and placing critical infrastructures on higher grounds. Also, embankments that are virtually unbreachable may limit the impact and thereby enhance manageability, because they prevent sudden flooding and they limit the amount of inflowing water.

Another way to increase manageability is by differentiating the protection levels within the river valley according to differences in potential flood impact. This means that more vulnerable areas will be protected from flooding because other (less-vulnerable) areas flood first. This will prevent that large areas are flooded simultaneously resulting in sudden and large impacts. Systems with differentiated protection levels thus have a high proportionality and a high manageability.

Manageability is also determined by the recovery threshold, thus when the ability to recover from the flood impacts is high. Developed countries are usually better able to recover from floods than developing countries.

The effectiveness of measures is case-dependent. For example, as demonstrated in the flood cases, making more room for the river (aimed at lowering water levels) will increase the resistance threshold, reduce the impacts and increase the proportionality, but when resulting protection levels are also differentiated within the river valley will result in increased robustness.

Summarizing, the following can be concluded:

- Systems with a high and equal protection standard have a high resistance threshold, but this does not necessarily make them robust for extreme discharges;

- Systems with differentiated protection levels have a higher proportionality and a higher manageability than systems with equal protection levels;
- Systems with ‘unbreachable embankments’ and a large, valley-shaped flood-prone area have a higher proportionality and a higher manageability than systems with traditional embankments that may suddenly breach;
- Measures aimed at impact reduction increase robustness when they reduce those impacts below the recovery threshold.

7.2.5 Research question 5: What characterizes a robust drought risk system?

The drought cases (Chapter 5 and 6) have shown how different system configurations score on the robustness criteria. This gave insight into what enhances a drought risk system’s robustness. The insights are case-specific and therefore discussed per case.

In the **streamflow drought case**, water is provided to municipal water users through a man-made reservoir. The amount of water supply could be increased by enlarging the reservoir’s storage capacity, for example by adapting its operating rules (raising water levels). Another option to increase supply is by accessing alternative water resources (e.g., groundwater wells, desalination plants or a pipeline to another reservoir). This would also increase the supply reliability and therefore the resistance threshold, because if one source is depleted, other sources are still available.

Demand reduction, for example by motivating industries and individuals to conserve water on a structural basis (thus not only during the drought), increases the resistance threshold as well as the manageability, because larger droughts are needed to cause water shortage, and a smaller demand (the amount people are used to) costs less to replace when supply is lacking.

Drought contingency plans may reduce the drought impact during a drought. It was demonstrated that hedging (temporary water conservation when reservoir is not empty yet), reduces the total impact of large drought events, but increases the impact of smaller drought events. The effect on robustness depends on how the criteria are weighed, because the resistance threshold is smaller than without hedging, but the manageability scores higher. Prioritization among different, competing water users

may also reduce the drought impact, but can only be applied in combination with hedging. It is recommended that future research explores the effect of prioritization. Drought insurance is an example of a measure that increases manageability by increasing the recovery threshold.

In the **agricultural drought case**, supply water originated from both rainfall and external river water, and was used for cultivated crops. Because rainfall varies in time, storage capacity is important. In this case, excess rainfall is stored in the soil, canals and water basins, where it is available for crops. A limited amount of external river water can also be stored in the canals by water level management. In this case study, the limiting factor of external water supply was the water quality (not the water quantity), and therefore (in-)dependence on this water resource was proposed as additional robustness criterion.

The resistance threshold can be increased by increasing the internal storage capacity⁶, but only when this water is available for all farmers. Local measures implemented by an individual farmer, for example soil management or installing water basins, only have a local effect on the storage capacity. They will therefore reduce the total impact of the drought, but they do not increase the resistance threshold of the region, since other farmers will still experience water shortage with the same drought magnitude.

Manageability is high when drought impacts are low over the full range of drought magnitudes. Drought impact is determined by the water demand and the economic function related to this demand. Water demand for agriculture is determined by the crop type. If the cultivated crops are diverse, thus sensitive to water shortage in different parts of the growing season, it is less likely that the entire crop yield of the region is lost in a single drought event. Crop diversity thus limits the impact and thereby enhances the manageability.

⁶ Note that increase of internal storage capacity qualifies as demand reduction in the Netherlands, because water supply is used to denote external surface water, for example from a river or lake outside the region considered. Measures that increase the storage capacity within the region will reduce the demand for this external water source.

Installing sprinklers will reduce the impact from precipitation deficit, but will increase the demand for external water and therefore make the system more dependent on the external water source, which is not a robust solution when this source is not reliable. The reliability of the external supply can be increased by enlarging the capacity of the contingency supply, which is in fact a different inlet point for the same river water that is less likely to be closed for quality reasons.

Comparing the results of the two drought cases shows that demand reduction has a positive effect on robustness, but not always for the same reason. In the agricultural drought case, reducing demand for external water (by increasing local storage capacity) is considered a robust solution, because it reduces the total impact, but in fact the total agricultural demand for water in general (including rainfall) is not reduced. Therefore it did not increase the resistance threshold. In the streamflow drought case, demand reduction (by encouraging water conservation) is considered a robust solution because it reduces the total drought impact and it also increases the resistance threshold. How certain types of measures affect different robustness criteria is thus case-specific.

Summarizing, the following can be concluded:

- Systems with large storage capacity in comparison to the demand have a high resistance threshold;
- The resistance threshold can be increased by enlarging the storage capacity, if this water is available for all water users;
- Measures aimed at demand reduction reduce the impact and therefore increase the manageability;
- Drought contingency plans, including short-term measures such as rationing and prioritization, increase manageability, but they also reduce the resistance threshold.
- Diversity in drought sensitivity among water users (e.g., crop diversity) limits the impact and thereby enhances the manageability.

7.3 Reflection

7.3.1 Assumptions in a system robustness analysis

System definition

When operationalizing concepts such as robustness and resilience, it is important to specify the system and scale on which the concept is applied (see also Carpenter et al. 2001). Choices must be made regarding the spatial scale, and internal/external system components. These choices may influence the outcomes of a robustness analysis.

First, the scale needs to be chosen. Applying robustness analysis on a regional or national scale seems more relevant than applying it on a local scale, for example the scale of one polder or one city, because it is more likely that impacts become unacceptable when they cover a large area. On the other hand, acceptability of impacts also depends on the perspective. A national government may be concerned with impacts that exceed the country's coping capacity, and may therefore be interested in an analysis carried out on a regional or basin scale. In contrast, local authorities may be concerned with impacts exceeding a city's coping capacity and may be interested in an analysis on the local scale. Robustness analysis may thus also be relevant on the local scale. This is supported by research in the field of urban flood management, demonstrating the role of urban planning in reducing flood impacts in cities (e.g., Zevenbergen et al. 2008).

Second, what is internal and external to the system needs to be defined. The disturbance should be chosen external to the system, which means it cannot be affected by measures taken within the system. For example, in the IJssel case the disturbance (discharge) was chosen at the upstream bifurcation point from the Rhine river. Any measure implemented downstream was considered internal and affected how the system responded to the different discharge waves at the bifurcation point. When future studies also aim to analyse the effect of adapting the bifurcation point, for example to divert less water to the IJssel at high discharges, the boundary should be chosen further upstream. In that case, the bifurcation point becomes part of the system.

Internal to the system are all characteristics and processes that determine the functioning of the system and the societal impact of disturbances. This thesis focused on economic functioning of a region, instead of the functioning of physical elements within the system. For example, studying the robustness of embankments is considered less relevant for long-term decision making when the impact on society is not taken into account. Likewise, studying the robustness of a water reservoir is less relevant for decision making, because it is just one element in a water management system. Failure of a reservoir does not necessarily result in large impacts when alternative sources are available or when water users are not economically dependent on water.

How the system is defined also determines the effect of measures on system robustness. This was demonstrated in the two drought cases, which differed in the type of water user and the main water resource. In the streamflow drought case, the reservoir was considered the only resource. A reduction in water use directly meant a reduction in demand of water from the reservoir. However, other options exist to reduce water demand without reducing the actual water use, for example water harvesting in cities (capturing rainfall on roofs or in rainwater tanks to be used for watering gardens and lawns). Including such measures in a robustness analysis thus requires a broader system definition, namely including rainfall and water use on the scale of individual users.

Disturbance indicator and range

To quantify system robustness, the disturbance indicator needs to be chosen as well as the disturbance range for which the analysis is carried out. The disturbance in both flood cases was quantified as the river's peak discharge, which enters the system at the upstream part. However, the duration of the flood wave also characterises the flood wave and also determines the flood impact. Using more than one indicator to describe the disturbance magnitude is not desirable, because the response curve becomes 3-dimensional (impact as a function of both flood wave peak and flood wave duration). This makes it difficult to score the proportionality of the response. One solution is to perform a sensitivity analysis and then choose the disturbance indicator that determines the response best. An assumption is then needed for the second disturbance indicator, preferably reflecting the worst-case scenario. After all,

robustness analysis is about testing whether the system can remain functioning under a wide range of disturbance magnitudes.

Choosing a disturbance indicator for the drought cases was found more difficult, because drought is not a quantity of water but the amount of water that is lacking: water shortage. Calculating water shortage requires reference to what is considered a sufficient amount of water, which depends on the water users within the system. This makes it difficult to define a drought indicator that is independent of internal system characteristics. In the drought cases it was chosen to define a reference water use which is not influenced by changes in the system. For example, the agricultural drought case used precipitation deficit as the disturbance. The deficit is the difference between the available precipitation and the precipitation amount required for optimal crop growth. An optimal precipitation amount was assumed according to a reference crop. Likewise, the streamflow drought case needed an assumption on average water demand to be able to determine streamflow deficit, the disturbance indicator. Also in this case a reference water demand was chosen and not adapted in response to changes in the system.

The disturbance indicator can be chosen based on variables used to forecast droughts. In the Netherlands it is common to forecast drought based on Cumulative Precipitation Deficit (CPD). This was also used as drought indicator in the agricultural drought case. This allows using the robustness analysis results as part of a forecast, because it shows at what forecasted value impacts can be expected. In the United States it is common to monitor droughts based on the Standardized Precipitation Index (McKee et al. 1993, NDMC 2014). However, because this is a spatially distributed indicator, it should first be summarized for a region before it can be used as drought disturbance indicator.

The range of disturbance magnitudes to consider is an arbitrary choice as well. The aim of a robustness analysis is to analyse impacts for a wide range of plausible disturbances, including the ones with a low probability in the current climate. In the cases, the range was chosen based on historic measurements and available climate projections of disturbance magnitudes. When different climate change projections become available, the disturbance range could be extended. This problem was not encountered in the flood cases, because the maximum disturbance magnitude was mainly determined by

what was physically possible. In these cases, larger discharges would cause upstream flooding and never reach the system under study. In the drought cases, however, the maximum disturbance magnitude was determined by the worst case climate scenario, making it sensitive for new climate information. It is not expected that a slight change in the range would significantly affect the results, because in robust systems the impacts increase proportionally with further increasing disturbance magnitudes. A system that is robust within the considered range will most likely be also robust for more extreme events.

System response and recovery threshold

The novelty of the system robustness analysis method is that it explicitly compares impact with a critical threshold: the recovery threshold. This requires an indicator for system response, representing 'system functioning', and determining a recovery threshold, beyond which the system cannot remain functioning. It is, however, difficult to express system functioning in one indicator. The flood cases used economic flood damage as an indicator for response to flooding, making use of available data from flood risk analyses in the same area. This response was then compared with regional Gross Domestic Product, as an indicator of the region's economic capacity. The question is whether economic flood damage can be considered a good indicator for system functioning, because the functioning of a society also depends on whether critical goods, such as electricity and drinking water, can still be supplied. It also depends on how many people are affected at once, and whether industries that are critical for the economy are damaged. Understanding societal disruption and the potential for disaster may thus require additional models, for example those developed for vulnerability analysis (Marchand 2009, Adger 2006).

The same difficulty applies for representing drought response. The agricultural drought case used crop yield deficit as indicator for system response, but this does not directly reflect economic impact, since crop prices vary due to price elasticity, and because it is unknown how well farmers can deal with individual losses. Direct and indirect economic drought impact is determined by complex interactions between agricultural producers and supplying or buying industries within or outside the agricultural sector (Bockarjova 2007). Although several methods are available to estimate economic

drought impact (see Logar and Bergh 2013), they are not yet readily available for application in a specific case. To understand how a region can remain functioning during drought events, agro-hydrological models need to be connected with macro-economic models.

7.3.2 How to use the robustness criteria?

This thesis proposed three criteria to assess system robustness, which were scored in the cases with a value between 0 and 1. This may give the impression that a score of 1 on all criteria is required to obtain a fully robust system, which is not true. A robust system is one where the impacts stay below the recovery threshold for a wide range of disturbance magnitudes. A score of 1 on the resistance threshold would imply that the system can withstand the entire range of disturbance magnitudes, and that manageability and proportionality are not needed. A system that can withstand any disturbance magnitude is not realistic, because it is very costly and often not desirable. Furthermore, some systems have low resistance threshold because of other reasons, for example when frequent flooding is desired because it has a positive effect on agriculture in floodplains. Systems with a lower resistance threshold additionally require a high manageability and high proportionality to provide robustness for the remaining disturbance range. Thus, the resistance may be low when manageability and proportionality are high. Robustness should therefore be assessed by looking at the combined score on all three criteria.

Assessing robustness may be simplified by measuring the resistance range and the resilience range, where the resistance range is determined by the resistance threshold and the resilience range by the manageability and proportionality. However, two systems with comparable ranges may still score differently on the robustness criteria. Figure 32 shows response curves of two systems with similar resistance and resilience ranges. At first sight, these systems have the same robustness, since the total robustness range is equal. However, the second system scores better on proportionality (no sudden increase of the impact) as well as on manageability (lower impact). Based on the robustness criteria, the second system would thus be preferred.

De Bruijn (2005) compared resistant systems with resilient systems, where resistant systems have a high resistance threshold and low proportionality, and resilient systems have a low resistance threshold and a high proportionality. She concluded that resilient systems can cope more easily with unexpected conditions, because of their high proportionality. A robustness perspective is slightly different: each system has some degree of resistance and some degree of resilience and this combination determines its robustness for extreme flood events. The resistance threshold may be low or high, as long as the response is proportional and manageable.

It may seem that proportionality and manageability always go hand in hand, but a system with a steep but proportional response curve will score lower on manageability than a system with a less steep but proportional response curve. This is visualized in Figure 33.

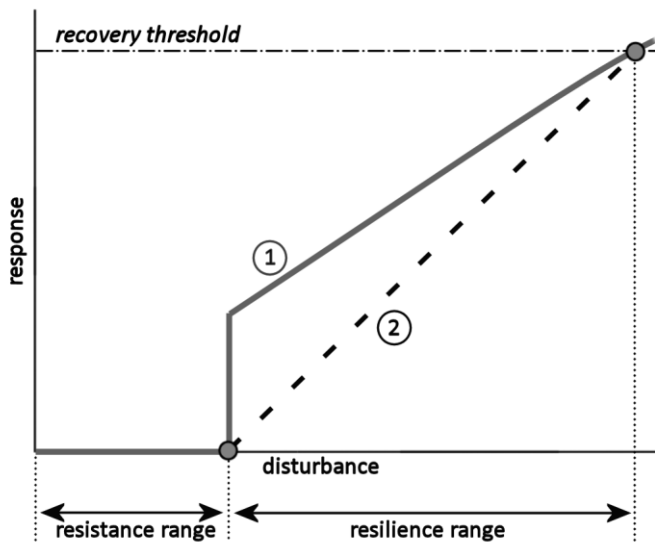


Figure 32 Response curves of two hypothetical systems with equal resistance and resilience: 1) low proportionality and 2) high proportionality

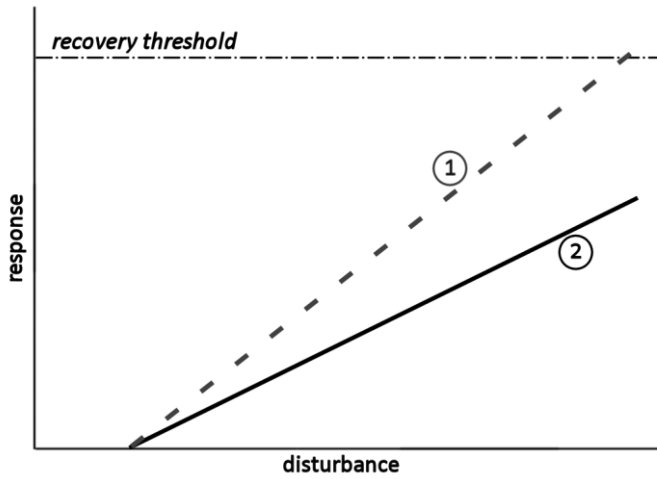


Figure 33 Response curves of two hypothetical systems with equal proportionality, but nr.2 scores higher on manageability

7.3.3 System robustness in comparison to other concepts

Resilience approach and resilience principles

The resilience approach as proposed for climate change adaptation has similarities with system robustness analysis. The resilience approach (Wardekker et al. 2010, Dessai and Van der Sluijs 2007) uses a broad definition of resilience including the ability to withstand and recover from disturbing events (similar to system robustness) and the ability to adapt to changes. The design of management options to enhance resilience can be inspired by system mechanisms and processes ('resilience principles') that are believed to limit the impact of disturbing events and trends. Resilience principles originate from ecological and system dynamics literature and have been operationalized in the context of climate change adaptation (Wardekker et al. 2010, Dessai and Van der Sluijs 2007, Barnett 2001, Watt and Craig 1986): homeostasis, omnivory, high flux, flatness, buffering and redundancy. Some of the mentioned principles were found to increase robustness in the agricultural drought case in this thesis. For example, storage capacity, crop diversity and various water resources, in line with the principles buffering, omnivory and redundancy. Another mechanism, modularity, may be added to this list. Low modularity means that system components are connected, allowing shocks to travel rapidly through the system (Walker and Salt

2006). For example, modularity in electricity networks assures that power outage in one area does not spread to other areas, and splitting up floodplains by constructing compartmentalization dikes will reduce the flood extent. The principles may also provide inspiration for options to increase robustness to extreme events. The robustness analysis method is complementary in that it supports the evaluation of these options instead of just providing a long-list of options. It must be noted that some of the resilience principles relate to the capacity to adapt, which is outside the scope of a robustness analysis.

Robust decision making

In the introduction, system robustness was contrasted with decision robustness, where a robust decision reflects the choice for a strategy that performs well under a range of future scenarios. They differ in object, time scale, type of disturbance and type of uncertainty, and therefore can be used in different decision making contexts. A key difference is that system robustness values strategies that reduce the impact from extreme events, whereas robust decision making values strategies that can be adapted over time, to avoid overinvestment or underinvestment when the future develops differently than expected.

Both methods are complementary in the following way. Robust decision making requires a choice on relevant decision performance criteria, for example risk and cost. When the risk is reduced against acceptable costs in many of the considered futures, the choice for this strategy is considered a robust decision. However, this thesis has shown that even when the risk is acceptable, the potential impacts from low-probability events may not be acceptable. Depending on the criteria used, a robust decision does not automatically lead to a system that can cope with the consequences of extreme droughts. Haasnoot et al. (2013) have also noted that dealing with variability is difficult in an adaptive approach, because signposts and triggers are more difficult to define for variability than for gradual changes. Moreover, climate-related trends can often not be detected from highly variable data series (e.g., Diermanse et al. 2010). Both methods may be combined by using system robustness as one of the performance criteria in robust decision making.

7.4 Implications and recommendations for flood risk management

Flood risk management is a continuous process of analysis, assessment and action to keep flood risk at an acceptable level against acceptable societal costs. Flood risk management strategies are combinations of measures (both structural and non-structural) to improve flood risk management as part of the sustainable development of a region. Therefore, to assess flood risk management strategies, decision criteria should not only include investment costs and flood risk, but also sustainability criteria such as equity, biodiversity and economic side-effects, and criteria to deal with uncertainty such as robustness and flexibility (De Bruijn et al. 2008). The method developed in this thesis allows quantifying system robustness to use it as additional criterion in flood risk management decision making.

When robustness is valued in addition to acceptable flood risk, the preference for a flood risk management strategy may change. Many strategies are possible and the most feasible one depends on the current system and the socio-economic and cultural context. Some countries may prefer an embanked river valley such as in the Netherlands (high resistance threshold), whereas other countries prefer a natural, unembanked floodplain such as in the Mekong delta (see De Bruijn 2005). De Bruijn showed that it is often expensive to enhance resilience in a system with already a high resistance threshold, because there is often less space due to the 'levee effect' (Tobin 1995, White 1945). The 'levee effect' means that well-protected areas attract socio-economic development, which increases the area's vulnerability to flooding. This may require a higher protection level by raising the embankments, attracting even more socio-economic development, etc. Significantly reducing vulnerability in these systems requires large investments. This thesis has explored other possibilities to increase the resilience range, even if the resistance threshold is high. Promising measures to increase robustness in a highly resistant system include differentiating protection levels and strengthening existing embankments so they become nearly unbreachable. Although costs were not taken into account, it is believed that these measures are feasible in the context of the Netherlands.

Current flood risk management in the Netherlands is based on design standards for flood protection infrastructure. The flood-prone area is considered safe when this

protection can withstand water levels with a predefined return period. This is a risk-based approach in the sense that areas with potentially large impacts receive higher protection. An advanced risk-based approach, however, would also include measures to limit the potential flood impact. This is subject to ongoing debate in the Netherlands. In line with the European flood risk directive (European-Parliament 2007), the Netherlands National Government introduced the 'multiple-tiered flood risk management approach' (NationalGovernment 2009), which states that flood risk management should build on three tiers: 1) protection against flooding, 2) spatial planning to limit flood impact, and 3) emergency management to limit casualties. This approach acknowledges that flood risk can also be reduced by spatial planning measures. In theory, implementing spatial planning measures that reduce flood impact may avoid further raising and strengthening of embankments when flood risk otherwise increases due to climate change and socio-economic developments. In practice, however, raising embankments often seems more cost-effective than spatial planning measures, and therefore potential flood impact is still expected to increase in the future.

Although the multiple-tiered approach stimulates thinking about flood impact reduction, it may give the wrong impression that the first layer can only be used to avoid flooding, and that impacts can only be reduced by spatial planning (second layer). This thesis has shown that impacts can also be reduced by adapting the first layer; differentiating protection standards and unbreachable embankments are typical examples of measures that enhance protection against flooding and at the same time reduce the potential flood impacts. Furthermore, robust systems have shown to be better able to cope with extreme events, which may be an additional argument to choose measures that reduce the flood impact.

Recommendations for flood risk management

It is recommended to analyse a system's robustness to a large range of plausible floods as part of a flood risk analysis. This thesis showed that robustness analysis adds to a narrow risk approach in flood risk management. Assessing an area's flood risk solely on a single-value risk metric implies that as long as the probability is small enough, the

corresponding flood impact is acceptable. Additionally using the robustness criteria may aid to avoid societally unacceptable flood impacts.

It is recommended to define a wide range of flood magnitudes for which to provide system robustness. It is common practice to provide protection (resistance) against a limited range of flood magnitudes. Additionally, strategies to reduce the impact and/or increase the recovery threshold should be considered in order to deal with beyond-design flood magnitudes. The total range of flood magnitudes considered should be chosen large enough to include all plausible ones.

It is recommended to always consider measures aimed at flood impact reduction. From a robustness perspective, measures aimed at impact reduction are often desirable, even if the risk reduction is small. If measures reduce the impact for all extreme flood events, they automatically increase the robustness range.

It is recommended to manage flood risks for entire river valleys instead of individual dike ring areas. In this way, potential floods affecting the entire river valley are also taken into account and more vulnerable areas could be protected by allowing controlled flooding of less-vulnerable areas if this reduces the total impact in the entire river valley.

7.5 Implications and recommendations for drought risk management

Drought risk management, similar to flood risk management, is a systematic and continuous process to prevent, mitigate and prepare for the adverse impacts of droughts. It aims to keep drought risk at an acceptable level against acceptable societal costs, and requires an analysis of drought probabilities and corresponding societal impacts. However, drought risk management is still in its infancy. Although it is widely acknowledged that countries should move from drought crisis management to drought risk management (Wilhite 2011, Rossi and Cancelliere 2012, Xerochore 2010), drought management planning still mainly relies on a measure of water supply reliability: the probability of meeting the water demand (Iglesias et al. 2009, Rossi and Cancelliere 2012). Because robustness analysis requires knowing the societal consequences of

droughts, it supports a move to a risk-based approach. However, few methods exist to quickly quantify the societal impact of droughts as part of a decision analysis.

Drought risk management typically includes measures aimed at demand reduction and supply increase, and can be implemented in the long term or the short term (for a review see Dziegielewski 2003, Rossi and Cancelliere 2012). Long-term measures are implemented well before a drought event is expected and are aimed at high supply reliability by adapting supply and/or demand. Long-term supply can be increased by, for example, reservoirs, desalination plants and pipelines to long-distance resources. Long-term demand can be reduced by, for example, changing to drought-resistant crops or installing water recycling systems in urban areas. Short-term measures are also planned in advance, but implemented as soon as water shortage is expected. These include transporting water (supply increase), temporary water conservation and prioritization among users (demand reduction). Robust drought risk management requires a combination of all four types of measures, so that the long-term balance between supply and demand is acceptable and impacts during droughts are limited.

Resistance in drought risk systems is determined by the supply reliability. Resilience means that impacts from droughts are limited and can be recovered from. How resistance and resilience are best combined depends on the context and is a political choice. For example, the United States has built large reservoirs in the 50's and 60's, because it would benefit socio-economic development in many regions and there was sufficient space and finances to do so. Reservoirs provide high resistance to droughts when their storage capacity is large compared to the demand. The streamflow drought case showed that high resistance to droughts may go hand in hand with high proportionality. This may be explained by the fact that only one water user (municipal water use) was taken into account. Taking into account different competing water users may affect the proportionality.

Building a water supply reservoir attracts economic development, which increases water demand. Similar to floods, where the economic growth and population growth require higher protection standards, increasing water demand requires new water resources to maintain the supply reliability. This 'dam effect' is comparable to the levee effect in flood risk management (see above). If a local reservoir is not sufficient, other

solutions such as pipelines have to be found. Many urban areas with large concentration of economic activities transport water over large distances in order to meet demands (McDonald et al. 2014), for example San Francisco in California (United States). Only adapting the supply to meet increasing demands is not considered a robust solution, because when demand is increasing, the impact of a drought will also increase. It was demonstrated that when it is aimed to reduce impacts from extreme drought events, other measures such as demand reduction or short-term measures may be more effective than supply increase. Furthermore, increasing supply by accessing other resources may have negative side-effects. For example, groundwater resources can also be depleted and a second reservoir may be vulnerable to the same drought event and therefore not reliable as an alternative source of supply.

Planning and implementing short-term measures may be very effective to reduce drought impact during drought. Because droughts build up slowly in time and reservoir levels can be monitored quite well, action can be taken before droughts become very severe. However, the effectiveness of short-term measures also depends on how well drought development can be predicted and on water managers who have to take decisions on short-term measures. The analysis in the streamflow drought case assumed that plans for short-term measures can be designed beforehand and will be implemented as is. In practice, water managers will adapt their decisions to the situation and incorporate predictions about how the situation will develop in the short term. This is very difficult, because impact reduction measures have to be implemented before the drought becomes too severe (e.g., before the reservoir is empty). This means that people are impacted before storage is depleted. This is only a good strategy when the drought indeed develops further. Evaluating short-term measures thus may require models that include the behaviour of water managers during drought.

The agricultural drought system (the Netherlands) was also considered robust, despite the small resistance range, because the resilience range was high. Compared to the United States, there is less space to provide storage capacity. Also, relatively little storage is needed because over-year droughts are not part of the climate. The resilience range is large due to crop diversity and access to two different water resources (rainfall and external surface water). It was shown that the robustness

criteria can be meaningfully quantified and the analysis provided insight into the mechanisms behind robustness. Because the results were not compared with a more traditional decision criterion (either supply reliability or drought risk), it is unknown whether robustness criteria would affect the ranking of strategies. This requires more research.

Recommendations for drought risk management

It is recommended to complement drought risk analysis with robustness analysis. Solely relying on water supply reliability as decision criterion may lead to highly-resistant systems with potentially large drought impacts. Additionally using robustness criteria aids to avoid societally unacceptable drought impacts.

It is recommended to define a wide range of drought magnitudes for which to provide robustness. It is often aimed to increase supply reliability, which implies resistance against a range of drought magnitudes. Additionally, decision makers should explore the impact of low-probability droughts that exceed this resistance threshold. The total range of drought magnitudes should be chosen large enough to include plausible ones according to the worst-case climate change scenario.

It is recommended to put more emphasis on measures aimed at demand reduction. The streamflow drought case has shown that reducing demand scores better on robustness than increasing supply, even when both types of measures score equal on supply reliability. Although more applications are needed to extend this conclusion for drought risk systems in general, it is expected that measures aimed at demand reduction always increase the ability to deal with extreme drought events.

7.6 Recommendations for further research

The following is recommended for further research on robustness analysis as part of flood and drought risk management:

- Test the robustness analysis framework for systems with different flood types, for example coastal floods and pluvial floods in urban areas. This thesis investigated fluvial flooding only.

- Compare an analysis based on costs and risks with an analysis based on investment costs, risks and system robustness.
- Further develop methods to define and quantify a level of impact that is considered unmanageable.
- Apply the framework on a drought case with various competing water users. The drought cases in this thesis considered single user groups only. A robustness analysis becomes more interesting when various users of the same water resource are taken into account, because this allows taking into account prioritization, which may enhance a system's robustness to drought.
- Further develop methods to quantify societal impacts of droughts. Converting water shortage into societal costs is a prerequisite for drought risk analysis as well as for robustness analysis.
- Further develop methods to quantify the regional or national socio-economic impact of agricultural yield deficit due to drought.

Bibliography

- Adger, W. N. 2006. Vulnerability. *Global Environmental Change*, 16(3), 268-281.
- Anderies, J. M., Janssen, M. A. and Ostrom, E. 2004. A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecology and Society*, 9(1).
- Asselman, N., Ijmker, J., Kolen, B. and Maaskant, B., in prep. *Deltaprogramme Rivers: Flood risk analysis for the Meuse (In Dutch: Proeve Maas)*. Delft: Deltares.
- Bakker, A. and Bessembinder, J., 2012. *Time series transformation tool: description of the program to generate time series consistent with the KNMI '06 climate scenarios*. De Bilt, Utrecht, The Netherlands: KNMI.
- Barnett, J. 2001. Adapting to Climate Change in Pacific Island Countries: The Problem of Uncertainty. *World Development*, 29(6), 977-993.
- Barredo, J. 2007. Major flood disasters in Europe: 1950–2005. *Natural Hazards*, 42(1), 125-148.
- Beersma, J. and Buishand, A. 2004. Joint probability of precipitation and discharge deficits in the Netherlands. *Water resources research*, 40.
- Beersma, J. J. and Buishand, T. A. 2007. Drought in the Netherlands: Regional frequency analysis versus time series simulation. *Journal of Hydrology*, 347, 332-346.
- Begon, M., Harper, J. L. and Townsend, C. R., 1996. *Ecology: individuals, populations and communities*. Malden, MA, United States: Blackwell Science Ltd.
- Bockarjova, M., 2007. *Major disasters in modern economies: an input-output based approach at modelling imbalances and disproportions*. (PhD). Twente University.
- Bouwer, L. M. 2013. Projections of Future Extreme Weather Losses Under Changes in Climate and Exposure. *Risk Analysis*, 33(5), 915-930.
- Bouwer, L. M., Crompton, R. P., Faust, E., Höppe, P. and Jr., R. A. P. 2007. Confronting Disaster Losses. *Science Policy Forum*, 318.
- Brandsma, T. and Buishand, T. A. 1998. Simulation of extreme precipitation in the Rhine basin by nearest-neighbour resampling. *Journal of Hydrology and Earth System Sciences Discussions*, 2, 195-209.
- Brozović, N., Sunding, D. L. and Zilberman, D. 2007. Estimating business and residential water supply interruption losses from catastrophic events. *Water resources research*, 43(8), W08423.
- Bruggeman, W., Haasnoot, M., Hommes, S., Linde, A. t., Van der Brugge, R., Rijken, B., Dammers, E. and Van den Born, G. J., 2011. *Deltascenarios: Climate and socio-economic change scenarios for the Delta Program (In Dutch: Deltascenario's: Verkenning van mogelijke fysieke en sociaaleconomische ontwikkelingen in de 21ste eeuw op basis van KNMI'06 en WLO-scenario's, voor gebruik in het deltaprogramma 2011-2012)*. Deltares & PBL.
- Carlson, J. M. and Doyle, J. 2002. Complexity and robustness. *Proceedings of the national academy of sciences*, 99(suppl 1), 2538-2545.

- Carpenter, S., Walker, B., Anderies, J. M. and Abel, N. 2001. From metaphor to measurement: resilience of what to what. *Ecosystems*, 4(8), 765-781.
- CBS, 2013. *Statline: electronic database of Central Bureau of Statistics, the Netherlands* [online]. Available from: www.statline.cbs.nl [Accessed May 2013].
- CBS, PBL and UR, W., 2013. *Productiewaarde land- en tuinbouw, 1995-2012* [online]. CBS, the Hague, the Netherlands. Available from: <http://www.compendiumvoordeleefomgeving.nl/indicatoren/nl2125-Productiewaarde-landbouw.html?i=11-61> [Accessed July 2014].
- Clarke, L. 2005. Worst-Case Thinking: An Idea Whose Time Has Come. *Natural Hazards Observer*, 29(3), 1-3.
- Dalhuisen, J. M., Florax, R. J. G. M., De Groot, H. L. F. and Nijkamp, P. 2003. Price and Income Elasticities of Residential Water Demand: A Meta-Analysis. *Land Economics*, 79(2).
- De Bruijn, K. 2004. Resilience indicators for flood risk management systems of lowland rivers. *International Journal of River Basin Management*, 2(3), 199-210.
- De Bruijn, K. M., 2005. *Resilience and flood risk management. A systems approach applied to lowland rivers*. (PhD). Delft University of Technology.
- De Bruijn, K. M., Mens, M. J. P. and Klijn, F., A method for developing long-term strategies for flood risk management. ed. *Flood Risk Management Research into practice*, 30 september - 2 october 2008 Oxford.
- De Lange, W. J., Prinsen, G. F., Hoogewoud, J. C., Veldhuizen, A. A., Verkaik, J., Oude Essink, G. H. P., van Walsum, P. E. V., Delsman, J. R., Hunink, J. C., Massop, H. T. L. and Kroon, T. 2014. An operational, multi-scale, multi-model system for consensus-based, integrated water management and policy analysis: The Netherlands Hydrological Instrument. *Environmental Modelling & Software*, 59(0), 98-108.
- De Moel, H., Asselman, N. E. M. and Aerts, J. C. J. H. 2012. Uncertainty and sensitivity analysis of coastal flood damage estimates in the west of the Netherlands. *Nat. Hazards Earth Syst. Sci.*, 12(4), 1045-1058.
- Deltaprogramme, 2011. *Delta programma 2012 (in Dutch)*. Ministerie van Infrastructuur en Milieu, Ministerie van Economische zaken, Landbouw en Innovatie.
- DeltaProgramme, 2013. *Delta Programme 2013: The road towards the Delta Decisions* The Hague: Ministries of infrastructure & environment and economic affairs, agriculture & innovation.
- Dessai, S. and Van der Sluijs, J. P., 2007. *Uncertainty and Climate Change Adaptation: A Scoping Study*. Utrecht: Copernicus Institute.
- Diermanse, F., Kwadijk, J. C. J., Beckers, J. V. L. and Crebas, J. I., 2010. Statistical trend analysis of annual maximum discharges of the Rhine and Meuse rivers. *BHS third international symposium*. New Castle.
- Dixon, L. S., Moore, N. Y. and Pint, E. M., 1996. *Drought management policies and economic effects in urban areas of California, 1987-1992*. Santa Monica, California, United States: RAND.

- Downton, M. W., Morss, R. E., Wilhelmi, O. V., Grunfest, E. and Higgins, M. L. 2005. Interactions between scientific uncertainty and flood management decisions: Two case studies in Colorado. *Environmental Hazards*, 6(3), 134-146.
- Dracup, J. A., Lee, K. S. and Paulson, E. G. 1980. On the statistical characteristics of drought events. *Water resources research*, 16(2), 289-296.
- Dziegielewska, B., 2003. Long-Term and Short-Term Measures for Coping with Drought. In: Rossi, G., et al. eds. *Tools for Drought Mitigation in Mediterranean Regions*. Springer Netherlands, 319-339.
- EM-DAT, 2009. *Emergency Events Database* [online]. Available from: <http://www.emdat.be> [Accessed August 2014].
- Directive 2007/60/EC of the European Parliament and of the Council on the assessment and management of flood risks 2007.
- Folke, C. 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. *Global Environmental Change*, 16(3), 253-267.
- Giannikopoulou, A. S., Gada, F. K., Kampragou, E. and Assimacopoulou, D. submitted. Risk-based assessment of drought mitigation options: The Case of Syros Island, Greece. *Water Resources Management*.
- Gouldby, B. and Samuels, P., 2005. *Language of risk. FLOODsite project definitions*. FLOODsite project.
- Groves, D. G., Fischbach, J. R., Bloom, E., Knopman, D. and Keefe, R., 2013. *Adapting to a Changing Colorado River: Making Future Water Deliveries More Reliable Through Robust Management Strategies*. RAND Corporation.
- Haasnoot, M., Kwakkel, J. H., Walker, W. E. and ter Maat, J. 2013. Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change*, 23(2), 485-498.
- Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E. and Deursen, W. A. v. 2012. Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change*, 115(3-4), 795-819.
- Haasnoot, M., van Deursen, W. P. A., Guillaume, J. H. A., Kwakkel, J. H., van Beek, E. and Middelkoop, H. 2014. Fit for purpose? Building and evaluating a fast, integrated model for exploring water policy pathways. *Environmental Modelling & Software*, 60(0), 99-120.
- Hall, J. and Borgomeo, E. 2013. Risk-based principles for defining and managing water security. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 371(2002).
- Hall, J. and Solomatine, D. 2008. A framework for uncertainty analysis in flood risk management decisions. *International Journal of River Basin Management*, 6(2), 85-98.
- Hashimoto, T., Loucks, D. P. and Stedinger, J. R. 1982a. Robustness of water resources systems. *Water resources research*, 18(1), 21-26.
- Hashimoto, T., Stedinger, J. R. and Loucks, D. P. 1982b. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.*, 18(1), 14-20.

- Hisdal, H. and Tallaksen, L. M., 2000. *Drought event definition, ARIDE Technical Report No. 6*. Oslo, Norway: University of Oslo.
- Holling, C. S. 1973. Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, 4(1), 1-23.
- Holling, C. S., 1978. Myths of ecological stability: resilience and the problem of failure. In: Smart, C. F. and Stanbury, W. T. eds. *Studies in crisis management*. Montreal, Canada: Butterworth, 97-109.
- Holling, C. S., 1996. Engineering resilience versus ecological resilience. In: Schulze, P. ed. *Engineering within ecological constraints*. Washington: National Academy, 31-43.
- Hooijer, A., Klijn, F., Pedroli, G. B. M. and Van Os, A. G. 2004. Towards sustainable flood risk management in the Rhine and Meuse river basins: synopsis of the findings of IRMA-SPONGE. *River Research and Applications*, 20(3), 343-357.
- Howitt, R., Medellín-Azuara, J., MacEwan, D., Lund, J. and Sumner, D., 2014. *Economic Analysis of the 2014 Drought for California Agriculture*. California, United States: Center for Watershed Sciences, University of California, Davis, California.
- Iglesias, A., Garrote, L. and Martín-Carrasco, F. 2009. Drought risk management in mediterranean river basins. *Integrated Environmental Assessment and Management*, 5(1), 11-16.
- IPCC, 2012. *Managing the risk of extreme events and disasters to advance climate change adaptation: A special report of the Intergovernmental Panel on Climate Change*. Cambridge, UK.
- Jen, E. 2003. Stable or robust? What's the difference? *Complexity*, 8(3), 12-18.
- Jeuken, A., Beek, E. v., Duinen, R. v., Veen, A. v. d., Bocalon, A., Delsman, J., Pauw, P., Essink, G. O., Zee, S. v. d., Stofberg, S., Zuurbier, K., Stuyfzand, P., Appelman, W., Creusen, R., Paalman, M., Katschnig, D., Rozema, J., Mens, M., Kwakkel, J., Thissen, W., Veraart, J., Tolck, L. and Vries, A. d., 2012. *Balancing supply and demand of fresh water under increasing drought and salinisation in the Netherlands: Midterm report Knowledge for Climate Theme 2*. Utrecht, the Netherlands: Knowledge for Climate Programme.
- Jongman, B., Ward, P. J. and Aerts, J. C. J. H. 2012. Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change*, 22, 823-835.
- Jonkman, S. N., van Gelder, P. H. A. J. M. and Vrijling, J. K. 2003. An overview of quantitative risk measures for loss of life and economic damage. *Journal of Hazardous Materials*, 99(1), 1-30.
- Kaplan, S. and Garrick, B. J. 1981. On the quantitative definition of risk. *Risk Analysis*, 1(1), 11-27.
- Kind, J. M. 2014. Economically efficient flood protection standards for the Netherlands. *Journal of Flood Risk Management*, 7(2), 103-117.
- Kjeldsen, T. R. and Rosbjerg, D. 2004. Choice of reliability, resilience and vulnerability estimators for risk assessments of water resources systems / Choix d'estimateurs de fiabilité, de résilience et de vulnérabilité pour les analyses de risque de systèmes de ressources en eau. *Hydrological Sciences Journal*, 49(5), null-767.

- Klijin, F., Asselman, N. and Van der Most, H. 2009. Compartmentalisation: flood consequence reduction by splitting up large polder areas. *Journal of Flood Risk Management*, 3(1), 3-17.
- Klijin, F., Baan, P., De Bruijn, K. M. and Kwadijk, J., 2007. *The Netherlands' flood risks in a changing climate: Expected, estimated and calculated (in Dutch)*. Delft: WL Delft Hydraulics.
- Klijin, F., Knoop, J. M., Ligtoet, W. and Mens, M. J. P. 2012a. In search of robust flood risk management alternatives for the Netherlands. *Nat. Hazards Earth Syst. Sci.*, 12(5), 1469-1479.
- Klijin, F., Samuels, P. and Van Os, A. 2008. Towards Flood Risk Management in the EU: State of affairs with examples from various European countries. *Intl. J. River Basin Management*, 6(4), 307-321.
- Klijin, F., Velzen, E. v., Maat, J. t. and Hunink, J., 2012b. *Fresh water supply in the Netherlands: challenges for the 21st century (In Dutch: Zoetwatervoorziening in Nederland: Aangescherpte landelijke knelpuntenanalyse 21e eeuw)*. Delft: Deltares.
- Klinke, A. and Renn, O. 2011. Adaptive and integrative governance on risk and uncertainty. *Journal of Risk Research*, 15(3), 273-292.
- Knabb, R. D., Rhome, J. R. and Brown, D. P., 2006. *Tropical Cyclone Report Hurricane Katrina 23-30 August 2005*. Florida, US: National Hurricane Center.
- Kwadijk, J. C. J., Haasnoot, M., Mulder, J. P. M., Hoogvliet, M. M. C., Jeuken, A. B. M., van der Krogt, R. A. A., van Oostrom, N. G. C., Schelfhout, H. A., van Velzen, E. H., van Waveren, H. and de Wit, M. J. M. 2010. Using adaptation tipping points to prepare for climate change and sea level rise: a case study in the Netherlands. *Wiley interdisciplinary reviews: climate change*, 1(5), 729-740.
- Lempert, R., Kalra, N., Peyraud, S., Mao, Z., Tan, S. B., Cira, D. and Lotsch, A., 2013. *Ensuring Robust Flood Risk Management in Ho Chi Minh City*. Washington DC, United States: The World Bank.
- Lempert, R., Popper, S. W. and Bankes, S. C., 2003. *Shaping the Next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. Santa Monica: RAND.
- Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kroger, W., Lambert, J. H., Levermann, A., Montreuil, B., Nathwani, J., Nyer, R., Renn, O., Scharte, B., Scheffler, A., Schreurs, M. and Thiel-Clemen, T. 2014. Changing the resilience paradigm. *Nature Clim. Change*, 4(6), 407-409.
- Logar, I. and Bergh, J. J. M. 2013. Methods to Assess Costs of Drought Damages and Policies for Drought Mitigation and Adaptation: Review and Recommendations. *Water Resources Management*, 27(6), 1707-1720.
- Loucks, D. P. and Van Beek, E., 2005. *Water resources systems planning and management: An introduction to methods, models and applications*. Paris: United Nations Educational.
- Marchand, M., 2009. *Modelling Coastal Vulnerability. Design and evaluation of a vulnerability model for tropical storms and floods*. (PhD). Delft University of Technology.

- McDonald, R. I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P. A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G. and Montgomery, M. 2014. Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change*, 27(0), 96-105.
- McKee, T. B., doesken, N. J. and Kleist, J., The relationship of drought frequency and duration to time scales. ed. *Eight conference on applied climatology*, 1993 Anaheim, California.
- Mens, M., Van der Sluijs, J. P., Ter Maat, J. and Jeuken, A. submitted. Analysing the robustness of an agricultural drought risk system: a case in a coastal polder area in the Netherlands. *Water Resources Management*.
- Mens, M. J. P., Gilroy, K. and Williams, D. accepted. Developing system robustness analysis for drought risk management: an application to a water supply reservoir. *Natural Hazards and Earth System Sciences Discussions*.
- Mens, M. J. P. and Klijn, F. 2014. The added value of system robustness analysis for flood risk management. *Nat. Hazards Earth Syst. Sci. Discuss.*, 2, 2913-2945.
- Mens, M. J. P., Klijn, F., De Bruijn, K. M. and Van Beek, E. 2011. The meaning of system robustness for flood risk management. *Environmental Science & Policy*, 14(8), 1121-1131.
- Mens, M. J. P., Klijn, F. and Schielen, R. M. J. 2014. Enhancing flood risk system robustness in practice: insights from two river valleys. *International Journal of River Basin Management*, 1-8.
- Merz, B., Elmer, F. and Thielen, A. H. 2009. Significance of "high probability/low damage" versus "low probability/high damage" flood events. *Nat. Hazards Earth Syst. Sci.*, 9(3), 1033-1046.
- Merz, B., Hall, J., Disse, M. and Schumann, A. 2010. Fluvial flood risk management in a changing world. *Nat. Hazards Earth Syst. Sci.*, 10(3), 509-527.
- Meyer, V., Haase, D. and Scheuer, S. 2009. Flood risk assessment in european river basins—concept, methods, and challenges exemplified at the mulde river. *Integrated Environmental Assessment and Management*, 5(1), 17-26.
- Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P. and Stouffer, R. J. 2008. Stationarity Is Dead: Whither Water Management? *Science*, 319(5863), 573-574.
- Moy, W.-S., Cohon, J. L. and ReVelle, C. S. 1986. A Programming Model for Analysis of the Reliability, Resilience, and Vulnerability of a Water Supply Reservoir. *Water resources research*, 22(4), 489-498.
- Mulder, H. M. and Veldhuizen, A. A., 2014. *AGRICOM 2.01 Manual (in Dutch)*. Wageningen, the Netherlands: Alterra.
- NationalGovernment, 2009. *National Waterplan: A safe and liveable delta, today and in the future* Thieme, Deventer.
- NCHRP, 1995. *Characteristics and Changes in Freight Transportation Demand: A Guidebook for Planners and Policy Analysts*. National Cooperative Highway Research Program.
- NDMC, 2014. *Drought Impact Reporter* [online]. National Drought Mitigation Center. Available from: <http://droughtreporter.unl.edu/> [Accessed January 2014].

- NOAA, 2013. *NOAA: Billion-Dollar Weather/Climate Disasters* [online]. National Climatic Data Center Asheville. Available from: <http://www.ncdc.noaa.gov/billions/events> [Accessed August 2013].
- OECD, 2013. *Water Security for Better Lives*. OECD Publishing.
- Olsen, J. R., Kiang, J. and Waskom, R., 2010. *Proceedings of the workshop on nonstationarity, hydrologic frequency analysis, and water management*. Colorado, United States: Colorado State University.
- Park, J., Seager, T. P., Rao, P. S. C., Convertino, M. and Linkov, I. 2013. Integrating Risk and Resilience Approaches to Catastrophe Management in Engineering Systems. *Risk Analysis*, 33(3), 356-367.
- Pelt, S. and Swart, R. 2011. Climate Change Risk Management in Transnational River Basins: The Rhine. *Water Resources Management*, 25(14), 3837-3861.
- Preziosi, E., Del Bon, A., Romano, E., Petrangeli, A. B. and Casadei, S. 2013. Vulnerability to Drought of a Complex Water Supply System. The Upper Tiber Basin Case Study (Central Italy). *Water Resources Management*, 27(13), 4655-4678.
- Qiao, L., Hong, Y., McPherson, R., Shafer, M., Gade, D., Williams, D., Chen, S. and Lilly, D. 2014. Climate change and hydrological response in the trans-state Oologah Lake watershed: Evaluating dynamically downscaled NARCCAP and statistically downscaled CMIP3 simulations with VIC model. *Water Resources Management*, 28(10), 3291-3305.
- ResilienceAlliance, 2011. *The Resilience Alliance* [online]. Available from: www.resalliance.org [Accessed November 2011].
- Rijkswaterstaat, 2007. *Manual for assessing primary flood defences 2006*. the Hague, the Netherlands: Ministry of Transport, Public Works and Water Management.
- Rijnland, 2009. *Water management plan Rijnland 2010 - 2015 (In Dutch: Waterbeheerplan 2010-2015)*. Leiden, the Netherlands: Waterboard of Rijnland.
- Rosenhead, J., Elton, M. and Gupta, S. K. 1972. Robustness and optimality as criteria for strategic decisions. *Operational Research Quarterly*, 23(4), 413-431.
- Rossi, G. and Cancelliere, A. 2012. Managing drought risk in water supply systems in Europe: a review. *International Journal of Water Resources Development*, 29(2), 272-289.
- Salas, J. and Obeysekera, J. 2014. Revisiting the Concepts of Return Period and Risk for Nonstationary Hydrologic Extreme Events. *Journal of Hydrologic Engineering*, 19(3), 554-568.
- Scheffer, M. and Carpenter, S. 2003. Catastrophic regime shifts in ecosystems: linking theory to observation. *Trends in ecology and evolution*, 18(12).
- Scheffer, M., Carpenter, S., Foley, J. A., Folke, C. and Walker, B. 2001. Catastrophic shifts in ecosystems. *Nature*, 413(6856), 591-596.
- Sivakumar, M. V. K., Stefanski, R., Bazza, M., Zelaya, S., Wilhite, D. and Magalhaes, A. R. 2014. High Level Meeting on National Drought Policy: Summary and Major Outcomes. *Weather and Climate Extremes*, 3(0), 126-132.
- Slovic, P., Fischhoff, B., Lichtenstein, S., Corrigan, B. and Combs, B. 1977. Preference for Insuring against Probable Small Losses: Insurance Implications. *The Journal of Risk and Insurance*, 44(2), 237-258.

- Snelder, M., van Zuylen, H. J. and Immers, L. H. 2012. A framework for robustness analysis of road networks for short term variations in supply. *Transportation Research Part A: Policy and Practice*, 46(5), 828-842.
- Stakhiv, E. and Stewart, B. 2010. Needs for Climate Information in Support of Decision-Making in the Water Sector. *Procedia Environmental Sciences*, 1(0), 102-119.
- Steinschneider, S. and Brown, C. 2013. A semiparametric multivariate, multisite weather generator with low-frequency variability for use in climate risk assessments. *Water resources research*, 49(11), 7205-7220.
- Stelling, J., Sauer, U., Szallasi, Z., Doyle, F. J., III and Doyle, J. 2004. Robustness of Cellular Functions. *Cell*, 118(6), 675-685.
- Stirling, A. 1998. Risk at a turning point? *Journal of Risk Research*, 1(2), 97-109.
- Tobin, G. A. 1995. THE LEVEE LOVE AFFAIR: A STORMY RELATIONSHIP?1. *JAWRA Journal of the American Water Resources Association*, 31(3), 359-367.
- Tulsa, 2013. *Water rates* [online]. City of Tulsa. Available from: <https://www.cityoftulsa.org/city-services/utilities/rates.aspx> [Accessed August 2013].
- UNISDR, 2009. *Drought Risk Reduction Framework and Practices: Contributing to the Implementation of the Hyogo Framework for Action*. Geneva, Switzerland: United Nations secretariat of the International Strategy for Disaster Reduction (UNISDR).
- USBR, 2012. *USBR: West-Wide Climate Risk Assessments: Projected Streamflow* [online]. United States Bureau of Reclamation. Available from: <http://www.usbr.gov/WaterSMART/wcra/flowdata/index.html> [Accessed August 2013].
- Van Bakel, P. J. T. and Stuyt, L. C. P. M., 2011. *State of knowledge on salt tolerance of agricultural crops (In Dutch: Actualisering van de kennis van de zouttolerantie van landbouwgewassen, op basis van literatuuronderzoek, expertkennis en praktische ervaringen)*. Wageningen, the Netherlands: Alterra.
- Van den Hurk, B., Klein Tank, A., Lenderink, G., Ulden, A. v., Oldenborgh, G. J. v., Katsman, C., Brink, H. v. d., Keller, F., Bessembinder, J., Burgers, G., Komen, G., Hazeleger, W. and Drijfhout, S., 2006. *KNMI Climate Change Scenarios 2006 for the Netherlands*. De Bilt, Utrecht, the Netherlands: KNMI.
- Van der Meer, J., Ter Horst, W. L. A. and Van Velzen, E. H., Calculation of fragility curves for flood defence assets. ed. *FLOODrisk2008: Flood Risk Management: Research and Practice 2008* Oxford, UK.
- Van der Zee, S., Stofberg, S. and Leijnse, A. submitted. Modelling the impact of climate change on fresh water availability and root zone salinity: A management support perspective. *Water Resources Management*.
- Van Mierlo, M. C. L. M., Vrouwenvelder, A. C. W. M., Calle, E. O. F., Vrijling, J. K., Jonkman, S. N., De Bruijn, K. M. and Weerts, A. H. 2007. Assessment of flood risk accounting for river system behaviour. *International Journal of River Basin Management*, 5(2), 93-104.

- Van Velzen, E. H., Scholten, M. J. M. and Beyer, D., 2007. *Hydraulic boundary conditions for the Rhine (in Dutch: Achtergrondrapport HR2006 voor de Rijn)*. the Netherlands: Rijkswaterstaat.
- Vogel, R. M. and Stedinger, J. R. 1987. Generalized storage-reliability-yield relationships. *Journal of Hydrology*, 89(3–4), 303-327.
- Vrouwenvelder, A. C. W. M. and Steenbergen, H. M. G. M., 2003. *PC-Ring manual: probabilistic techniques (in Dutch: Theoriehandleiding PC-Ring, versie 4.0, deel C: rekentechnieken)*. the Netherlands: TNO.
- Walker, B. and Meyers, J. A. 2004. Thresholds in ecological and social–ecological systems: a developing database. *Ecology and Society*, 9(2).
- Walker, B. and Salt, D., 2006. *Resilience Thinking: Sustaining Ecosystems and People in a Changing World*. Washington: Island Press.
- Wardekker, J. A., de Jong, A., Knoop, J. M. and van der Sluijs, J. P. 2010. Operationalising a resilience approach to adapting an urban delta to uncertain climate changes. *Technological Forecasting and Social Change*, 77(6), 987-998.
- Watt, K. E. F. and Craig, P. P. 1986. System stability principles. *Systems Research*, 3(4), 191-201.
- Watts, G., Christerson, B. v., Hannaford, J. and Lonsdale, K. 2012. Testing the resilience of water supply systems to long droughts. *Journal of Hydrology*, 414–415(0), 255-267.
- White, G., 1945. *Human Adjustments to Floods*. (PhD). The University of Chicago.
- Wilhite, D. A. 2011. Breaking the Hydro-Illlogical Cycle: Progress or Status Quo for Drought Management in the United States. *European Water*, 34, 5-18.
- Wilhite, D. A. and Glantz, M. H. 1985. Understanding the Drought Phenomenon: The Role of Definitions. *Water International*, 10(3), 111-120.
- Wilhite, D. A., Hayes, M. J., Knutson, C. and Smith, K. H. 2000. Planning for drought: moving from crisis to risk management. *JAWRA Journal of the American Water Resources Association*, 36(4), 697-710.
- Wilhite, D. A., Sivakumar, M. V. K. and Pulwarty, R. 2014. Managing drought risk in a changing climate: The role of national drought policy. *Weather and Climate Extremes*, 3(1), 4-13.
- Williams, D., 2013. *Water Supply Yield Modeling at Oologah Lake (Oklahoma) with Downscaled Climate Projections (draft March 2013)*. Tulsa, Oklahoma, United States: Institute for Water Resources, US Army Corps of Engineers.
- WL|Delft Hydraulics, 2001. *Manual Delft-FLS 2.55*. Delft, the Netherlands: Deltares.
- WMO, 2013. *The global climate 2001 – 2010: A decade of climate extremes (summary report)*. Geneva, Switzerland: World Meteorological Organization.
- Xerochore, 2010. [online]. Available from: <http://www.feem-project.net/xerochore/index.php> [Accessed January 2014].
- Yevjevich, V., 1967. *An objective approach to definitions and investigations of continental hydrological droughts*. Fort Collins, CO, United States: Colorado State University.
- Zevenbergen, C., Veerbeek, W., Gersonius, B. and Van Herk, S. 2008. Challenges in urban flood management: travelling across spatial and temporal scales. *Journal of Flood Risk Management*, 1(2), 81-88.

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About the author

Marjolein Mens (1982) received her Master's degree in Hydrology and Qualitative Water Management at Wageningen University in January 2006. After her graduation, she started working for WL | Delft Hydraulics (now Deltares) in the Netherlands, at the Department of Flood Management and Hydrology. Among other things she contributed to a new method for developing long-term strategies for flood risk management, as part of the European project FLOODsite.

Since January 2008, she has been working as a researcher and advisor at the department of flood and drought risk analysis (Deltares). Here she was involved in several studies related to analysing flood risk as part of policy advice for the Netherlands' government and abroad. She has experience with flood inundation modelling, flood damage assessments, probabilistic risk assessments, and decision support tools.

In 2010, she also started working on her PhD research on *operationalizing the concept of robustness for dealing with extreme events in flood and drought risk management*, funded by the National Research Program 'Knowledge for Climate'. As a PhD candidate she was affiliated with Twente University. As part of her PhD, she spent two months as a visiting scholar at the Institute for Water Resources of the United States Army Corps of Engineers (Washington DC, United States), where she was involved in the Alliance for Global Water Adaptation.

Marjolein continues to work for Deltares as a researcher and advisor on flood and drought risk analysis and management. She will continue research on system robustness analysis in support of decision making for flood and drought risk management in the Netherlands and abroad.

Peer-reviewed journal publications

Mens M.J.P., Klijn F. & Schielen R.M.J. (2014). Enhancing flood risk system robustness in practice: insights from two river valleys. *International Journal of River Basin Management*, 1-8.

Mens M.J.P. & Klijn F. (2014). The added value of system robustness analysis for flood risk management. *Natural Hazards and Earth System Sciences Discussions*, 2, 2913-2945.

Klijn F., Knoop J.M., Ligtoet W. & Mens M.J.P. (2012). In search of robust flood risk management alternatives for the Netherlands. *Natural Hazards and Earth System Sciences*, 12(5), 1469-1479.

Mens M.J.P., Klijn F., De Bruijn K.M. & Van Beek E. (2011). The meaning of system robustness for flood risk management. *Environmental Science and Policy*, 14(8), 1121-1131.

Papers under review

Mens M.J.P., Gilroy K. & Williams D. (submitted). Developing system robustness analysis for drought risk management: An application on a water supply reservoir. *Natural Hazards and Earth System Sciences Discussions*.

Mens M.J.P., Van der Sluijs J.P., Ter Maat J. & Jeuken A. (submitted). Analysing the robustness of an agricultural drought risk system: A case in a coastal polder area in the Netherlands. *Water Resources Management*.

Thissen W., Kwakkel J., Mens M.J.P., Van der Sluijs J.P., Stemberger S., Wardekker A. & Wildschut D. (submitted). Dealing with uncertainties in fresh-water supply: Experiences in the Netherlands. *Water Resources Management*.

Conference proceedings

Klijn F., Mens M.J.P. & Asselman N. (2014). Robustness analysis for flood risk management planning: on risk-based decision making beyond simple economic reasoning, exemplified for the Meuse River (Netherlands). *6th International Conference on Flood Management (ICFM6)*, 2014, Sao Paulo, Brazil.

Dahm R., Dirks F., Visch J.V.D., Diermanse F., Mens M., Phi H.L. (2014). Robust Cost-Benefit Analysis to Assess Urban Flood Risk Management: A Case Study on Ho Chi Minh City. *13th International Conference on Urban Drainage*, 2014, Sarawak, Malaysia.

Mens M.J.P., Klijn F. & Schielen R. (2013). Enhancing flood risk system robustness in practice, In: Klijn F & Schweckendiek T (Eds.), *Comprehensive Flood Risk Management*, 2013, Taylor & Francis Group, London, United Kingdom.

Lumbroso D., Mens M.J.P. & Van der Vat M. (2009). A framework for Decision Support Systems for flood event management – application to the Thames and the Schelde Estuaries, In: Samuels P, Huntington S, Allsop W & Harrop J (Eds.), *Flood Risk Management: Research and practice*, 2009, Taylor & Francis Group, London, United Kingdom.

Mens M.J.P., Van der Vat M. & Lumbroso D. (2009). A comparison of evacuation models for flood event management Application on the Schelde and Thames estuaries, In: Samuels P, Huntington S, Allsop W & Harrop J (Eds.), *Flood Risk Management: Research and practice*, 2009, Taylor & Francis Group, London, United Kingdom.

De Bruijn K.M., Mens M.J.P. & Klijn F. (2009). A method for developing long-term strategies for flood risk management, In: Samuels P, Huntington S, Allsop W & Harrop J (Eds.), *Flood Risk Management: Research and practice*, 2009, Taylor & Francis Group, London, United Kingdom.

Marchand M., De Bruijn K.M., Mens M.J.P., Slinger J., Cuppen M., Krywkow J. & Van der Veen A. (2009). Flood risk management: experiences from the Schelde Estuary case study, In: Samuels P., Huntington S., Allsop W. & Harrop J. (Eds.), *Flood Risk Management: Research and practice*, 2009, Taylor & Francis Group, London, United Kingdom.

Publications in Dutch magazines

Mens M.J.P., Van Loon-Steensma J.M. & Eikelboom T. (2013). Deltadijken dragen bij aan 'robuust' systeem. *Vakblad H₂O*, nr.4/2013.

Online: <http://vakbladh2o.nl/images/magazine-archieff/april13.pdf>

Mens M.J.P. (2011). Naar robuuste systemen. *Nederlandse Vereniging voor Risicoanalyse en Bedrijfszekerheid (NVRB)*.

Online: <http://www.nvr.nl/archief/wetenschapswaardigheden/item/128-naar-robuuste-systemen.html>

Mens M., Dahm R., Ebskamp M. & Elffrink A. (2010). Verkennend modelleren: inzicht in het effect van onzekerheden. *Vakblad H₂O*. nr.11/2010: 46-49.

Online publication

Mens M.J.P. & Haasnoot M. (2012). Deltafact robuustheid. *STOWA Deltaproof*. Online: http://deltaproof.stowa.nl/Publicaties/deltafact/Robuustheid_veiligheid.aspx?pld=2

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