Master thesis

The optimal capacity for temporal control measures for dikes in the IJssel-Vecht delta

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Abstract

In the IJssel-Vecht delta, and other parts of The Netherlands, there is gap between the current safety and the required safety against floods. This is caused by the fact that dikes are not reinforced instantly, but that the dike reinforcements are spread out over a timespan of several decades, up to 2050. The water board Drents Overijsselse Delta needs to take temporal control measures in order to fill this gap and protect their citizens. As the resources and expenses for the measures are not endless, it is necessary to provide more insight in the consequences and the logistics aspects that arise when measures are deployed.

The goal of this research is to determine the optimal capacity for temporal control measures for dikes in case of extreme water levels by quantifying the coincidence probabilities of extreme water levels and performing a cost-benefit analyses. The term capacity is used to denote the required amount of material, equipment, and manpower. And the coincidence probability is the probability of simultaneous occurrence of extreme water levels in multiple water systems.

The complexity of the problem increases due to the convergence of the IJssel, Vecht and Zwarte Meer in the IJssel-Vecht delta. These three systems are controlled by five main structures; whose functions basically are to separate the water systems from each other. Further the IJssel-Vecht delta of WDO Delta is divided by the water systems into dike rings 9 Vollenhove, 10 Mastenbroek, 11 IJsseldelta and 53 Salland, whereby dike ring 53 carries the greatest economic risk.

The physical threats in the water system are caused by high discharges from the IJssel and Vecht, and by storm surges from the lake area. The results from the third test round for water safety showed that major parts of the dikes in the IJssel-Vecht delta do not meet their norms. While it is possible and required to define a clear protocol for the primary defences structures that do not meet their norm, there is no such protocol available. Another concern is the overlap between temporal control measures, for dikes that do not meet their norms, and the measures that are deployed in emergency situations. These measure are of the same type and have similar capacity requirements. For a successful performance of the deployment of the temporal measures and to justify the deployment, it is necessary to implement the protocols rightfully in the organisation.

To provide more insight in the threats a copula-based assessment is applied on the water systems of the IJssel-Vecht delta to derive the coincidence probabilities. Copulas are a flexible tool for modelling the dependence structure of two or more random variables. They allow to build joint distributions from two or more variables while maintaining the statistical properties of their marginal distributions. The historical data that is used are the water levels at Deventer (IJssel) and Vechterweerd beneden (Vecht), and the national wind data at De Bilt, representing the storm surge at Zwarte Meer. There is a significant correlation between the annual maximum water levels of the IJssel and the Vecht. However, the other variables do not show any correlation. Therefore, the focus is on the bivariate combination of the IJssel and Vecht. These results show that the coincidence probability of high water level events is highest in the month January and February. And the probability that in a single year the highest water levels in the IJssel and Vecht occur in the same period of 5 days is at least a factor 14 to 19 higher than when independence is assumed. The exact value of the factor depends on the return periods of the water levels. The conditional probabilities show that, in general, the probability of simultaneous deployment of temporal control measures for both IJssel and Vecht is relatively low. For example, when it is assumed that temporal measures are deployed for the IJssel with a return period of 1000 years and for the Vecht with a return period of 100 years, the probability is that in one out of twelve times it is necessary to deploy measures in both systems at the same time.

A cost-benefit analysis based on a risk approach is performed to provide more insight in the consequences of flooding and possibilities of decreasing the consequences by the deployment of temporal control measures. The risk-based approach means that, rather than seeking to protect against a single design threshold, it should be accepted that it is not possible to eliminate the risk entirely. Risk has two components: probability times consequence. Deployment of measures will decrease the (failure) probability but measures also brings costs. These investment cost consists of yearly costs and deployment costs. The yearly costs are costs for storage and agreements with contractors. The deployment costs are the costs when the measures are actually deployed, which is once every few years. The sum of the risk and the investment costs are the total costs. For the total costs there is an optimum point at which the summation of the damage and the investment is minimal. If more measures are taken, the investments are higher than the reduction in damage. And if less measures are taken, the expected damage becomes greater than the reduction in investment costs.

The above described theory is implemented in an econometric model in which the total costs for a specified set of temporal measures can be derived. The model is divided into five activities; input, output, processes, controls and mechanisms. The input is the failure probabilities and consequences for the dike stretches and the output is the total costs. The controls are the set of measures from which can be chosen and the mechanism is the selection of measures.

The optimal capacity for the water systems in the IJssel-Vecht delta are derived by calculating the total costs for several set of measures with the model for each system. The result is multiple sets of measures which each have their own risk and investment costs, these form a single dot in the cost-benefit plot. These dots were used to create the cost-benefits relations for each system. For the IJssel the total costs and the required capacity to reach this optimum show that investing in temporal measures to increase the flood safety is worth doing until it is practically not possible to take any more temporal measures. The reason is that the costs of consequences are much higher than the investments. For the Vecht the optimum is reached much sooner and the optimal capacity requirements for the Vecht are more realistic than those for the IJssel. For Zwarte Meer the optimum is reached very soon after the reference situation. Only a few measures are required to reach the optimum, because the failure probability is already high and the economic damage in the area is relatively low.

This research distinguishes itself from other studies by being helpful for the operational issues instead of the norms for dike reinforcements. The copula-based assessment provides insight into the coincidence probabilities of extreme water levels in multiple systems, and the cost-benefit model provides the possibility to quantify the duty of care (‘zorgplicht’) of the water boards for a single system. Especially the latter can prove to be helpful for the water boards in specifying the grey area between meeting the norms and doing whatever is possible to increase the safety for their inhabitants.

Preface

With this thesis I complete my Master’s program Civil Engineering and Management at the University of Twente. Which is a memorable moment, and a moment we all know that was inevitable. Just as the past five years at the University of Twente, the process during this thesis research seemed to go flawless, but in both cases it took a little bit of effort of course.

The thesis provided me with more insight in the water safety issues at a technical and policy level, and I would like to thank the water board Drents Overijsselse Delta for this opportunity. With special thanks to Margreet Krol who guided me through the whole process during a somewhat tumultuous time. I was very happy with the facilities and the possibilities at their organisation.

Further, I would like to thank Jord Warmink and Denie Augustijn for their supervision on behalf of the University of Twente. In the few feedback sessions we had they always knew to ask the right questions and point out the shortcomings in my research.

Lastly, I want to thank my friends and family for their support and the great times we had and will have. They guided me during the study and always presented me a healthy amount of distractions. Thank you all.

Sido Grin

Enschede, September 2016

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1| Introduction

Dike reinforcements are planned up to the year 2050 to meet the new water safety norms and protect The Netherlands in the most optimal way against floods, but what should be done in the meantime? The easy way out is to accept that the dikes are not yet strong enough, and thereby accept the increased risk on the economy and population for the coming decades. However, it would be much wiser to prepare for extreme water levels during the transitional period. This research presents a method which helps in optimizing (the capacity required for) these preparations.

1.1 Background

In response to the redefinition of the safety norms in The Netherlands and the transitional period up to the dike reinforcements, the water board Drents Overijsselse Delta further investigates the water safety conditions in their area. Hereby of particular interest are the temporal control measures that can be taken in anticipation of extreme water levels. The temporal control measures are measures that are taken at dikes that currently do not meet the safety norm. A few examples of such measures are the placement of sand bags or big bags to prevent the overflow of water, or depositing sand on the inner embankment to increase the mass and prevent the formation of piping channels. The water board sees it as its duty to take these measures when there is a threat of flooding. This means that enough material, equipment, and manpower should be available to take these measures when a warning for extreme water levels is given.

A complexity in the required preparations is caused by convergence of the IJssel, Vecht, and Zwarte Meer in the area of the water board. According to a recent bachelor thesis study by Bink (2013) it is plausible that this convergence of water systems will force the prioritization and suboptimal use of materials. However, this conclusion is highly uncertain because it is not precisely known how the systems interact with each other during extreme conditions. Therefore, it is necessary to assess the probability of simultaneous occurrence of extreme water levels in the three systems.

In most models the coincidence probability, or interaction between systems, is taken into account with the use of (linear) relations between two systems, as is done by Geerse (2011) for the Hydra-Zoet model. For the calculation of extreme water levels in the Vecht dominated locations they coupled every Vecht discharge to a IJssel discharge that could occur for this Vecht discharge. By doing this the influence of the IJssel on the Vecht is taken into account. These type of models match with the focus of the water safety approach on design and reinforcements of dikes (Zhong et al., 2013; Kind, 2011; Geerse, 2011). This study, however, focuses on the planning and preparation for the period when dikes do not meet the norms and are not yet reinforced. A field which is less thoroughly researched, namely in current practice it comes down to take whatever measures are possible with the given resources in times of emergency situations.

The planning and preparation, in this case for the deployment of temporal control measures, is according to De Leeuw et al. (2012) the first of four phases for the logistics of flood disasters. The other three phases are; monitoring extreme conditions, actual flooding, and recovery. This research limits itself to the first phase, as shown in Figure 1. This part relates to the preparation needed to prevent a flooding from happening as much as possible. Important logistics aspects hereby are the process of planning, cost effective flow and storage of goods and materials. The time-phased forecasts for the occurrence of extreme conditions which activate the execution of plans, and the execution itself are not explicit included within this research.

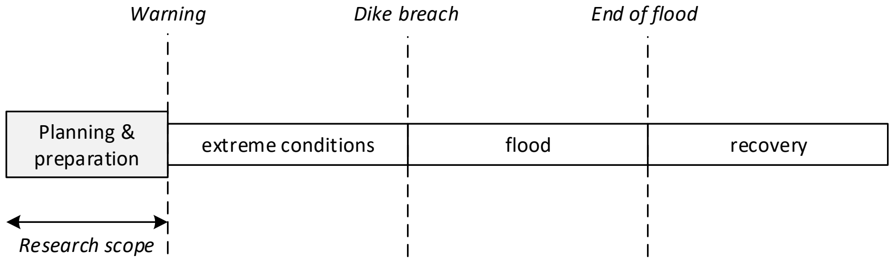


Figure 1 Phases associated with the research scope

1.2 Problem definition

The problem for water board Drents Overijsselse Delta is that a temporal solution needs to be determined for several dike locations that currently do not meet the norms. This problem is caused by the fact that dikes are not reinforced instantly, but that the dike improvements are spread out over a timespan of several decades, up to 2050. The water board needs to take temporal control measures in order to fill this gap and protect their citizens. The complexity of the problem increases due to the convergence of the IJssel, Vecht and Zwarte Meer in the IJssel-Vecht delta. As the resources and expenses for the measures are not endless, it is necessary to provide more insight in extreme water level threats by the three systems and their consequences, and the logistics aspects that arise when measures are deployed.

1.3 Objective and research questions

As defined by the problem definition it is necessary to provide more insight in the consequences and the logistic aspects that arise when measures are deployed. In addition, it is needed to include the complexity caused by the converging three water systems IJssel, Vecht, and IJsselmeer. This presents the following objective.

> *Determining the optimal capacity for temporal control measures for dikes in case of extreme water levels by quantifying the coincidence probabilities of extreme water levels and performing a cost-benefit analysis.*

The term capacity is used to denote the required amount of material, equipment, and manpower, which will shape the costs for the possibility to deploy temporal control measures. The measures are formulated as 'temporal control measures' to distinguish these measures from the emergency measures during an emergency situation. Furthermore, of major interest are the interactions between the three water systems. This aspect is included within the objective in the term coincidence probability. The coincidence probability is defined as the probability of simultaneous occurrence of events (Prohaska, Ilic, & Majkic, 2008). The objective can be formulated as a main research question and four sub-questions, which are given below.

> *What is the optimal capacity that should be reserved to balance the expenditures for temporal control measures and the flood damage due to extreme water levels in the IJssel-Vecht delta?*

1. *How does the water system in the IJssel-Vecht delta function?*
2. *What are the threats in the IJssel-Vecht delta and how are they currently dealt with?*
3. *What are the coincidence probabilities of extreme water levels for the three water systems in the IJssel-Vecht delta?*
4. *What is the relation between risk reduction and investment costs for the deployment of temporal control measures in the IJssel-Vecht delta?*

1.4 Research outline and methodology

The research outline is shown in the schematisation in Figure 2. The chapters 2 till 5 all correspond with a single research sub-question.

Chapter 2 answers the first research sub-question by a literature study. Hereby the water systems and their interaction are explored, the leading control structures are identified, and characteristics of the dike rings in the IJssel-Vecht delta are presented.

The problem analysis in Chapter 3 points out the extreme water level threats and shows which dike locations currently cannot cope with these water levels. Further, in this chapter it is discussed how the water board and their partners deal with the extreme water levels.

The coincidence probabilities of the high water events are addressed in Chapter 4. The methodology is a so-called copula-based assessment, which consist of four basic steps; selecting data, fitting marginal distributions, defining copula-functions, and deriving coincidence probabilities. These steps are carried out by the tools MATLAB, EasyFit, software 'R', and MS Excel.

The last sub-question is answered in Chapter 5 by applying a cost-benefit analysis on the temporal measures. The model needs input like the failure probabilities and the consequences to assess the risk, these form the impact assessment. Also it is required to know what capacity is required to take a measure. Each measure uses different amounts of material, equipment, and manpower. With these inputs it is possible to derive the costs and benefits for a certain set of measures. Lastly, the optimum balance between the risk reduction and the investment costs are derived for the IJssel-Vecht delta by using the results for multiple set of measures.

The results for each of the sub-questions are discussed in Chapter 6 and conclusions are drawn in Chapter 7. In addition, Chapter 8 includes some recommendations.

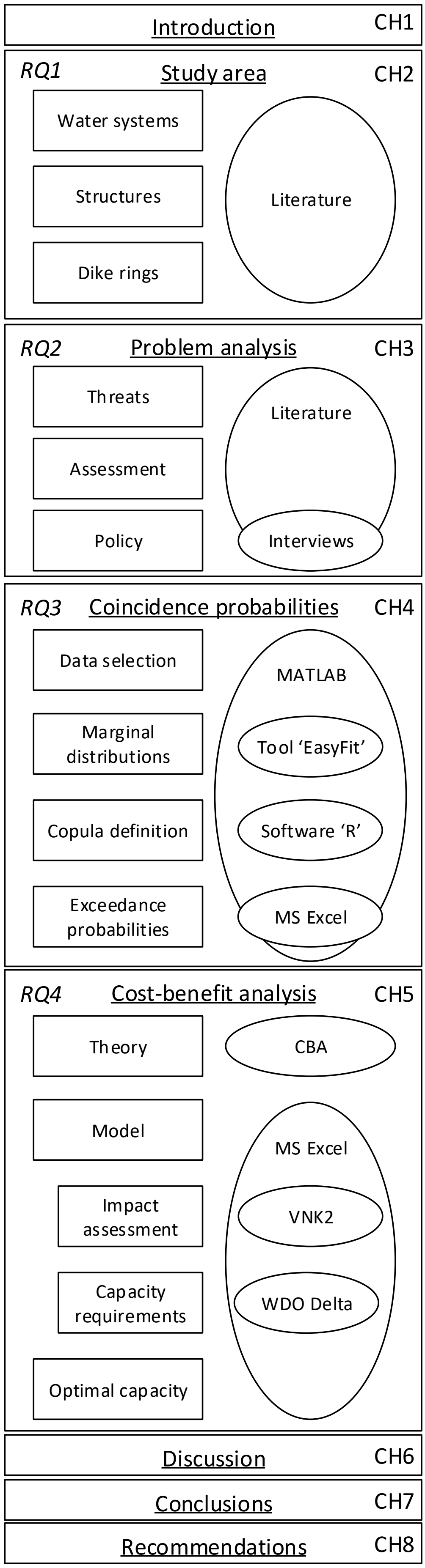


Figure 2 Research schematization

2| Study area

The study area is the IJssel-Vecht delta in the region of water board Drents Overijsselse Delta. The most important water system, structures, and developments are described in this chapter.

2.1 Overview

The area consists of three main water systems; IJssel, Vecht, and Zwarte Meer. The system of the IJssel is dependent on the discharge at Lobith, and two upstream locations for the Vecht are Dalfsen and Ommen. The lake area, Zwarte Meer, is influenced by the discharge of the IJssel and Vecht and by the wind set-up from Ketelmeer. There are five main water structures in the study area; Ramspol, Kadoelersluis, Zwartsluis, Spooldersluis and a barrier in Zwolle. The dike rings (DR) that are included within the area are dike ring 9 Vollenhove, 10 Mastenbroek, 11 IJsseldelta, and 53 Salland.

These water systems, structures, and dike rings are described in more detail on the next pages. An overview of the water systems is given in Figure 3.

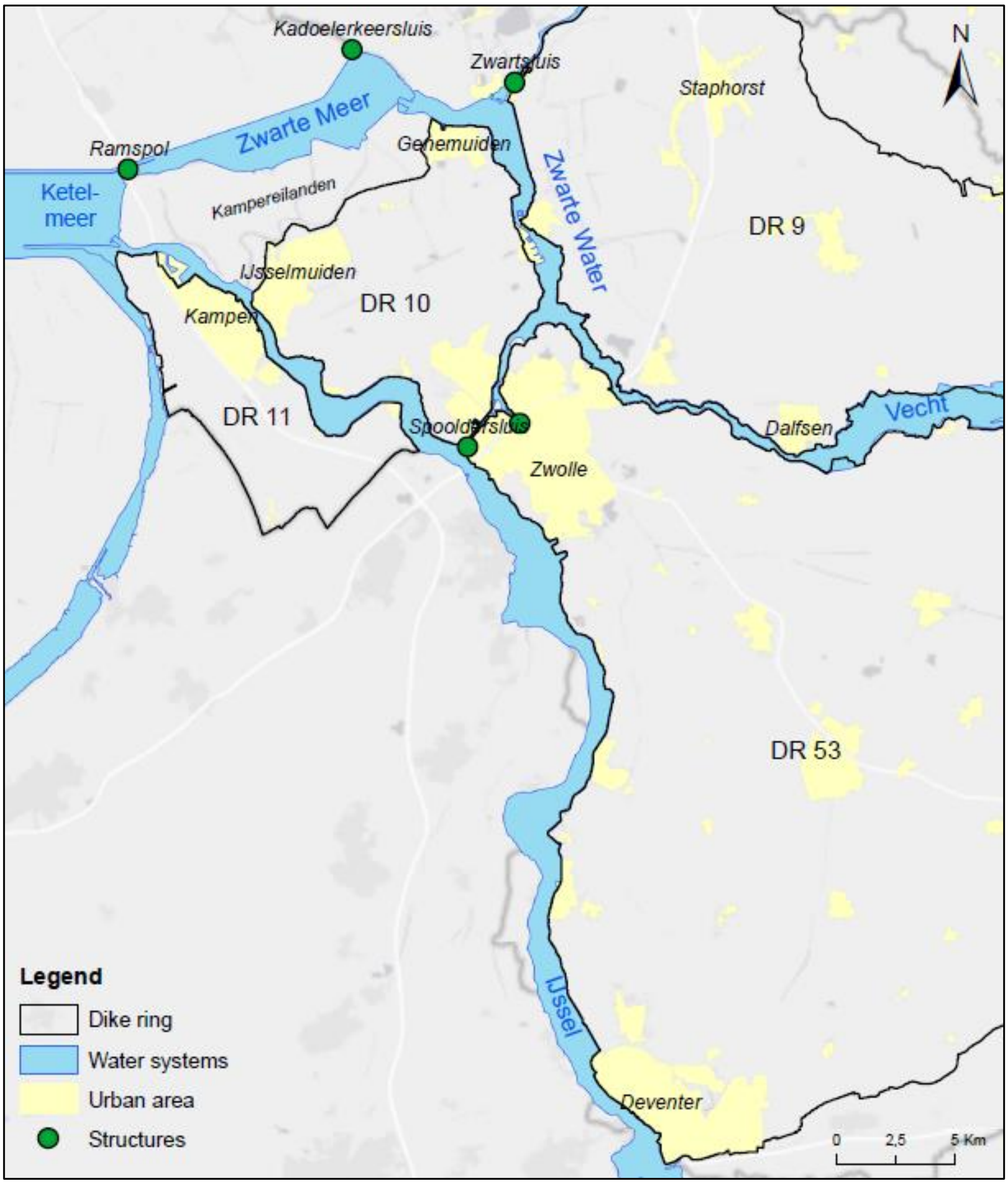


Figure 3 IJssel-Vecht delta

2.2 Water systems

The three water systems are described below.

IJssel

The system of the IJssel strongly depends on the discharge at Lobith. When the Rhine enters The Netherlands it splits into three branches. At the Pannerdensche Kop it splits into the Waal and Pannerdensch Kanaal. Subsequently the Pannerdensch Kanaal splits into the Nederrijn and the IJssel at the IJsselkop. The distribution in the bifurcation points has major effects on the downstream water system. Consequently, studies have been performed on the uncertainty in the distribution points. According to Ogink (2006) the uncertainties of the discharge distribution range from 120 till 150 m3/s and 85 till 100 m3/s due to morphodynamics and hydraulic roughness for Pannerdensche Kop and IJsselkop, respectively. The discharge distribution for a peak discharge of 16,000 m^3 in Lobith is presented in Figure 4 (Geerse C. , 2013). From the Pannerdensche Kop, the IJssel continues from Westervoort to Zutphen, Deventer, Kampen, and finally from the Ketelmeer into the IJsselmeer. Its length is approximately 125 km (Rijkswaterstaat, 2016).

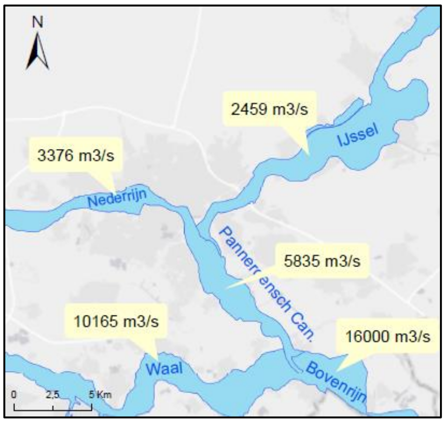


Figure 4 Bifurcation points Panerdensche Kop and IJsselkop with discharge distribution for design discharge 16000 m3/s at Lobith

Vecht & Zwarte Water

The Vecht enters The Netherlands east of De Haandrik, it passes Ommen and Dalfsen, and near Zwolle it flows over into Zwarte Water. The Zwarte Water continues in Zwarte Meer. For the Vecht the upstream discharge is critical for the water levels. In the Zwarte Water the water system develops from discharge dominated towards more wind dominated.

Zwarte Meer

The lake area, Zwarte Meer, is influenced by both the discharge of the IJssel and Vecht, and by the wind set-up from Lake IJssel. Between Zwarte Meer and the dike at the IJssel, Kamperzeedijk, there is an area outside of the dikes called Kampereiland. In the Kampereiland there are three waterways: Ganzendiep, Goot, and Veneriete. (Chbab, 2012)

Figure 5 The three water systems Zwarte Water, Vecht, and IJssel (from left to right)

2.3 Structures

There are five main water structures in the study area; Ramspol, Kadoelersluis, Zwartsluis, Spooldersluis and the barrier in Zwolle. Their location is shown in Figure 3.

Ramspol

The Ramspolkering is an inflatable rubber dam (balgstuw) and is meant to shut off the Vecht delta from Lake IJssel during a westerly storm, to prevent a storm surge generated above Lake IJssel to flow into the area. It is situated between Ketelmeer and Zwarte Meer. When the water level is above 0.5 m+NAP and the water flows towards the east, the Ramspolkering will be activated. The barrier will then have a height of 3.65 m+NAP. The barrier will be deactivated when the water level at the Ketelmeer (outside) is lower than the water level of Zwarte Meer (inside). After opening, the water then flows from east to west, relieving the Vecht delta again. Activation of the barrier takes 1 hour, while deactivation takes 3 hours (Geerse C. , 2011).

Kadoelerkeersluis

The third work is the Kadoelerkeersluis. When closed it protects the northern area against high water levels in Zwarte Meer. It closes when the water level in Zwarte Meer reaches 1.0 m+NAP. Opening and closing both take an hour. (Chbab, 2012)

Zwartsluis

The structure of Zwartsluis actually consists of three structures. The Grote Kolksluis, Meppelerdiepsluis and pumping station Zedemuden. These three structures regulate the exchange of water between Zwarte Water and canal Meppelerdiep. The structure makes it possible to discharge water in the Vecht, even when the water level in the Vecht is higher than in Meppelerdiep.

Spooldersluis

The Spooldersluis is located at the west of Zwolle. It separates the systems of IJssel and the Vecht, and protects the hinterland against high water levels in the IJssel.

Barrier Zwolle

The barrier (klepkering) at Zwolle protects the inner city of Zwolle and the hinterland of Salland against high water levels at Zwarte Meer and Vecht. It activates when the water level is above 1.0 m+NAP and the flow is directed from Zwarte Meer towards the inner city of Zwolle (Chbab, 2012).

Figure 6 The structures, upper row: Ramspol and Kadoelerkeersluis; bottom row: Zwartsluis, Spooldersluis, barrier Zwolle

2.4 Dike ring

The IJssel-Vecht delta contains four dike rings; 9 Vollenhove, 10 Mastenbroek, 11 IJsseldelta and 53 Groot-Salland, as presented in Figure 3. The characteristics and flood risks are presented for each dike ring in Table 1 and Table 2, respectively.

Table 1 Dike rings characteristics (Vergouwe, 2014)

Dike ring	Length dikes (km)	Area (ha)	Population
9 Vollenhove	46.0	58,200	88,600
10 Mastenbroek	47.5	9,540	32,000
11 IJsseldelta	32.4	13,700	47,800
53 Salland	83.0	40,900	205,500

Table 2 Dike rings flood risks (Vergouwe, 2014)

Dike ring	Flood probability per year	Economic risk per year (million)	Avg. damage per flood (million)	Casualties risk per year	Casualties per flood
9 Vollenhove	1/100	6.3	440	0.2	13
10 Mastenbroek	1/240	3.2	780	0.1	20
11 IJsseldelta	1/260	3.1	810	0.1	35
53 Salland	1/110	26.4	3000	0.5	60

Dike ring 9 Vollenhove

The majority of the area protected by dike ring 9 is in Overijssel province; a small portion of it is in the province of Drenthe. The primary flood defences in the system protect the Kop van Overijssel area from flooding by the Overijsselse Vecht river, Zwarte Meer lake and the Zwarte Water river. An interesting part of the water defences along Zwarte Water is Stenendijk levee near Hasselt. This retaining wall, a kilometre long, is Medieval, making it the oldest brickwork flood defence structure in the Netherlands. It was built and maintained by local residents themselves, each person being made responsible for their own section of wall, and is consequently a patchwork of different types of brickwork. The structure was not entirely fit for purpose, incidentally. In the early 19th century the levees at Zwartsluis and Hasselt breached due to a combination of storm conditions and poor maintenance at several locations. (Vergouwe, 2014)

Dike ring 10 Mastenbroek

Dike ring 10 protects a Medieval polder situated between the IJssel and Zwarte Water rivers in Overijssel province. The polder is protected by several levees, including the Kamperzeedijk, which was built before the 14th century, making it one of the oldest flood defence structures in the Netherlands. It marks the border with Kampereiland, the unembanked area that was regularly flooded by the Zuyder Zee in the past. A number of ponds can still be seen along the levee, created as a result of several levee breaches. One of the most severe floods in Mastenbroek polder was the great flood of 1825, when Kamperzeedijk failed in several locations and the polder was completely inundated during a storm surge. (Vergouwe, 2014)

Dike ring 11 IJsseldelta

Dike ring 11 is located in the estuary of the river IJssel, protecting an area that lies partly in Overijssel province and partly in Gelderland. The levee system is bordered to the west by Vossemeer and Drontermeer lakes and to the south by the Veluwe upland heath. In 1926 the majority of the area was flooded after a levee breach at Zalk. Since the area was still regularly flooded by the Zuiderzee at until 1932, many houses had been built on dwelling mounds and damage was limited. As part of the Room for the Rivers project, the navigation channel of the IJssel is deepened and a high water channel is being dug. The high water channel transects levee system 11, connecting the river with Drontermeer lake. This is necessary to guarantee flood protection in the area in the future. The measures should be complete by 2019. (Vergouwe, 2014)

Dike ring 53 Salland

The primary water defences in dike ring 53 protect the Salland region from flooding by the IJssel, Zwarte Water and Overijsselse Vecht rivers. The protected area is in Overijssel province and is mainly rural, with some large towns like Zwolle and Deventer. The protected area gradually slopes downwards in the downstream direction of the river. If the upstream flood defences along the IJssel breach, the water will flow to the lower-lying areas around Zwolle. If at the same time the water in the IJssel and Overijsselse Vecht were to rise to high levels, this might threaten the town of Zwolle. The area did not flood during the last major flood event in the IJssel valley in January 1926. (Vergouwe, 2014)

Ring sections and dike stretches

The dike rings are separated into dike stretches and ring sections.

A ring section is a part of the dike whereby the flooded area and the impact (damage and casualties) are nearly independent from the exact location of the breach. The ring sections are used for flooding simulations. For dikes ring 9, 10, 11 and 53 there are respectively 9, 16, 4 and 13 ring sections determined.

Further, the dike ring is divided into dike stretches for the derivation of failure probabilities. A dike stretch is a part of the dike whereby the characteristics regarding strength and loads are nearly homogeneous. Dike ring 9, 10, 11 and 53 are separated into respectively 51, 55, 44 and 72 dike stretches. The belonging water system to the dike stretches are shown in Table 3.

Table 3 Dike stretches and their water system

Dike ring	**Dike stretches**	**Water system**
9 Vollenhove	1-43	Vecht
	44-51	Lake
10 Mastenbroek	1-18	IJssel
	19-31	Lake
	32-55	Vecht
11 IJsseldelta	1-4	Lake
	5-44	IJssel
53 Salland	1-42	IJssel
	43-72	Vecht

3| Problem analysis

The convergence of the three water systems IJssel, Vecht and Zwarte Meer causes water safety threats for the IJssel-Vecht delta. These threats are further elaborated in this chapter. Further it is shown which dike locations currently cannot cope with these threats, and it is discussed how the water board and their partners deal with the extreme water level problems that occur.

3.1 Threats for water safety

The dike rings in the Drents Overijsselse Delta are threatened by storms in the lake area, and by high discharges in the IJssel or in the Vecht, or by combinations of these three events. In other words, the dominant natural variables for the water system are the lake water level, wind speed, wind direction, discharge IJssel, and discharge Vecht.

IJssel

The water levels in the locations along the IJssel are solely determined by the discharge of the IJssel, i.e. these locations are IJssel-dominated (Geerse, 2013). The Vecht can hardly influence the IJssel locations since the mouth of the Vecht is further downstream than the IJssel's mouth in the lake. Besides, the discharges of the Vecht are much lower than the ones in the IJssel (by about a factor 5) (Geerse, 2011).

Vecht & Zwarte Water

The water levels in the Vecht are solely dominated by the Vecht discharge. However, for Zwarte Water the levels are not only dominated by the discharge of the Vecht, but the water levels are also influenced by the wind set-up. This is the wind set-up coming from the Ketelmeer and Zwarte Meer.

Zwarte Meer

While the Zwarte Meer is separated from the IJssel by the structure Ramspol, the IJssel discharge still influences the water levels in the lake. Because the dikes in the downstream part of the IJssel at the north side of the river are designed for overtopping when high IJssel discharges occur. This concerns the dike stretch from IJsselmuiden to Ramspol (Geerse, 2011). However, most important for Zwarte Meer is the storm surge. Threatening situations occur due to certain combinations of wind speed and wind directions. When the wind direction is between South West and North a threatening situation can occur. A significant increase in water levels on IJsselmeer, Ketelmeer, and Zwarte Meer starts when the wind speed is greater than 4 Beaufort (20-28 km/h). A threatening situation occurs in more extreme situations, when the wind speed is 10 Beaufort (89-102 km/h) or greater (Verhoeven & Vermeulen, 2011).

3.2 Dike assessment

During the third test round for water safety ('Derde toetsing waterveiligheid') a total length of 1225 km primary water defences in The Netherlands was identified as insufficient in January 2011 (Rijkswaterstaat, 2016). From the total 192 km of primary water defences in the IJssel-Vecht delta a total of 104 km was insufficient in 2011 (IVW/Waterbeheer;, 2011).

In the dike assessment for dike ring 9 Vollenhove a total 19 out of 51 dike stretches did not pass the water safety tests. The failure mechanisms were overtopping and overflow, macro stability inner slope, and stability outer slope. For dike ring 10 Mastenbroek a total of 32 out of 55 dike stretches were regarded as insufficient. The two leading failure mechanisms hereby were macro stability inner slope,and piping and heave. Also for dike ring 53 Salland a major part of the dike was insufficient, namely a total of 59 out of 72 dike stretches, whereby piping and heave is the most critical failure mechanism. Remarkable for dike ring 53 Salland is that the failure contribution by three structures in

Deventer is relatively high, in comparison with the nearby dike rings. An overview of the insufficient dikes in the IJssel-Vecht delta is given in Figure 7.

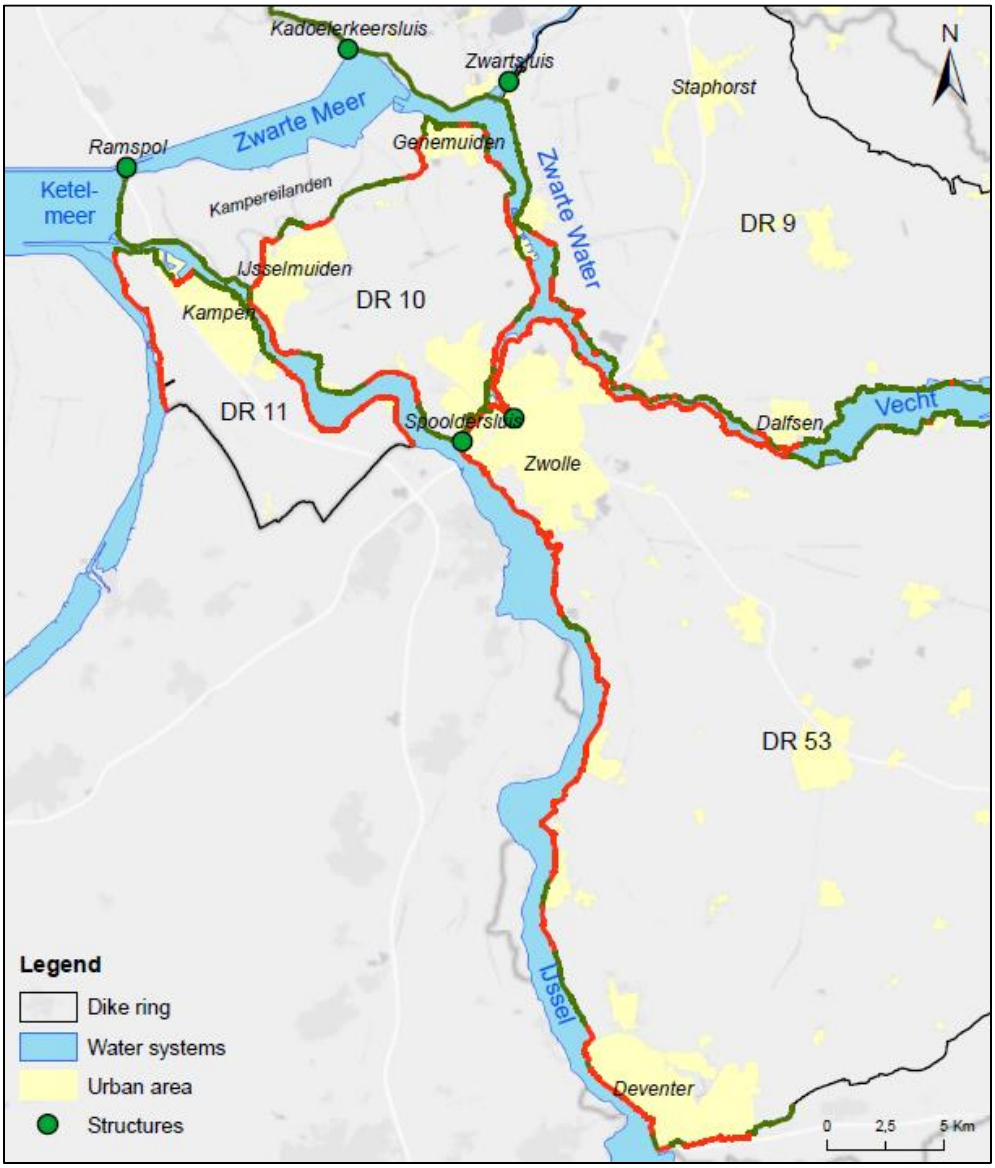


Figure 7 Dike assessment IJssel-Vecht delta

Remark is that the focus of the third test round was on the failure probabilities instead of on the flood risks. With the newly introduced safety norms the focus is on flood risk, rather than seeking to protect against a single design threshold. Hereby the flood risk is defined by the flood probability and the consequences that are related to this probability. When the focus is on the flood risk it may seem that the risk is reduced more when sufficient dike stretches according to the third test round are strengthened instead of insufficient dike stretches due to the higher consequences for the sufficient dike stretches.

Multiple projects are (being) executed or planned in order to increase the water safety. The major projects are the "Room for the River" projects in the IJssel, like Reevediep and the flood channel Veessen – Wapenveld. The objective of these projects is to lower the water levels in IJssel during peak discharges by given back room to the river. Also along the Vecht and Zwarte Water projects are planned to increase the safety in the IJssel-Vecht delta. An overview of the projects can be found in *Appendix A*.

3.3 Water safety policy for high outer waters

The dike reinforcement projects are spread over several decades up to 2050. It is simply not possible to reinforce the dikes in an instant, therefore a water safety policy with temporal measures is required to deal with high water levels until the projects are finished. This safety policy for the IJssel-Vecht delta is presented in several protocols and plans, which are discussed in this section.

Water safety policy and temporal control measures

The water safety policy for this temporal situation is shaped by the deployment of control measures. The temporal control measures are deployed before an (extreme) crisis situation is at hand. In other words, the protocols for the temporal control measures are set in motion when the estimated water levels are higher than the dike's current norm, but the water levels do not exceed the dike's required norm. The application of temporal control measures in the water safety policy is taken into account by WDO Delta in the 'Hoogwaterklapper noodmaatregelen' and 'Protocol Kampereilanden'.

In 'Hoogwaterklapper noodmaatregelen' by Van der Nat (2012) a set of temporal measures is defined for the dikes along the IJssel and Vecht. This document presents possibilities for the deployment of control measures in case of high water situations along the dikes. Suitable measures are allocated to each dike stretch, depending on the failure type. For these measures it is determined when to start with the deployment, the required amount of manpower and material, and the costs. The document can be used to quickly get insight in the applicability of control measures. However, it is not a protocol, it only presents options for the deployment of measures, and shows the logistic requirements.

A protocol for temporal control measures is recently designed for the Kampereilanden (WDO Delta, 2015). This area is located along Zwarte Meer, outside the primary dikes. The protocol thus is for regional dikes. The protocol has a total of four steps and is shaped by the head of operation & maintenance, regional employees, and the KEI-brigade. The employees are; the operator who is on watch, a specialist defences, a hydrologist, and information coordinator. The KEI-brigade are volunteers that will deploy the measures. The most important aspect of the protocol is that decision points are clearly defined. For example, volunteers are gathered together when the water level is 0.5 m+NAP and the water level keeps increasing. And when the water level exceeds 0.7 m+NAP, the final step is the deployment of the measures.

It can be concluded that there is no clear protocol for the primary defence structures that do not meet their norm. The 'Hoogwaterklapper' only gives insight in the logistic requirements and the protocol Kampereilanden concerns regional defence structures.

Emergency plan – high outer waters

Temporal control measures are also part of the emergency plan. The emergency plan for extreme water levels is determined in the emergency plan "high outer waters" by WDO Delta (2016). It concerns issues caused by the waters outside the dike ring. A summary of the emergency plan can be found in *Appendix B*.

The emergency plan functions as guideline, and is mostly important to give directions to all actors that are involved. Every high water situation is different, there is no pre-defined solution. Assuming that the dikes meet their norms it is impossible to predict where the dike will fail. The situation depends on the current state of the dikes and the conditions that will occur. During emergency situations the volunteers on the dikes are the most important factor to monitor the situation and decide where to take measures.

This is the case for emergency situations, however, for the use of temporal measures it is known which dike stretches do not meet the requirements, and it is known beforehand that measures should be taken at those locations. Which means that the temporal measures can and should be stipulated in a protocol.

Furthermore, an interesting issue is that the temporal measures and the emergency plan are seen as independent from each other. The temporal measures are placed under the regular activities, so they are situated in phase 0 in the emergency plan schedule. Nevertheless, there certainly is an interaction between the two. The temporal measures are of the same type as the measures taken during an emergency situation. The same type of materials and manpower are used for both situations. Thereby, the materials, manpower and the available time can only be used once per high water event. So when the materials are used for temporal measures, they cannot be used again in a later stage when an emergency situation occurs. So it should be made certain that the pre-determined locations for the temporal control measures carry the greatest risk at that specific moment compared to dike locations that already meet their norm. This is an interesting point for the complexity of the three water system in the IJssel-Vecht delta.

Notifications and warnings

The decision to initiate the protocols for temporal control measures or emergency situations starts with a notification or warning. These can be caused by failures of technical installations, high water level measurements, high water level forecasts, extreme rainfall forecasts, or other external messages.

IJssel – water level forecasts

When the water level in the Rhine at Lobith is 14.00 +m NAP and an increase in water level is estimated to 15.00 +m NAP, the high water level coverage by Rijkswaterstaat Oost-Nederland will start. They will form an emergency team which communicates with the different parties.

The water levels for two days ahead can be estimated with an accuracy of 10-15cm. Estimates for more than two days ahead should be seen as indications of increase or decrease in water levels, the accuracy of these estimates is 20-40 cm. (van Toorn, 2011)

Ketelmeer and Zwarte Meer - storm warnings WDIJ

The storm warnings for Lake IJssel are given by Rijkswaterstaat. A storm level is estimated based on the water level in Lake IJssel, wind direction and wind speed. A warning will be given to the water board when the alarm level for certain dike area is reached. The expected water levels on Lake IJssel and Ketelmeer will be combined with the data about the current state of the defences by the water board.

The wind speed and direction is not easy to estimate, therefore the forecast of a storm can only take place between 0.5 – 1.0 day ahead (Verhoeven & Vermeulen, 2011). So, the time to prepare for a storm is very limited.

Vecht

There is no warning system by Rijkswaterstaat for the Vecht. Information for the Vecht is derived from the monitoring system of the water boards itself. High discharges and/or water levels are detected by the water boards Drents Overijsselse Delta and Vechtstromen.

A threatening situation can be forecasted 1.5 – 2 days ahead (Verhoeven & Vermeulen, 2011).

Overview

An overview of the flooding threats by the three systems for each dike ring is given in Table 4. In addition, it shows that dike ring 10 Mastenbroek is the only dike ring that is threatened by each water systems.

Table 4 Flooding threats and warning times for each dike ring, source: (Verhoeven & Vermeulen, 2011)

Dike ring	**Discharge IJssel**	**Discharge Vecht**	**Ketelmeer**
Warning time	*4 to 5 days*	*1.5 to 2 days*	*0.5 to 1 day*
9 Vollenhove	-	X	-
10 Mastenbroek	X	X	X
11 IJsseldelta	X	-	X
53 Salland	X	X	-

4| Coincidence probabilities

The problem analysis in the previous chapter showed the singular threats by the three systems, but a complexity in the safety threat is caused by convergence of extreme water levels in the IJssel, Vecht, and Zwarte Meer. In this chapter the coincidence probabilities between these systems are quantified to provide more insight in this complexity. The coincidence probabilities are analysed with a copula-based assessment. Therefore, this chapter starts with a general explanation of copula functions, and then continues with the actual application on the IJssel-Vecht delta.

4.1 Theoretical framework – copulas

There are several examples of successful application of copula functions for hydrological uses. Bender et al. (2016) introduced an approach to model multivariate data when the maxima of both variables in a year are unlikely to occur always simultaneously. As a case they used the confluence of the Rhine River and the Sieg River. The approach leads to distinctively different results compared to the very conservative approach of analysing the annual maximum values of both variables.

A study by Chen et al. (2012) analysed the risk of flooding as a result of flood coincidences by considering flood magnitudes and time (dates) of occurrence. Two four-dimensional copula functions were developed for the joint distribution of flood magnitudes and occurrence dates. Based on their model, the coincidence and conditional probabilities for any return period were obtained. According to their analysis results, it is possible to raise the flood control water level for Three Gorges Reservoir in the Upper Yangtze River in May and June, while in September a certain flood control storage is needed. Furthermore, the results showed that the Jialing River has the most significant impact on the inflow in the reservoir.

A trivariate frequency analyses of peak discharges, hydrograph volumes and suspended sediment concentrations using copulas was performed by Bezak et al. (2014). With the use of statistical and graphical tests they selected the most appropriate copula model. The Gumbel-Hougaard copula was selected as the most appropriate model for all their stations in Slovenia.

The above mentioned studies show the potential of applying copulas in several hydrological issues. All the more reason to explore how copula functions work and how they can be applied to the study area.

Properties

Copulas are a flexible tool for modelling the dependence structure of two or more random variables. They allow to build joint distributions from two or more variables while maintaining the statistical properties of their marginal distributions (Biller & Corlu, 2012). A representation of a copula is given in Figure 8.

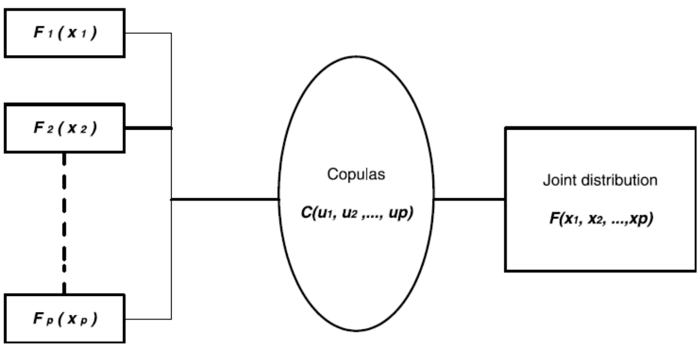


Figure 8 Representation of a copula (Favre et al., 2004)

Consider a random vector $(x_1, x_2, \dots, x_p)$ and suppose that the marginal cumulative distribution functions $\left(F_1(x_1), F_2(x_2), \dots, F_p(x_p)\right)$ are continuous. By applying the probability integral transform to each component, the random vector has uniformly distributed marginals $(U_1, U_2, \dots, U_p)$, as shown in Equation 1. The probability integral transform relates to the result that data values that are modelled as being random variables from any given continuous distribution can be converted to random variables having a uniform distribution.

$$(U_1, U_2, \dots, U_p) = \left(F_1(x_1), F_2(x_2), \dots, F_p(x_p)\right) \quad (1)$$

In a copula (C) it is assumed that random variables $(x_1, x_2, \dots, x_p)$ are related to each other. The relationship between these variables is described through the joint distribution function (Pr) of the uniformly distributed marginals $(U_1, U_2, \dots, U_p)$, as shown in Equation 2.

$$C(u_1, \dots, u_p) = Pr(U_1 \le u_1, \dots, U_p \le u_p) \qquad (2)$$

To complete the copula construction, arbitrary marginal distribution functions are selected. This gives a multivariate distribution function, i.e. joint distribution.

$$C\left(F_1(x_1), \dots, F_p(x_p)\right) = F(x_1, \dots, x_p) \qquad (3)$$

In the copula function it is possible to integrate different families of probability distributions for each variable. The foundation for the copula function by Sklar (1959) showed that any multivariate distribution can be written in the above form (Equation 3). The study also showed that if the marginal distributions are continuous there always is a unique copula representation. In other words, from Sklar's theorem, it is seen that for continuous multivariate distribution functions the univariate margins and the multivariate dependence structure can be separated, and the dependence structure can be represented by a copula.

Marginal distributions

As mentioned above, the statistical properties of the marginal distributions are maintained in the constructed joint distributions.

The most common used marginal distributions for annual maximum flood analysis is the Generalised Extreme Value (GEV) distribution. The GEV distribution combines three simpler distributions into a single form, allowing a continuous range of possible shapes that includes all three of the simpler distributions. The three cases covered are the Gumbel, Fréchet and Weibull families, also known as type I, II and III extreme value distributions

The Gumbel distribution is mostly used for water data, like extreme discharges and water levels, while the Weibull distribution is more often used for extreme wind speed data (Xiao et al., 2006; Carta et al., 2009).

Another distribution, the generalised logistic (GL) distribution, is suggested by Shaw et al. (2011). The advantage of the GL distribution over the GEV is that fitting the GEV more often results in a distribution with an upper bound. Shaw et al. (2011) state that it is debatable whether an upper bound is expected on the basis of meteorological and hydrological conditions in any region. Reaching such a bound normally occurs over such a long return period that for practical purposes the assumption of an unbounded distribution can be taken as reasonable.

The above mentioned distributions apply to annual maxima. With peaks-over-threshold (POT) series the generalised Pareto (GP) distribution should be chosen (Van den Brink et al., 2005; Shaw et al., 2011).

Where a three-parameter distribution is fitted and the k parameter is close to zero relative to the estimated standard error, then it is recommended that the equivalent two-parameter distribution is used (Shaw, Beveb, Chapell, & Lamb, 2011).

The parameters α, β, k, σ and μ are parameters for the shape, scale, or location. The meaning of the parameter symbol differs for each type of distribution. Estimation of these parameters can be done by well-known methods as the method of moments (MOM), maximum likelihood estimates (MLE), least-squares estimates (LSE), and method of L-moments (MOLM). The compatibility of a random sample with a theoretical probability distribution function is tested by goodness-of-fit (GOF) tests, like the Kolmogorov-Smirnov (KS) test, Anderson Darling (AD) test, and Chi-squared test.

Table 5 Marginal probability density functions and cumulative distribution functions

Distribution	Probability Density Function (PDF)	Cumulative Distribution function (CDF)	Range
Gumbel	$f(x)=\frac{1}{\sigma}\exp(-z-exp(-z))$	$F(x)=\exp(-exp(-z))$	$\sigma>0$ $-\infty<x<\infty$
Fréchet	$f(x)=\frac{\alpha}{\beta}\left(\frac{\beta}{x-\gamma}\right)^{\alpha+1}\exp\left(-\left(\frac{\beta}{x-\gamma}\right)^{\alpha}\right)$	$F(x)=\exp\left(-\left(\frac{\beta}{x-\gamma}\right)^{\alpha}\right)$	$\alpha>0$ $\beta>0$ $\gamma<x<\infty$
Weibull (3p)	$f(x)=\frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}\exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)$	$F(x)=1-\exp\left(-\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)$	$\alpha>0$ $\beta>0$ $\gamma<x<\infty$
GEV	$f(x)=\frac{1}{\sigma}\exp\left(-(1+kz)^{-\frac{1}{k}}\right)(1+kz)^{-1-\frac{1}{k}} \quad k\neq0$ $f(x)=\frac{1}{\sigma}\exp(-z-exp(-z)) \quad k=0$	$F(x)=\exp\left(-(1+kz)^{-\frac{1}{k}}\right) \quad k\neq0$ $F(x)=\exp(-exp(-z)) \quad k=0$	$1+kz>0 \quad k\neq0$ $-\infty<x<\infty \quad k=0$
GL	$f(x)=\frac{(1+kz)^{-1-\frac{1}{k}}}{\sigma\left(1+(1+kz)^{-\frac{1}{k}}\right)^{2}} \quad k\neq0$ $f(x)=\frac{\exp(-z)}{\sigma(1+\exp(-z))^{2}} \quad k=0$	$F(x)=\frac{1}{1+(1+kz)^{-\frac{1}{k}}} \quad k\neq0$ $F(x)=\frac{1}{1+\exp(-z)} \quad k=0$	$1+kz>0 \quad k\neq0$ $-\infty<x<\infty \quad k=0$
GP	$f(x)=\frac{1}{\sigma}\left(1+\frac{k(x-\mu)}{\sigma}\right)^{-1-\frac{1}{k}} \quad k\neq0$ $f(x)=\frac{1}{\sigma}\exp\left(-\frac{(x-\mu)}{\sigma}\right) \quad k=0$	$f(x)=1-\left(1+\frac{k(x-\mu)}{\sigma}\right)^{-\frac{1}{k}} \quad k\neq0$ $f(x)=1-\exp\left(-\frac{(x-\mu)}{\sigma}\right) \quad k=0$	$\sigma>0$ $\mu\leq x<\infty$ $\mu\leq x\leq\mu-\sigma/k$

**Where,* $z=\frac{x-\mu}{\sigma}$

Type of copulas

A popular family of copulas is given by Archimedean copulas. Namely the Clayton, Frank, and Gumbel copulas, since they are relatively easy to construct, flexible and capable of covering the full range of tail dependence (Bender et al., 2016). The need for input models with asymmetric dependence structures arises in situations where extreme positive realizations have a tendency to occur together (Biller & Corlu, 2012). Other type of copulas are meta-elliptical copulas, like normal and t-copulas. Different choices of generator yield different families of copulas. The trivariate copula functions of the Archimedean copulas are shown in Table 6.

Table 6 Archimedean copula properties

Copula	**Generator**	**Param.**	**Equation (trivariate)**
Clayton	$\frac{t^{-\theta}-1}{\theta}$	$\theta \geq -1$	$\left(u_1^{-\theta}+u_2^{-\theta}+u_3^{-\theta}-2\right)^{-\frac{1}{\theta}}$
Frank	$-\log\left(\frac{e^{-\theta t}-1}{e^{-\theta}-1}\right)$	$\theta \in \mathbb{R}$	$-\frac{1}{\theta} ln\left(1+\frac{(\exp(-\theta u_1)-1)(\exp(-\theta u_2)-1)(\exp(-\theta u_3)-1)}{(\exp(-\theta)-1)^2}\right)$
Gumbel-Hougaard	$\lvert\log(t)\rvert^{\theta}$	$\theta \geq 1$	$\exp\left(-\left(\left(-ln(u_1)^{\theta}\right)+\left(-ln(u_2)^{\theta}\right)+\left(-ln(u_3)^{\theta}\right)^{\frac{1}{\theta}}\right)\right)$

The Clayton copula is also called Cook and Johnson copula (Nelsen, 2006). As u approaches zero, the marginal distributions become independent. The Clayton copula cannot account for negative dependence. It shows strong left tail dependence and relatively weak right tail dependency. When correlation between two events is strongest in the left tail of the joint distribution, Clayton is an appropriate modelling choice (Wang et al., 2009).

The Frank copula permits both negative and positive dependence between the marginal distributions and the dependence is symmetric in both tails. When θ approaches zero, the marginal distributions are independent. Because of its properties, the Frank copula has been widely used in empirical applications (Wang et al., 2009).

Similar to the Clayton copula, the Gumbel copula does not allow negative dependence. Contrary to the Clayton copula, however, the Gumbel copula exhibits strong right tail dependence and relatively weak left tail dependence. If outcomes are known to be strongly correlated at high values but less correlated at low values, then the Gumbel copula is an appropriate choice (Wang et al., 2009). Figure 9 shows the tail dependencies for the bivariate Clayton, Frank and Gumbel copulas.

The interest for tail dependencies is motivated by the pitfalls of correlation (Biller & Corlu, 2012). Tail dependencies form an alternative way to understand and model dependence.

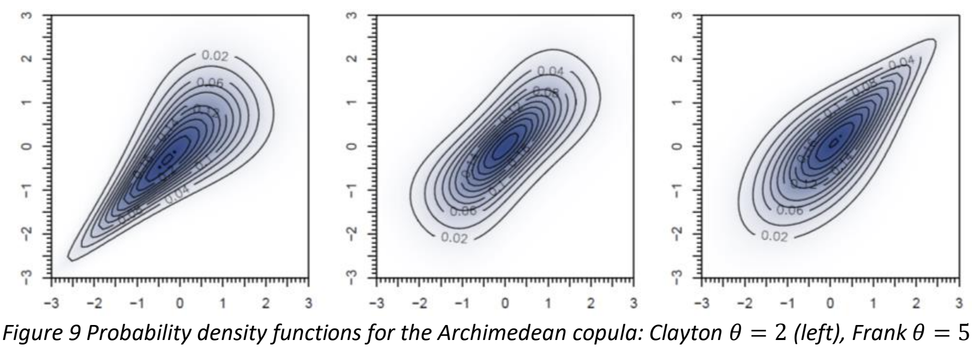


Figure 9 Probability density functions for the Archimedean copula: Clayton $\theta = 2$ (left), Frank $\theta = 5.7$ (middle), Gumbel $\theta = 2$ (right) (Scholzel & Friederichs, 2008)

Parameter estimation

When a copula is being considered as a model the parameter(s) need to be estimated. This section reviews different strategies for the determination of the parameter(s). As the dependence structure is not influenced by the individual behaviour of the variables, it is just to consider only rank-based estimators (Genest & Favre, 2007).

Examples of rank-based estimators are estimates based on Kendall's tau and Spearman's rho. The popularity of Kendall's tau is that closed-form expressions for the population value of Kendall's tau are available for many common parametric copulas. Table 7 presents an expression for the population value of Kendall's tau (τ) for the three most common Archimedean copulas.

Other rank-based estimation methods are the maximum likelihood method, and the maximum pseudo-likelihood method. Where the first method assumes that the data are observations, the latter uses pseudo-observations, i.e. the scaled ranks. The maximum likelihood methods are less attractive than the inversion of Kendall's tau or Spearman's rho, because it involves numerical work and requires the existence of a density (Genest & Favre, 2007). However, according to Kojadinovic & Yan (2010) the maximum pseudo-likelihood estimator appears to be the best choice in terms of mean square error in all situations, except for small and weakly dependent samples.

Table 7 Expressions for Kendall's tau (Genest & Favre, 2007; Wang et al., 2009)

Copula	**Kendall's tau**
Clayton	$\frac{\theta}{\theta + 2}$
Frank*	$1 - \frac{4}{\theta} + \frac{4D_1(\theta)}{\theta}$
Gumbel-Hougaard	$1 - \frac{1}{\theta}$

$^*D_1(\theta)$ is the first Debye function, which is $D_1(\theta) = \int_0^{\theta} \frac{\left(\frac{x}{\theta}\right)}{e^x - 1} dx$

Goodness-of-fit

An important step in the process is the choice and adjustment of the copula function which best fits the data. To identify the best-fitting copula function a goodness-of-fit test can be performed. This test assesses the goodness of the estimated copula parameters in capturing the joint distributional characteristics of the available input data.

This can be done by graphical tests with Chi-plots and K-plots (Fisher & Switzer, 1985; Fisher & Switzer, 2001), but a more formal and recognised goodness-of-fit test for copula functions is the Cramér-von Mises test by Genest et al. (2006). According to Genest et al. (2009) the Cramér-von Mises test is the most powerful goodness of fit test based on empirical processes. A S_n value closer to zero means a better fit. In addition, it is possible to derive p-values associated with the Cramér-von Mises statistics. The p-value is the probability that the current result would have found if the copula structure was not adapted to the data, i.e. if the copula parameter remained the standard value. The test is defined by:

$$S_n = \sum_{i=1}^{n} \left(C_n(U_i) - C_\theta(U_i)\right)^2 \qquad (4)$$

Where vector U_i are the pseudo-observation calculated from analysed sample, C_θ is the tested theoretical copula, and C_n is the empirical copula, which is defined as:

$$C_{n(u)} = \frac{1}{n} \sum_{i=1}^{n} 1(U_i \leq u) \qquad (5)$$

4.2 Method

The copula-based assessment starts with the selection of historical data for each water system. As the coincidence regards extreme high water situations, the annual maxima will be used. This makes it necessary to have a long period of historical data.

The second step is to derive distributions for each of the systems. Hereby a distinction is made between the occurrence and the magnitude of the peaks. The result is a distribution function for every marginal system.

The following step is the copula model definition. It starts with selecting the data for the overlapping period and assessing the bivariate dependence between the systems through the correlations. Then the Archimedean copula are fitted for both the bivariate as the trivariate situation. The best fitting copula is selected for each combination.

The resulting coincidence probabilities of the occurrence and the magnitudes are combined, for both the bivariate and trivariate cases, to finally achieve the coincidence probabilities for the different combinations of events.

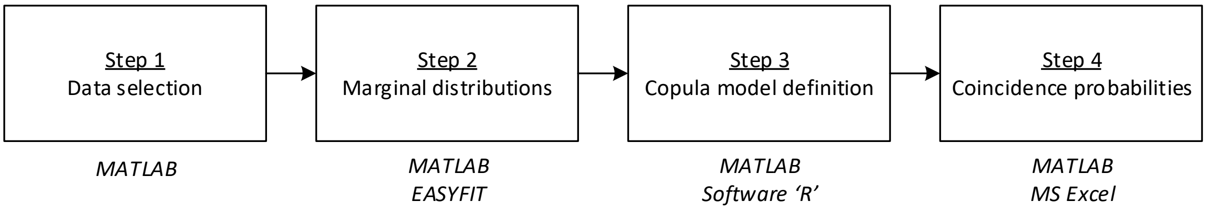


Figure 10 Copula method

4.3 Data selection

The first step is to select the data from which daily and annual winter year maxima are derived. The daily maxima are used for validation and cross-correlation of data, while the annual maxima are used for deriving the marginal distributions and the copula functions. For determination of the marginal distributions the whole data set of each system is used, but for determination of the copulas function the overlapping periods are used.

For the IJssel and Vecht water levels are chosen instead of discharge, because more historic data is available for water levels. The same argument applies for the selection of national wind data as a representative for storm surges at Ketelmeer and Zwarte Meer.

Deventer (IJssel)

For the IJssel system the water levels at the location of Deventer are used. Which is available from 1811-1996 as daily measurements. From 1996-2013 the data is given in hourly measurements, and from 2013-2016 for every ten minutes. The location Deventer is chosen in favour of Olst, because the data of Olst was missing for the years 1981-1985.

Vechterweerd Beneden (Vecht)

For Vechterweerd Beneden the water levels are available from 1940-2016. However, the years 1987, 1988, and 1990 are missing. From 1940-1986 the water levels are measured daily, from 1989-2013 hourly, and from 2013-2016 every ten minutes. The data of Vechterweerd Beneden is favoured over location Mond der Vecht, because the water levels at Mond der Vecht are influenced by storm surges from the lake area.

De Bilt (storm surge)

For the storm surge the wind data at the nationwide representative location of De Bilt is used. The wind data consists of daily values for wind direction and maximum wind speed from 1901-2016. A storm surge at Ketelmeer and Zwarte Meer is only represented by the wind data when the wind is coming from between South West and North. Within the data the wind direction between SW and N is presented by values between 213 and 360, as presented in Figure 11.

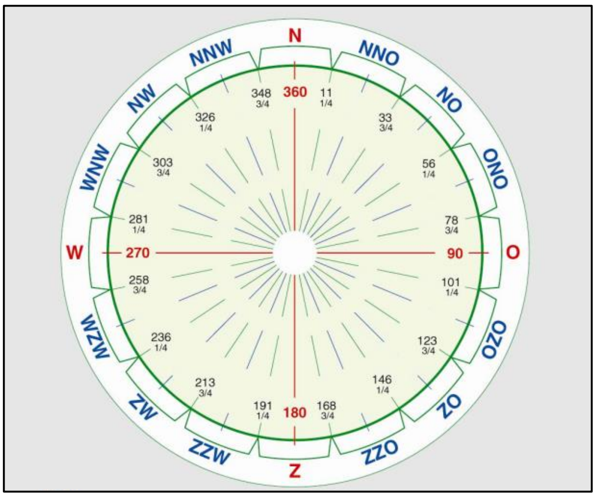


Figure 11 Wind compass (KNMI, 2010)

The first idea was to use water levels at one of the locations nearby the Ketelmeer and Zwarte Meer. Unfortunately, the data at these locations did not span many historical years, for the location Ramspol, data was only available from 1990 till now. At other locations the water levels in the data were influenced by the discharges of the IJssel and Vecht, or by the tidal waves of the Zuiderzee before 1932. Two other location that measured wind data are Marknesse and Stavoren, which are closer to the study area, but data is only available starting from 1989 and 1990, respectively.

The application of the national wind data as representative for storm surge in the lake area is validated by assessing the correlation between the wind data and the water levels at Ramspol. The Pearson coefficient for the daily maxima is 0.46, with a very small p-value of 8.7*10^-240, which means that the null hypothesis of no correlation can be rejected. For the annual maxima the correlation coefficient is even higher, a Pearson coefficient value of 0.60, with a p-value of 0.0014. With a dataset of 26 values the p-value is still small. In other words, there is a significant correlation between the wind speed at De Bilt, with given direction, and the water level at Ramspol. More details about the validation process can be found in *Appendix C*.

Data overview

An overview of the selected data is presented in Table 8. Figure 12 presents the maxima of the normalized magnitude for each day of the year. Figure 13 presents the maxima of the magnitude for each year. The values for the IJssel and Vecht are water levels, and for the wind data the wind speed is shown. The used normalization method is 'feature scaling', which brings all values into the range [0,1] by using Equation 6.

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (6)$$

Figure 12 suggests that the occurrence of the annual maxima for every single system is more likely to be in the winter months, than in the summer months. Figure 13 shows a high variation of the maximums for each year. In other words, there is no cycle or wave whereby series of years with high magnitudes are alternated with series of low magnitudes.

For more information, *Appendix D* presents figures with the daily maxima, minima, and mean of the magnitude for each system. And figures with the annual maxima, minima, and mean of the magnitude for each system.

Table 8 Selected data

Location	Parameters	Time period	Comments
Deventer (IJssel)	Water levels	1811 – 2016	
Vechterweerd (Vecht)	Water levels	1940 – 2016	Missing data 1987;1988;1990
De Bilt (Netherlands)	Wind speed; wind direction	1904 – 2016	Represents storm surge

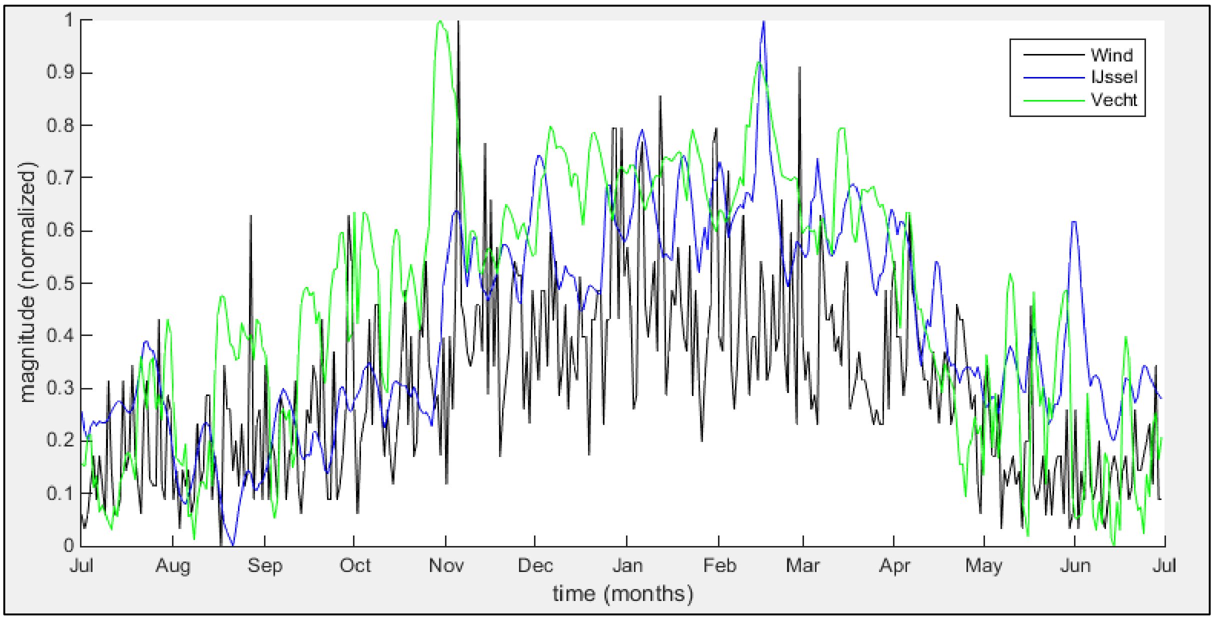


Figure 12 Maximum daily magnitude for the Wind, IJssel, and Vecht locations

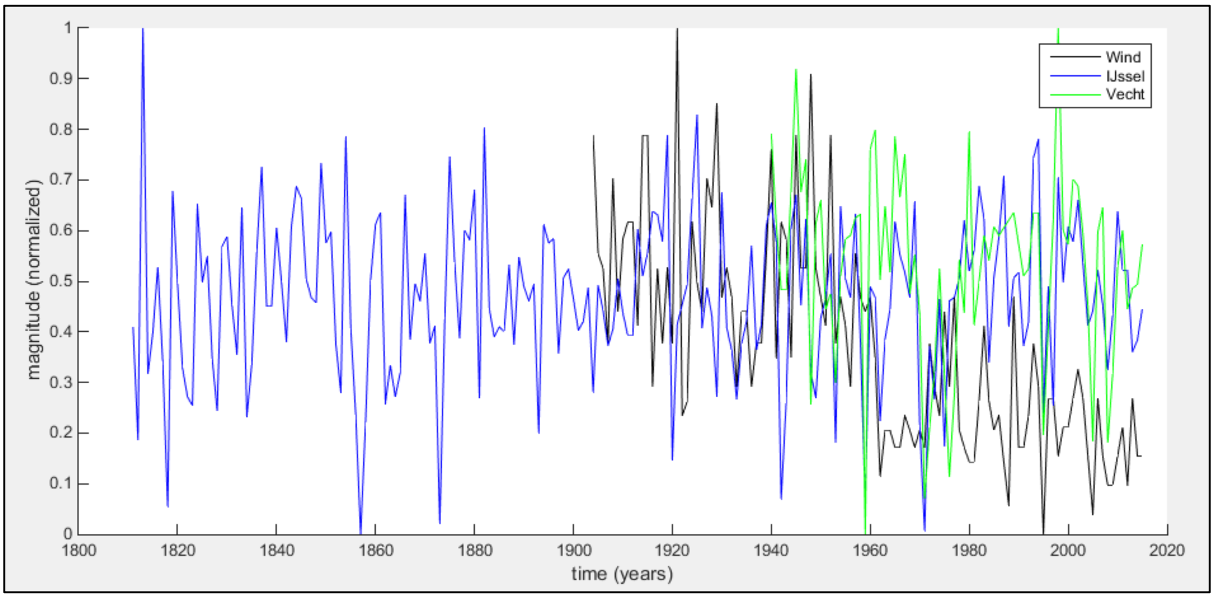


Figure 13 Maximum annual magnitudes for the WInd, IJssel, and Vecht locations

4.4 Marginal distributions

From the selected data the annual maxima are used for the determination of marginal distributions for each water system, for both the occurrence dates and the magnitudes. Which resulted in 112, 206, and 74 data points for the Wind, IJssel, and Vecht, respectively. The extreme value distributions that are being fitted to the annual maxima are the Gumbel, Fréchet, Weibull, Generalised Extreme Value, and Generalised Logistic distributions.

Distribution fitting

The above mentioned distributions are fitted with the tool EasyFit. The parameter estimation method for each distribution is presented in Table 9. The goodness-of-fit for each distribution is determined with the Kolmogorov-Smirnov (KS) test, Anderson Darling (AD) test, and Chi-squared test.

Table 9 Parameter estimation method per distribution

Distribution	Parameter estimation method
Gumbel	Method of moments
Fréchet (2P)	Least squares method
Fréchet (3P)	Maximum likelihood method
Weibull (2P)	Least squares method
Weibull (3P)	Maximum likelihood method
Generalised Extreme Value	Method of L-moments
Generalised Logistic	Method of L-moments

Goodness-of-fit

For the occurrence dates of the IJssel and Vecht the Generalised Logistic distribution displays the best scores for all the three tests (KS-test, AD-test, and chi-squared). For occurrence dates of the Wind the Generalised Extreme Value distribution scores the best on all tests.

With regard to the magnitudes, the Generalised Logistic distribution scores best for the IJssel and Vecht. However, for the Vecht the Gumbel distribution also displays a good fit. The Gumbel distribution scores best on the Chi-squared test, and second on the other two tests. However, the Gumbel distributions seems to allocate a lower probability to extreme water levels than the Generalised Logistic distribution.

The Generalised Extreme Value distribution is ranked second and third on the KS-test for the IJssel and Vecht, respectively. But as described by Shaw et al. (2011), the Generalised Extreme Value distribution has an upper bound, while this is not the case for the Generalised Logistic distribution. As an upper bound is debatable on basis of meteorological and hydrological conditions, this gives an additional motivation to choose for the Generalised Logistic distribution.

The magnitudes of the Wind data are, according to the KS-test, best represented by the Fréchet distribution. But the Weibull distribution scores best on the AD-test and the Chi-squared test. The Weibull distribution is chosen, because previous studies showed that the Weibull distribution is in general a good representation for wind data (Carta et al., 2009; Xiao, Li et al., 2006).

An overview of the test scores, the estimated parameters, and the discussed probability distributions are shown in Table 10, 11 and 12. For all the three tests a value closer to zero means a better fit.

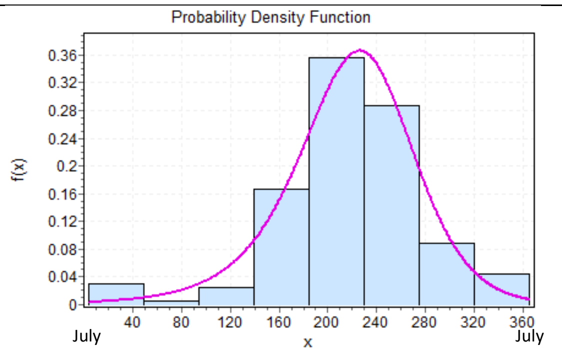
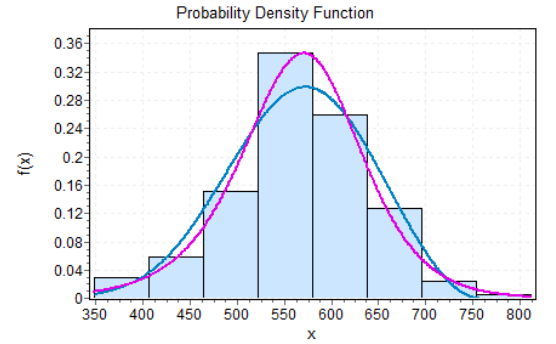
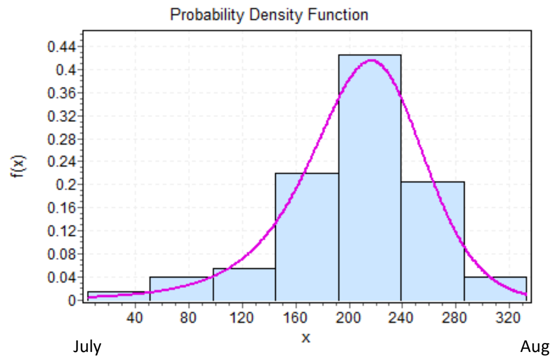
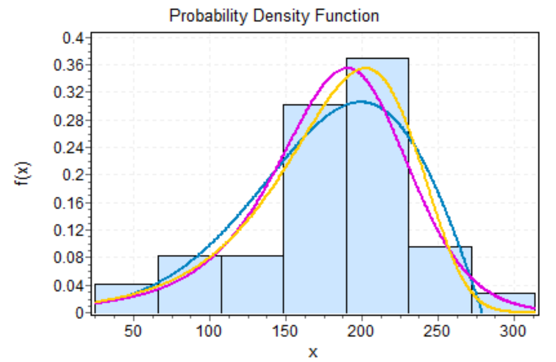
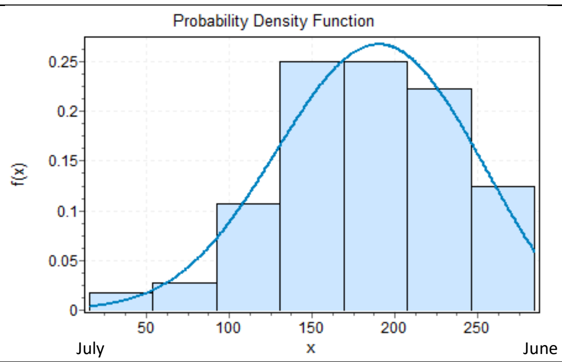
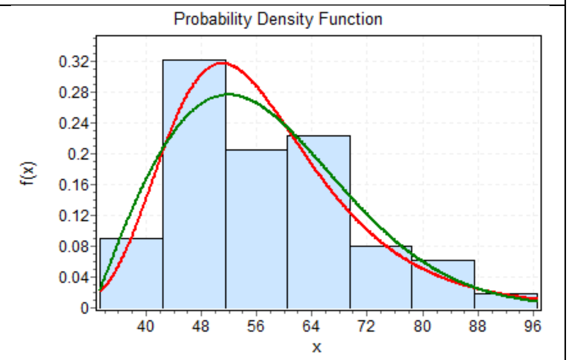
Table 10 Probability distributions parameters and goodness-of-fit scores for occurrence dates

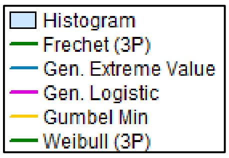
	Distribution	Parameters	Goodness-of-fit		
			KS	*AD*	*Chi²*
IJssel	Gen. Logistic	$k = -0.07905$ $\sigma = 31.006$ $\mu = 221.04$	*0.042*	*0.57*	*5.4*
Vecht	Gen. Logistic	$k = -0.11106$ $\sigma = 28.690$ $\mu = 210.23$	0.068	0.30	3.0
Wind	Gen. Ext. Value	$k = -0.35751$ $\sigma = 57.109$ $\mu = 166.88$	0.043	0.23	1.8

Table 11 Probability distributions parameters and goodness-of-fit scores for magnitudes

	Distribution	Parameters	Goodness-of-fit tests		
			KS	*AD*	*Chi²*
IJssel	Gen. Logistic	$k = -0.03962$ $\sigma = 41.960$ $\mu = 567.15$	*0.036*	*0.25*	*6.5*
Vecht	Gen. Logistic	$k = -0.11764$ $\sigma = 29.421$ $\mu = 183.2$	0.059	0.38	6.9
Wind	Weibull	$\sigma = 1.9754$ $\beta = 27.708$ $\gamma = 32.54$	0.086	0.54	3.4

Table 12 Probability density functions with histogram

	Occurrence	Magnitudes
IJssel		
Vecht		
Wind		



4.5 Copula model definition

The third step of the copula model definition uses the daily and annual maxima for the overlapping period from 1940 to 2016. Because data for the years 1987, 1988, and 1990 is missing for the Vecht, the data covers a total of 74 years. The daily maxima are solely used for the determining the cross-correlation, and the annual maxima are used for the bivariate correlations. After deriving the correlations between the three systems the bivariate and trivariate copula functions are determined with the annual maxima.

Correlation

The bivariate correlation between the water systems is derived by calculating the Pearson (r), Kendall (τ) and Spearman (ρ) correlation coefficients. Pearson's correlation coefficient measures only linear dependence, whereas the other two coefficients are based on ranks and are more appropriate for expressing dependence between variables (Bezak et al, 2014).

The values of the correlation coefficients and the p-values are presented in Table 13. The correlation coefficient is a number between -1 and 1. The correlation expresses the degree that, on an average, two variables change correspondingly. The p-value is the probability that the current result would have found if the correlation coefficient were in fact zero, i.e. the null hypothesis. If this probability is lower than the conventional 5% ($p<0.05$) the correlation coefficient is called statistically significant with a 95% confidence interval.

Table 13 Correlation coefficients and p-values for the relations between IJssel, Vecht, and Wind

	Pearson		**Kendall**		**Spearman**	
	r	p	τ	p	ρ	p
IJssel-Vecht						
Occurrences	0.4450	0.0001	0.3456	< 0.0001	0.4388	0.0001
Magnitudes	0.5994	< 0.0001	0.3802	< 0.0001	0.5421	< 0.0001
IJssel-Wind						
Occurrences	-0.2443	0.0372	-0.156	0.0525	-0.234	0.0463
Magnitudes	0.0084	0.944	0.0363	0.6605	0.0529	0.6566
Vecht-Wind						
Occurrences	-0.302	0.0094	-0.1384	0.0855	-0.2212	0.06
Magnitudes	0.1451	0.2206	0.1466	0.0735	0.1937	0.1006

The scatter plots, in Figure 14, already suggest a correlation between the IJssel and Vecht water levels. This suggestion is confirmed by the values of the correlation coefficients, as can be seen in Table 13. The results show a significant correlation between the IJssel and Vecht, for both the occurrence dates as the magnitudes. For the occurrence dates the correlation coefficient of Pearson, Kendall, and Spearman have values of 0.45, 0.35, and 0.44, respectively. And for the magnitudes the coefficients have values of 0.60, 0.38, and 0.54.

The correlations between the IJssel and Wind, and Vecht and Wind, are negative, with values between -0.3 and -0.2. The negative correlations for the occurrence dates suggest that the annual maximum of the wind is not likely to occur on the same date as the annual maximum of the IJssel or Vecht, and vice versa. The negative correlations for the magnitudes suggest that if, for example, an extreme wind occurred in this year it is not likely that an extreme water level will occur in the IJssel or Vecht in the same year, and vice versa. However, these correlations are only statistical significant for the occurrence dates of the IJssel and Wind, not for the relation between the Vecht and Wind, nor for both of them in magnitudes. The above mentioned (non)relations should be noticeable in the copula functions that are derived in the next section.

Furthermore, the cross-correlation results in Figure 15 shows that the daily correlation between the IJssel and Vecht is the highest with a lag of 1 day, namely a value of 0.65. The physical interpretation from this is that the water level in the Vecht increases sooner than the water level in the IJssel, i.e. the Vecht reacts faster to hydrological events than the IJssel does.

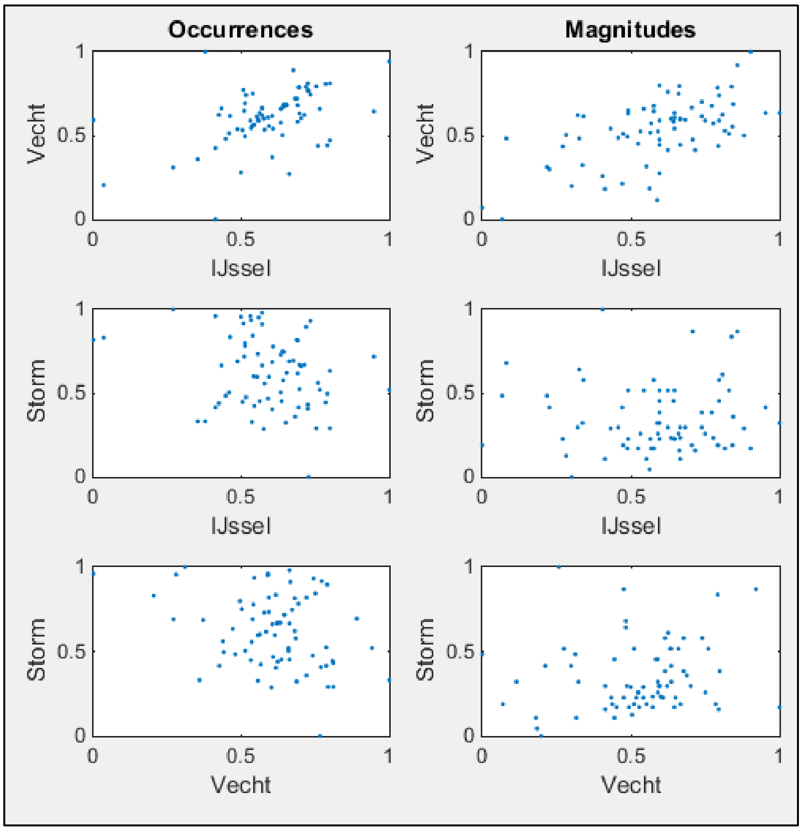


Figure 14 Scatter plots (2D) IJssel, Vecht, Wind with normalized data

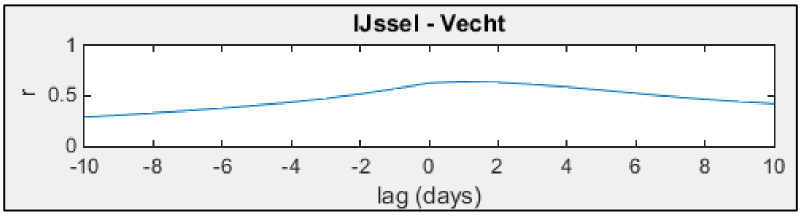


Figure 15 Cross-correlation magnitudes IJssel and Vecht

Fitting Copulas

The copulas Gumbel, Clayton, and Frank are fitted to the data with the use of the package 'Copula' for the software 'R'. This software makes it possible to fit multiple copula with an option for different estimation methods. In addition, it is possible to estimate the goodness-of-fit with different types of tests. In this case, the parameters of the Archimedean copulas are estimated by the inversion of Kendall's tau, and the goodness-of-fit is determined by the Cramer von Mises test of Genest et al. (2009).

The results of the copula fitting to the data are presented in Table 14. The θ symbol represents the parameter value of the copula. The *Sn* values relate to the Cramér-von Mises test. A value closer to zero means a better fit. The p-value is the probability that the current result would have found if the copula structure was not adapted to the data, i.e. if the copula parameter remained the standard value. This means that the copula function can be rejected with a 95% confidence interval if the p-value is smaller than 0.05. However, the combination of the lowest Sn-value and a low p-value can also mean that the data is best represented by the standard copula shape.

Table 14 Fitting results for trivariate and bivariate copulas Clayton, Frank, and Gumbel

	Clayton			**Frank**			**Gumbel**		
	θ	*Sn*	*P*	θ	*Sn*	*P*	θ	*Sn*	*P*
IJssel-Vecht									
Occurrences	1.1407	0.061	0.0035	3.6745	0.037	0.033	1.5704	0.031	0.13
Magnitudes	1.2323	0.029	0.17	3.9083	0.022	0.49	1.6162	0.027	0.26
IJssel-Wind									
Occurrences	-0.27228	-	-	-1.4477	0.029	0.26	1	0.028	0.25
Magnitudes	0.069706	-	-	0.30339	0.066	0.001	1.0349	0.065	0.002
Vecht- Wind									
Occurrences	-0.23644	-	-	-1.2245	0.042	0.039	1	0.019	0.77
Magnitudes	0.32077	-	-	1.2636	0.067	<0.001	1.1604	0.066	0.001
Trivariate									
Occurrences	0.2107	0.033	0.55	0.33411	0.040	0.34	1.1901	0.039	0.27
Magnitudes	0.54094	0.044	0.15	1.8251	0.046	0.11	1.2705	0.040	0.21

In the previous section it has been shown that the IJssel and Wind, and Vecht and Wind have negative correlations for their occurrences, i.e. they have a negative dependence. The Clayton and Gumbel copula cannot account for this negative dependence. In the results this can be seen by the negative Clayton parameters, and Gumbel parameters with a value of 1.0.

For the bivariate case of the IJssel and Vecht, the occurrence dates and magnitudes have the best fit for the Gumbel copula and Frank copula, respectively. The relation between IJssel and Wind, and Vecht and Wind, are both best presented for the occurrences dates and magnitudes by the Gumbel copula. In the trivariate situation the occurrence dates are best presented by the Clayton copula, while for the magnitudes this is the Gumbel copula. They both have the lowest Sn-values and the highest p-values.

Occurrence dates

For the occurrence dates of the bivariate cases, all with the Gumbel copula as best fit, the data has a right upper tail dependence. This means that outcomes are strongly correlated at high values but less correlated at low values. Figure 14 show that the annual maximums are mostly located on the right, i.e. they have high values. And looking at Table 14, it can be seen that the peaks therefore lay in the higher values of the occurrence dates. This declares why the correlation is stronger at the higher values, i.e. in the second half of the winter year. Also this suggest that a different choice of the start and end of the winter year could results in different fitting results for the copula. If, for example, the dates are shifted so that the peaks lay exactly in the centre on the x-axis, the Frank copula without tail dependencies might give the best fit.

Further exploration of the trivariate Clayton copula for the occurrence dates showed that the Clayton copula gives relatively seen extremely high probabilities of simultaneous occurrence, which means that the values might be corrupt. The second-best is the Gumbel copula, which also fits well for the bivariate occurrence dates. In addition, it is unclear why the goodness-of-fit for the bivariate cases could not derive results for the Clayton copula for the wind relations. Therefore, it would be wise to use the trivariate Gumbel copula for the occurrence dates instead of the Clayton copula.

Magnitudes

Regarding the magnitudes, the Frank copula for the IJssel and Vecht means that there is no strong left or right tail dependence. This suggest they are equally correlated for both the low as the high values. From a physical perspective it is unclear what could be expected. Although there certainly is a correlation between the IJssel and Vecht there is no clear reason to assume that the correlation is stronger in more extreme situations, i.e. with higher values for the magnitudes.

For the magnitudes of the Wind combinations the Gumbel copula provides the best fit, however the results do not differ much from those of the Frank copula. As the discharge and the storage capacity of the Vecht is relatively low compared to the IJssel, it could be expected that at local extremes with heavy rainfall and high wind speeds the Vecht and Wind are strongly correlated. This would result in a good fit for the Gumbel copula. However, this does not come forward in the results. Regarding the IJssel and Wind it is not strange that the results do not show any specific behaviour, because these two systems do not show any correlation.

In the trivariate situation the magnitudes are best presented by the Gumbel copula. Which is remarkable because the strong correlation between the IJssel and Vecht is best presented by the Frank copula. When the trivariate Gumbel copula is used to derive the exceedance probabilities this will result in much higher probabilities for the higher return periods than the trivariate Frank copula would.

4.6 Coincidence probabilities

The coincidence probabilities for the simultaneous occurrences and related magnitudes are derived by inserting the marginal probability distributions into the copula functions.

Occurrence dates

The Gumbel copula provided the best fit of the bivariate copulas, and also for the trivariate situation the Gumbel copula is the most appropriate because the trivariate Clayton copula showed unreliable results.

A coincidence of events is defined as the probability that the annual maxima take place within a period of five days. Therefore, the input for the copula functions is the sum of the exceedance probabilities for five consecutive days, for each system. For the trivariate case this is presented by Equation 7. Whereby dt is set to 2 days.

$$P_{occ}^{t} = P_t\big(t - dt < T_{ijssel} \leq t + 1;\;\; t - dt < T_{Vecht} \leq t + dt;\;\;\; t - dt < T_{Storm} \leq t + dt\big) \quad (7)$$

$P_{occ}^{t} = exceedance\ probability\ of\ coinciding\ flood\ occurence$
$t = day\ of\ the\ year$
$dt = time\ interval$

The results are presented in Figures 16, 17, 18 and 19. The blue lines present the copula function, and the orange lines present the probability when the systems are seen as independent from each other. Due to the correlation between the IJssel and the Vecht the bivariate copula function shows higher coincidence probabilities than the independent function, the difference is a factor 4.7. For the other bivariate cases this is not the case, as there is no correlation with the wind. The trivariate case (Figure 19) shows that when the wind is taken into account the coincidence probability is slightly higher than when the wind is excluded. A fully independent assumption gives a much lower probability, namely lower with a factor 5.3.

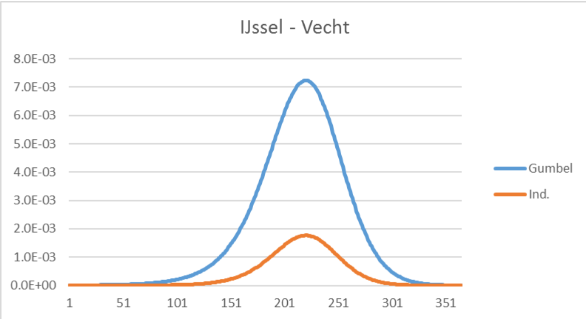


Figure 16 Occurrence probabilities IJssel-Vecht

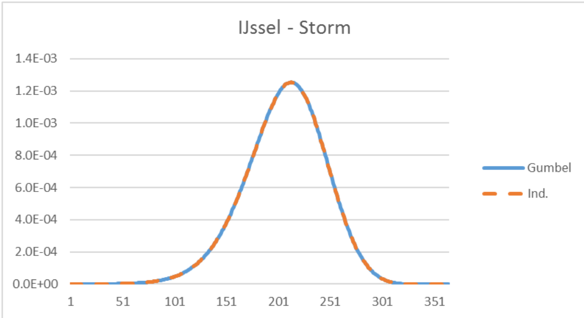


Figure 17 Occurrence probabilities IJssel-Wind

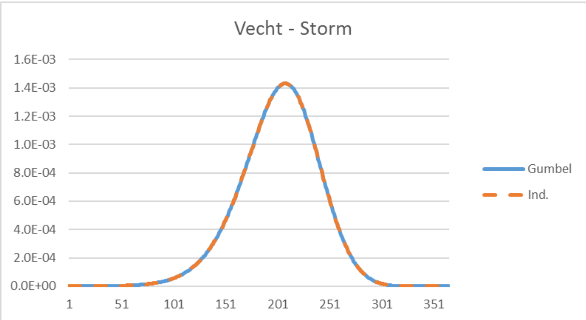


Figure 18 Occurrence probabilities Vecht-Wind

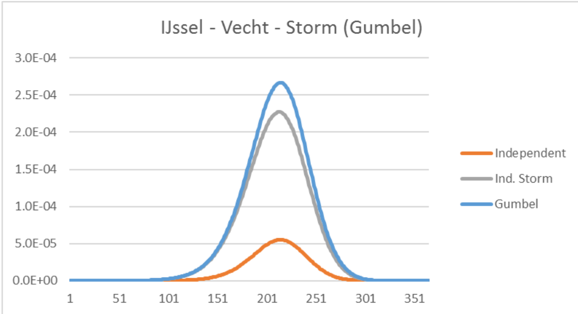


Figure 19 Occurrence probabilities IJssel-Vecht-Wind

Magnitudes

The exceedance probabilities between the magnitudes are derived with both the bivariate Frank and Gumbel copula for the IJssel and Vecht, and a bivariate Gumbel copula for the storm relations. For all three the events the trivariate Gumbel and Frank copula are used. The exceedance probabilities of the flood magnitude are derived by calculating the exceedance probabilities of combinations of events. For example, the exceedance probability that a 1/100 event in the IJssel occurs on the same time as a 1/100 event in the Vecht. In the trivariate case this is presented by Equation 8.

$$P_{magn}^{T} = P\left(H_{IJssel} > h_{ijssel}^{T};\ \ H_{Vecht} > h_{Vecht}^{T}, W_{Storm} > w_{Storm}^{T}\right) \quad (8)$$

$P_{magn}^{T} = exceedance\ probability\ of\ coinciding\ flood\ magnitudes$
$H = water\ levels$
$h = design\ water\ levels$

The results showed that for the IJssel and Vecht with the Frank copula the magnitudes are a factor 2.9 to 4.0 higher than when an independent situation is assumed, for respectively a 1/10 and a 1/3000 event. With the use of the Gumbel copula these factors are 2.9 and 41.2.

For the bivariate combination of IJssel and Wind the factor goes from 1.1 to 1.4, and for the bivariate combination Vecht and Wind from 1.4 to 4.3. For all of these combinations the factor increases with larger return periods, but for the Vecht and Wind this is more noticeable.

For the trivariate case with the Gumbel copula the magnitudes are a factor 4 to 150 higher than when an independent situation is assumed. Again the factor increases rapidly with larger return periods. However, when the Frank copula is used, just as for the bivariate IJssel and Vecht combination, the resulting factors are much smaller, namely 0.01 to 4.73.

Magnitudes & occurrences

It is assumed that the flood occurrence dates are independent of flood magnitudes. Which means that the probability of the yearly maximum occurring on a certain date differs per occurrence date, but that the magnitude of this yearly maximum does not have an effect on that probability. To illustrate, for the location Deventer along the IJssel, the annual maximum water level of 5.6 +mNAP in 2016 did not have a higher probability of occurring in January, or any other month or day, than the annual maximum water level of 6.4 +mNAP in 2010 had.

With the above described assumption, the flood coincidence probabilities of rivers are derived by multiplying the sum of occurrence probability with the magnitudes.

$$P_{comb}^{T} = P_{magn}^{T} \times \sum P_{occ}^{t} \qquad (9)$$

$P_{comb}^{T} = exceedance\ probability\ of\ coinciding\ flood$

By including the coincidence probabilities for the simultaneous occurrence over a period of 5 days, the coincidence probabilities become smaller than the probabilities for solely the magnitudes. However, the coincidence probabilities derived with the copula functions are much larger than when an independent situation is assumed.

For the bivariate cases of the IJssel and Vecht with the Frank copula, the coincidence probabilities are a factor 14 to 19 higher for return periods of 10 and 3000 years, respectively. And with the use of the Gumbel copula these factors are 14 and 195.

As there seem to be no correlation between the occurrence of river systems and the storm surges the coincidence probabilities for the other two combinations do not change.

For the trivariate case the coincidence probabilities are a factor 22 to 795 greater than when an independent situation is assumed for both the magnitudes as the occurrences. This remarkable increase for the trivariate case is caused by the choice for the Gumbel copula. However, when compared to the coincidence probabilities for the IJssel and Vecht, it is the question in how far the coincidence results for the trivariate case approach the reality. When the Frank copula is used for the trivariate coincidence probabilities the factors are only 0.1 to 25 greater than when an independent situation is assumed.

An overview of the results is presented in *Appendix E*.

4.7 Interpretation of the results

A few conclusions can be derived from the derivation of the coincidence probabilities.

Significant correlation IJssel-Vecht

The first conclusion is that there is significant correlation between the annual maximum water levels of the IJssel and the Vecht. This is for both the day of occurrence and the magnitudes. Whereby the cross-correlation for the daily water levels showed that the correlation is highest with a lag of 1 day. The correlation between the IJssel and Vecht is also reflected in the bivariate and trivariate copulas, and therefore in the final coincidence probabilities.

However, the other variables do not seem to have any correlation, which is noticeable in the unconvincing results for the fitting of the copulas. In addition, the choice of the type of trivariate copula has major effects on the final coincidence probabilities. Therefore, it would be wise to solely focus on the bivariate combination of the IJssel and Vecht.

Coincidence probability highest in January and February

The results for the IJssel and Vecht show that the coincidence probability of high water level events is highest in the month January and February. This is not surprising, but it certainly is confirmatory. This finding can be translated to logistic aspects by stating, for example, that during the summer months it is not necessary to have capacity ready for temporal control measures. This info can be useful for agreements with contractors and other parties.

The resulting coincidence probabilities for the combination of IJssel and Vecht are higher than when considering independent variables. With the Frank copula this is with a factor between 14 and 19, depending on the return periods. For the Gumbel copula the difference factor is between 14 and 195 higher than for the independent situation. These results show that it is important to include the correlation between the IJssel and Vecht when deriving exceedance probabilities.

Operational management

The above described results are interesting, but what do they mean for the operational management? To answer this question, it is needed to derive the conditional probabilities. The conditional probability is a measure of the probability of an event given that another event has occurred, which is derived by Equation 10.

$$P(A|B) = \frac{P(A \cap B)}{P(B)} \qquad (10)$$

If the event B is assumed to have occurred, the conditional probability of A given B $P(A|B)$ is determined by dividing the joint probability $P(A \cap B)$ with the probability that event B occurs $P(B)$. This can be translated to the probability that if high water levels occur in the IJssel, what would be the probability that high water levels also occur in the Vecht.

The results for the conditional probabilities are given in Table 15, for both the Frank as the Gumbel copula. Both copula results are presented because the results differ a lot, this shows that the correct choice of copula is very important. For a high water level event of 1/3000 in the IJssel, there is a probability of 1/1152 that a high water level event of 1/3000 also occurs in the Vecht, at least for the Frank copula. Use of the Gumbel copula gives a probability of 1/111.

The conditional probability can also be derived for other combinations of return periods. For example, when it is assumed that temporal measures are deployed for the IJssel with a return period of 1000 years and for the Vecht with a return period of 100 years. The Frank copula gives a probability of 1/39 that they occur at the same time, while the Gumbel copula gives a probability of 1/12. Which means that in the worst case, in one out of twelve times it is necessary to deploy temporal measures for both the IJssel as the Vecht.

Table 15 Conditional probabilities for different return periods

Return period in both systems	**Conditional probability**	
	Frank copula	*Gumbel copula*
1/3000	1/1152	1/111
1/2000	1/768	1/90
1/1000	1/385	1/62
1/100	1/40	1/18
1/10	1/5	1/5

5| Cost-benefit analysis

The quantification of the coincidence probability provides more insight into the threats in the complex area of the IJssel-Vecht delta, but it did not give any insight in the flood consequences and the possibilities of decreasing these consequences by deployment of temporal measures. The cost-benefit analysis presented in this chapter will do this by deriving the investment costs and the risk reduction for the deployment of a set of measures. Doing so the optimum balance between the costs and benefits are derived for the three systems in the IJssel-Vecht delta.

5.1 Theory

Flood management has shifted from a 'standard of protection' approach to a concept based on risk analysis (Shaw et al., 2011). Rather than seeking to protect against a single design threshold, the premise is to understand the risk of flooding from all events, and to accept that it may not be possible to eliminate the risk entirely. Risk is generally thought of having two components, which are the probability and consequence of an event, which is illustrated by Equation 11.

$$Risk = Probability \times Consequences \tag{11}$$

Both the probability and the consequences can be expressed in numerical terms for dikes and other water safety structures. Therefore, the risk term can be expressed as expected damage, mostly in euro/year (Kind, 2011; Vergouwe, 2014).

For a dike ring or water system the risk is determined by the summation of the risks for each dike stretch. The risk for a single dike stretch is derived by multiplying the failure probability of the dike stretch with the consequence when the corresponding ring sections fails. A dike stretch is a part of the dike whereby the characteristics regarding strength and loads are nearly homogeneous. And a ring section is a part of the dike whereby the flooded area and the impact (damage and casualties) are nearly independent from the exact location of the breach. The net present value (NPV) is applied to take into account that money in the present is worth more than the same amount in the future, because of earnings that could potentially be made with other investment and because of inflation. This gives the following equations.

$$Damage_{dike\ stretch_n} = Probability_{dike\ stretch_n} \times Consequences_{dike\ stretch_n} \tag{12}$$

$$Damage_{total} = \sum_{n=1}^{p} Damage_{dike\ stretch_n} \tag{13}$$

$$Damage_{NPV} = \frac{Damage_{total}}{(1+r)^n} \tag{14}$$

The risk can be reduced by hazard mitigation or by vulnerability and exposure mitigation (Molinari et al., 2013). Hazard mitigation takes place when dikes are reinforced or temporal measures are taken. Vulnerability and exposure mitigation relates to moving contents and people, as is done by the safety region ('veiligheidsregio') in case of a crisis situation. This study focuses on the deployment of temporal measures for dike stretches that do not meet the new norms.

Deployment of these temporal measures will decrease the failure probability but deployment of measures will also bring costs. The investment costs consist of yearly costs and deployment costs. The yearly costs are costs for storage and agreements with contractors. The deployment costs are the costs when the measures are actually deployed, this will not be every year but once every several years. The investment costs are calculated by Equation 15 and 16.

$$Investment_{deploy} = Probability_{deployment} \times \sum_{n=1}^{p} Investment_{measure_n} \tag{15}$$

$$Investment_{NPV} = \sum_{n=1}^{p} \frac{(Investment_{deploy} + Investment_{yearly})}{(1+r)^n} \tag{16}$$

When measures are deployed, the total costs per year for a dike ring or water system is the summation of the expected damage in Equation 14 and the investment costs in Equation 16.

$$Costs_{NPV} = Damage_{NPV} + Investment_{NPV} \tag{17}$$

For the total costs there is a point at which the summation of the damage and the investment is minimal. If more measures are taken, the investments are higher than the reduction in damage. And if less measures are taken, the expected damage becomes greater than the reduction in investment costs. This balance between the expected damage and the investment costs is presented in Figure 20. The above described econometric theory is partly derived from Kind (2011), who applied it on dike reinforcements.

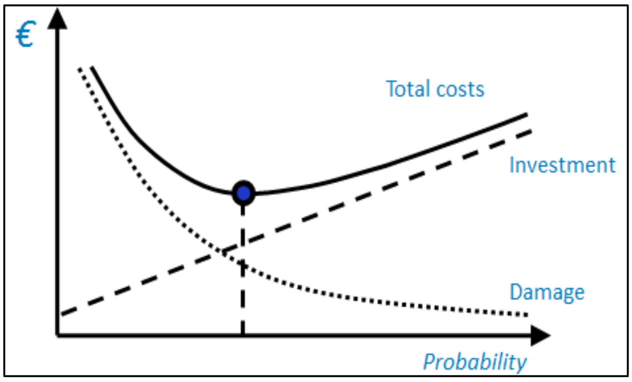


Figure 20 Economic model for temporal measures

5.2 Econometric model

The econometric model described in section 5.1 is made applicable to temporal measures with the use of a model that calculates the total costs for the measures chosen by the user. The model is divided into five activities; inputs, output, processes, controls and mechanisms. A schematization of the model is presented in Figure 21.

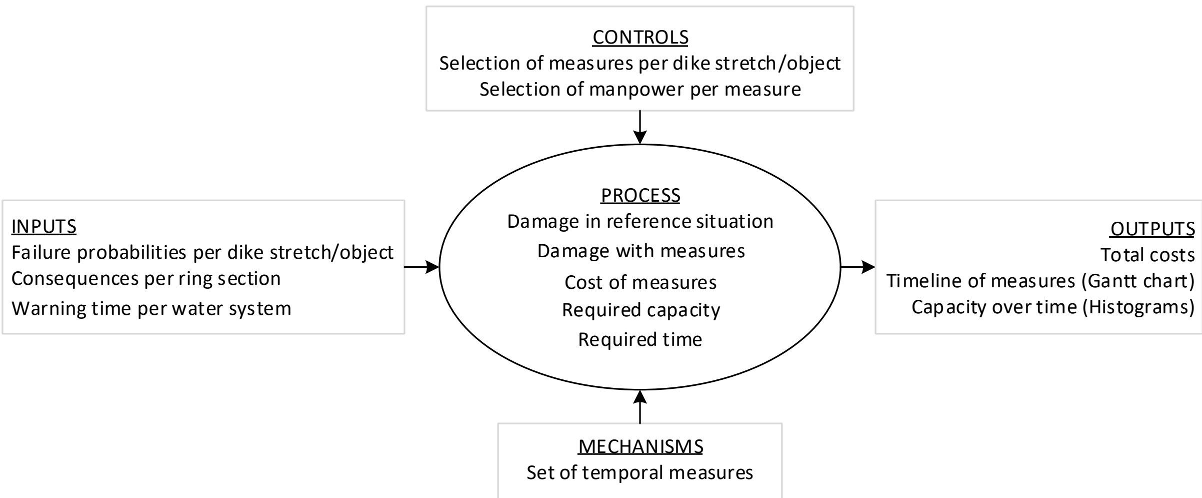


Figure 21 Schematization of econometric model for temporal measures

Inputs

One of the inputs is the failure probabilities for each dike stretch and object. In Dutch practice the failure probabilities are often derived by the use of the software PC-ring (Steenbergen et al., 2008). Input for this software are the dike characteristics and the failure schematisations for the relevant failure mechanisms.

Second, it is required to know the consequences when flooding occurs. The consequences of floods are derived by making use of flood simulations, damage modules, social cost-benefit analysis, and causality analysis. The flood simulations form the basis of calculations for the damages and casualties, which are by the model HIS-SSM. The consequences are mostly given in economic damage and casualties per ring section.

Furthermore, it is necessary to know the warning time for the water system, because this determines how much time there is for the deployment. Less time means that possibly more manpower and equipment should be employed.

Mechanisms

Mechanisms are the resources and tools that are required to complete the process. The mechanism for the model is the set of temporal measures with all their characteristics. These characteristics consist of the required capacity (material, equipment, manpower) and cost per 100 m for each measure. In addition, each measure has a reduction factor which is used to determine the reduction in failure probability when the measure is deployed. This mechanism is described in more detail in the section 5.3.

Controls

Controls are a form of input, but are used to direct the activity in the process. In this case the process is directed by the selection of the temporal measures and the amount of manpower allocated to those measures. The measures and manpower are selected per dike stretch.

Process

By the selection of measures (controls) the model calculates the expected damage and the investment costs. Firstly, the failure probabilities (input) are reduced for the dike stretches for which measures are selected. This reduction of failure probability depends on the selected measure, because each measure has a different reduction factor. The reduced failure probabilities of the dikes stretches are multiplied with the consequences (input), which remain unchanged. This gives a risk for each dike stretch. The sum of these risks give the total risk, i.e. the total expected damage.

The investments costs are shaped by the costs of the total required material, equipment, and man hours. The costs are determined by allocating a unit price to the different types of material, equipment and man hours. The secondary activities, like filling sandbags and transport, are included within the measures. Also the deposition costs for each measure are included in the cost calculation.

Output

The total costs are derived by the summation of the expected damage and the investment costs. The calculation of the total costs for a selected set of measures is the main output. This output is a single dot on the line of total costs in Figure 20. In addition, a Gantt chart is produced which shows the timeline of the deployment of the measures. This is done with information regarding the length of the measure, the construction speeds, and the amount of manpower. Also histograms are produced which show the required capacity over time. For example, this gives the amount of manpower per hour and the required amount of sandbags per hour.

5.3 Set of temporal measures

The total costs and the required capacity depend on the amount of measures that are selected, but they also depend on the type of measure. The measures differ in requirements and their efficiency in reducing the failure probability.

Type of temporal measures

The water board Groot-Salland, one of the water boards that merged into WDO Delta, developed the so-called 'Hoogwaterklapper' which contains information about multiple temporal measures for different failure mechanisms. The defined measures are shown in Table 16. The measures that are crossed out do not contain any further characteristics and therefore are not usable in the model.

Table 16 Type of temporal measures

Type of measure	Code	Description
Overflow and overtopping dike (HT)	HT.1.1	Sandbags 15 cm height
	HT.1.2	Sandbags 30 cm height
	HT.1.3	Sandbags 45 cm height
	HT.1.4	Sandbags 60 cm height
	HT.1.5	Sandbags 75 cm height
	HT.2	Erosion
	HT.3	Big bags
	HT.4	Straw bales
	HT.5	Emergency structure
	HT.6	Ground covering with foil/film
Piping and Heave (STPH)	STPH.1.1	Embankment (favourable conditions)
	STPH.1.2	Embankment (unfavourable conditions)
	STPH.2.1	Increase water level in ditch with weir
	STPH.2.2	Increase water level in ditch with sand bags
	STPH.3	Containment of wells
	STPH.4	Sheeting and covering with ground
	STPH.5	Apply clay (against underflow)
Macro stability inner slope (STBI)	~~STBI.1~~	~~Shutdown traffic~~
	STBI.2.1	Embankment (favourable conditions)
	STBI.2.2	Embankment (unfavourable conditions)
	~~STBI.3~~	~~Increase drainage~~
	~~STBI.4~~	~~Slope fading~~
	STBI.5.1	Apply extra weight (water container)
	STBI.5.2	Apply extra weight (big bags)
Macro stability outer slope (STBU)	~~STBU.1~~	~~Slope fading~~
	~~STBU.2~~	~~Shutdown traffic~~
	STBU.3.1	Apply extra weight (water container)
	STBU.3.2	Apply extra weight (big bags)
	STBU.4.1	Embankment (favourable conditions)
	STBU.4.2	Embankment (unfavourable conditions)
	STBU.5	Strengthening under water toe
Micro stability (STMI)	~~STMI.1~~	~~Slope fading by opening~~
	~~STMI.2~~	~~Drain (with sand)~~
	~~STMI.3~~	~~Slope fading by applying sand~~
	~~STMI.4~~	~~Apply extra weight~~
	~~STMI.5~~	~~Drain and apply filter layer~~
Stability dike revetment (STBK)	STBK.1	Apply geotextile and sand bags (bekramming)
	~~STBK.2~~	~~Overseeding~~
	~~STBK.3~~	~~Additional fertilizing~~
	~~STBK.4~~	~~Inject mold~~
	STBK.5	Apply extra geotextile and sand bags (2nd)
Stability fore shore (STVL)	~~STVL.1~~	~~Extra deposition~~
	~~STVL.2~~	~~Shallowing fore shore~~
Stability construction ground (STCG)	~~STCG.1~~	~~Shutdown traffic~~
	~~STCG.2~~	~~Embankment~~
	~~STCG.3~~	~~Drain~~
	~~STCG.4~~	~~Slope fading~~
	~~STCG.5~~	~~Apply extra weight~~
Stability construction object (STCO)	~~STCO.1~~	~~Increase water level in ditch~~
	~~STCO.2~~	~~Dam front side~~

Measure requirements

The amount of material, equipment, manpower is determined per 100 m for each measure. In addition, the construction speed and the costs are given per 100 m. An overview of the type of requirements is shown in the Table 17.

Table 17 Characteristics of measures

Category	**Type**	**Unit (/100 m)**
Material	Sand bags	#
	Big bags	#
	Straw bales	#
	Sand	m3
	Geotextile	m2
	Foil (landbouwfolie)	m
	Canvas (zeil)	m2
	Pens	#
	Steel wire	m
Equipment	Shovel	#
	Truck	#
	Tractor	#
	Tipper (kieper)	#
	Dock leveller (rijplaat)	#
	Pump	#
	Water container	#
Other	Minimal manpower	#
	Construction speed	man hours
	Costs*	euro/100 m

**for some measures the costs are expressed in euro/times of occurrence, instead of euro/100m.*

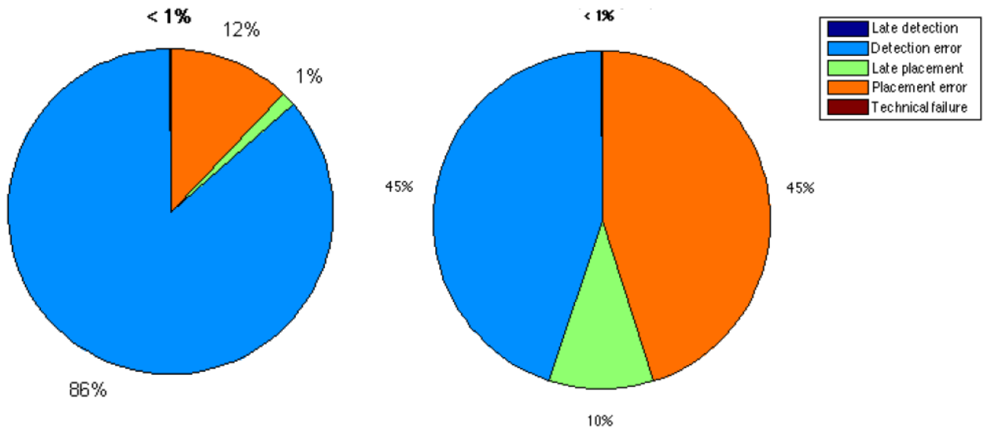
Failure probability reduction

As stated previously the risk is shaped by the multiplication of probability and consequences. The effect of a measure is that the dike is strengthened and the failure probability decreases. In its turn this results in a lower risk, i.e. a lower expected damage.

To determine the decrease in failure probability it is necessary to quantify the failure reduction. A study by Lendering (2014) and Van Dijk & Van der Plicht (2013) assessed the effectiveness and reliability of control measures for flood prevention. In these studies, dike ring 53 Salland was used as case study. The reduction in failure probability was assessed by implementing the measures in PC-ring. It was concluded that overtopping measures reduced the failure probability by a factor between 2 to 15, on the level of dike stretches. For piping measures, the reduction was between 5 and 50. The factor mainly depends on the increase in height by the measure (sand bags 15 cm or 30 cm), but also differ between dike stretches.

Furthermore, the study by Lendering (2014) showed that detection of weak spots is the most important factor for the successful deployment of measures. Also, technical failure is almost never the cause for dike failure, which means that a correct implementation of the measure will almost always have the desired effect. These findings are presented in the Pie charts in Figure 22. As a result of possibility of not detecting, the reduction in failure probability decreases. The reduction factor for overtopping measures becomes 2 to 6, and for piping measures a factor 1.2 to 2.7. A major part of these findings were done during the large-scale exercise 'Conecto' in 2013 (Lendering, 2014).

In the case of the temporal measures the weak dike locations are known, and detection does not play a role. Therefore, the theoretical derived reduction factors can be used directly, without the decrease due to detection errors.



Piping Overtopping and overflow

Figure 22 Reliability of control measures, source: (Lendering, 2014)

5.4 Optimal capacity for Drents Overijsselse Delta

The coincidence analysis of extreme water levels in Chapter 4 showed that it is most likely that extreme water levels do not occur in two or three systems at the same time. Therefore, the choice is made to perform a single cost-benefit analysis for each of the three systems.

Input

The input for the failure probabilities and the consequences are derived from the VNK2 studies for dike ring 9 Vollenhove, 10 Mastenbroek, 11 IJsseldelta, and 53 Salland (Van Dijk & Van der Plicht, 2013; Havinga, 2014; Van Dijk et al., 2014; Van Dijk & Van der Plicht, 2013). Within these studies the failure probabilities are given for each dike stretch, and the consequences per ring section. Hereby the failure probabilities are determined by three type of failure mechanisms: overflow and overtopping, inner and outer stability, and heave and piping. The failure probabilities and consequences for each dike ring are presented in *Appendix F*.

Controls

The selection of temporal measures is based on the 'Hoogwaterklapper' by Van der Nat (2012). In this study they presented measures for multiple dike stretches along the IJssel, Vecht, and Zwarte Meer. They also allocated the amount of manpower. Where possible, the temporal measures are taken from the 'Hoogwaterklapper', but in some cases the measures allocated to the dike stretches are not suitable for the failure mechanisms specified in the VNK studies. In those cases, the measures of HT.1 Sandbags 30cm and STPH1.2 Embankment are selected as standard measures for the failure mechanisms overflow & overtopping and piping & heave, respectively.

Process

In order to derive the optimum investment costs a cumulative process is implemented. This means that measures are selected one by one. The measure for the dike stretch with the highest risk reduction is selected first, and then the next. This results in multiple sets of measures with each their own expected damage and investment costs.

Important for the investment costs are the yearly costs and the probability of deployment. The yearly costs are costs for storage and agreements with contractors. The yearly costs are assumed to be 20% of the deployment costs. This is assumption is based on the current magnitude of the costs which is approximately 10,000 euro/year for the IJssel-Vecht delta. The probability of deployment is derived from the emergency plan for high outer waters. For each phase in the emergency plan a corresponding water level is selected for multiple locations. The temporal measures should be deployed in phase 1. According to the emergency plan the water level in phase 1 for the IJssel at location Deventer is 6.80 +mNAP. The distribution functions derived for the IJssel in Chapter 4 states that this corresponds to a deployment of 1/18 years. For the Vecht at location Vechterweerd the water level is 1.80 +mNAP, which corresponds to a deployment once in two (1/2) years. For the Zwarte Meer a storm surge takes place at a wind speed around 60 km/h (8 Beaufort), this is equal to 1/3 years. The NPV is calculated for a period of 30 years, this period represents the period from 2020 to 2050, with a discount rate of 3.0% (Rijksoverheid, 2015). The year 2020 is when the preparations start and it is possible to deploy the measures, and 2050 is the year in which the dike reinforcement should be finished.

Output

The results for the different set of measures are showed as circle points in Figures 23, 24 and 25. The x-axis shows the decrease in failure probabilities and the y-axis shows the costs in NPV. These calculated points are used to derive a relation for both the economic damage as the investment costs. The economic damage is presented by a power function, and the investment costs by a linear function. The total cost is the sum of these functions. By extending the functions over the x-axis it is possible to derive the minimum total costs, which are presented in Table 18.

IJssel

For the IJssel the minimum total costs are reached at a total cost with a NPV of 100 million euro, whereby the failure probability is reduced up to 1/275 years by the deployment of temporal measures. The investment costs have a NPV value of 56 million euro and the expected damage has an NPV of 44 million euro. To give an indication of the magnitude of the measures, the required amount of sandbags would be about 1.9 million, the amount of sand 1.8 million m3, and the maximum amount of manpower approximately 1570 men.

The above mentioned required amount of capacity is very high. They show that investing in temporal measures to increase the water safety is worth doing until it practically is not possible anymore. This is caused by the fact that the consequences are much higher than the investments.

Vecht

For the Vecht the minimum total costs are reached at a NPV of 105 million euro, whereby the failure probability is reduced up to 1/59 years. Hereby the investment costs are 51 million euro and the expected damage is 54 million euro. A total amount of 87,000 sandbags, 190,000 m3 sand and 105 men are required to deploy the measures.

The capacity requirement for the Vecht are more realistic than those for the IJssel. This is confirmed by the fact that when the total set of temporal measures are deployed the investment costs almost approaches the optimum investments that should be made. For the IJssel this is far from the case, the data is extremely extrapolated before the optimum is reached.

Zwarte Meer

For the area along Zwarte Meer the minimal total costs are reached at a NPV of 4.4 million euro, whereby the failure probability is reduced up to 1/469 years. The investment costs are 0.7 million euro and the expected damage is 3.7 million euro. A total amount of 7,000 sandbags, 3,600 m3 sand and 6 men are required to deploy the measures.

The minimum total cost is reached very soon after the reference situation, because the failure probability is already low and the economic damage in the area is also relatively low. Only a few measures are required to reach the optimum.

Table 18 Optimum capacity characteristics for IJssel, Vecht and Zwarte Meer

System	**Failure probability** *1/T*	**Economic damage** *NPV mill.euro*	**Investment costs** *NPV mill.euro*	**Total costs** *NPV mill.euro*	**Sandbags** *amount*	**Sand** *m3*	**Manpower** *amount*
IJssel	275	43.9	56.2	100.1	1,900,000	1,800,000	1570
Vecht	59	53.5	51.3	104.8	87,000	190,000	105
Lake	469	3.7	0.7	4.4	7,000	3,600	6

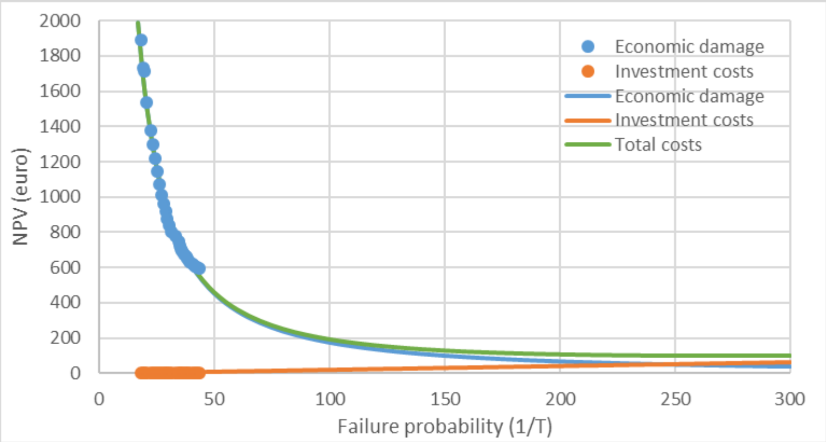


Figure 23 Cost-benefit relations IJssel

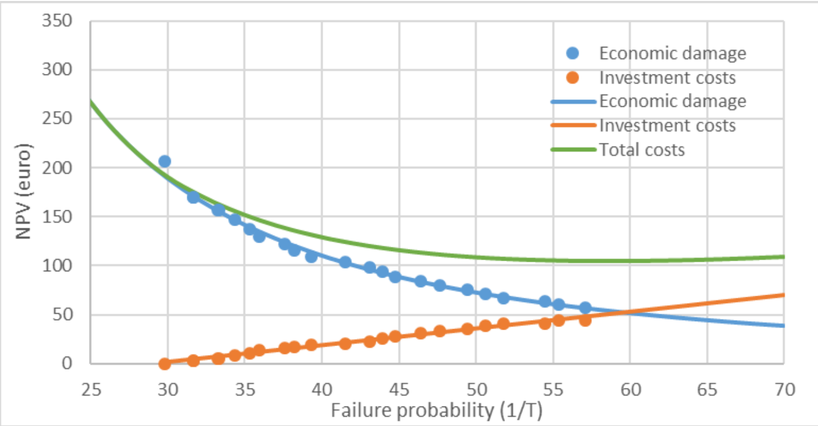


Figure 24 Cost-benefit relations Vecht

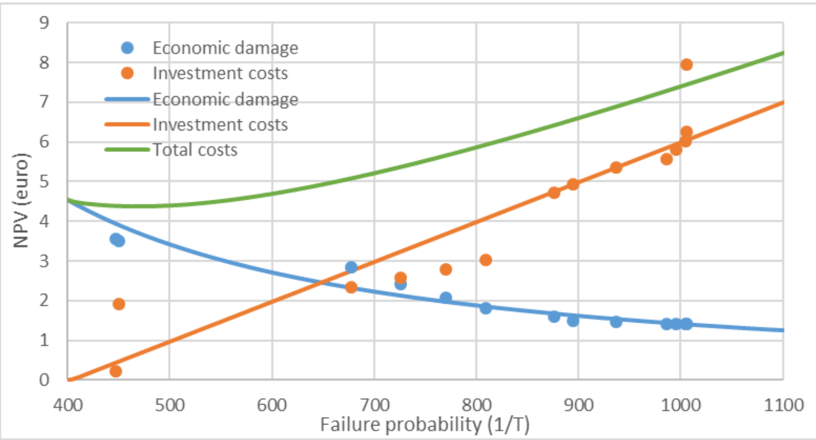


Figure 25 Cost-benefit relations Zwarte Meer

5.5 Sensitivity analysis

The results of the cost-benefit analysis are effected by multiple variables, i.e. the optimum point of minimal total costs is sensitive for these variables. To assess the sensitivity of the results the cost-benefit analysis for the Vecht is used as a basis, because for the Vecht the deployment of all pre-set measures approaches the optimum point for the Vecht. The sensitivity of the total costs is derived for multiple variables, and the effects on the optimum point are derived for the probability of deployment and the reduction factor, as will be motivated below.

<u>Sensitivity of total costs</u>

To assess this sensitivity, the effects on the total costs are assessed for the following variables: the failure probability per dike stretch, damage per ring section, probability of deployment, reduction factors for the measures, discount rate of the net present value (NPV), and the percentage allocated to the yearly costs. Each of the variables is varied with -25%, -10%, 10% and 25%. The results are shown in Figure 26.

The total costs are most sensitive to the failure probabilities of the dike stretches and the damage per ring section. These variables are determined by extensive studies of the national authorities using multiple type of models. Therefore, these variables are approached of having low uncertainty and are not further elaborated.

Logically, the discount rate of the NPV also has a high influence on the total costs, which are expressed in NPV. A higher discount rate that the money in the present is worth even more than the same amount in the future, therefore the NPV decreases.

Further the total costs are rather sensitive to the probability of deployment. The probability of deployment determines how often the measures should be deployed, and clearly that influences the total costs. When measures are more often deployed, the investment costs increase, as shown in Figure 27. The economic damage is not effected by the probability of deployment.

The effect of the reduction factor on the total costs is smaller than the probability of deployment, but still the total costs is quite sensitive to this variable. When the reduction factor increases, the total costs decreases. The measures have more effect which means that the failure probability and therefore the economic damage decrease. The change in economic damage is shown in Figure 28.

Furthermore, the total costs seem to be less sensitive to the percentage that is allocated to the yearly costs. It does influence the total costs, but to a much smaller extent than the other variables.

The sensitivity of the results to the probability of deployment and reduction factor for the measures are explored in more detail in the next section, because they show to effect the total costs and are assumed to be more uncertain than the failure probabilities per dike stretch and the economic damage per ring section.

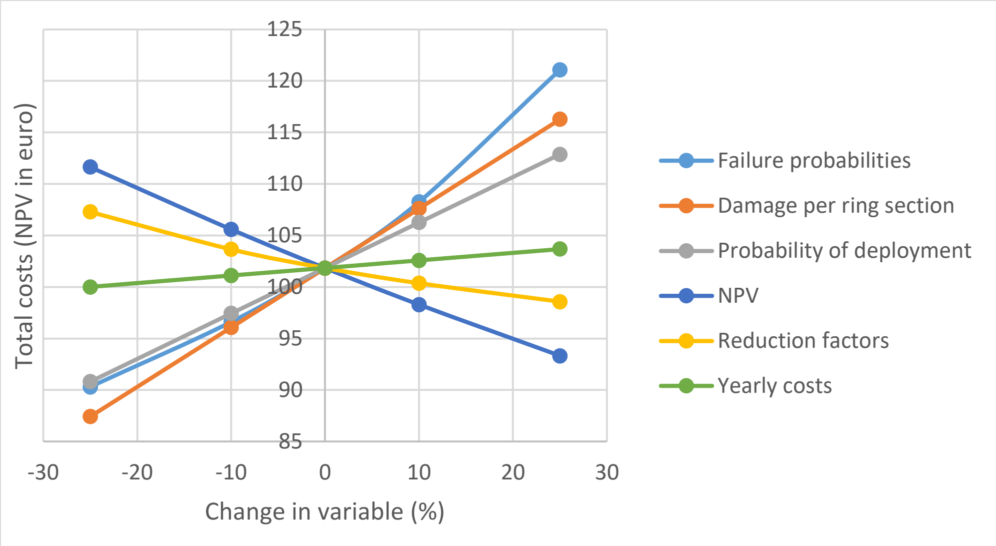


Figure 26 Sensitivity diagram for the total costs

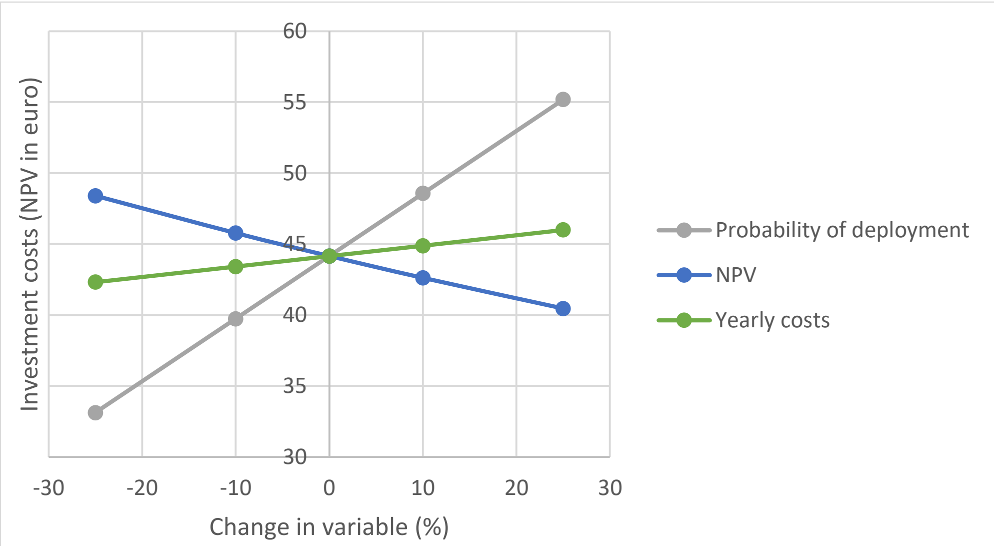


Figure 27 Sensitivity diagram for the investment costs

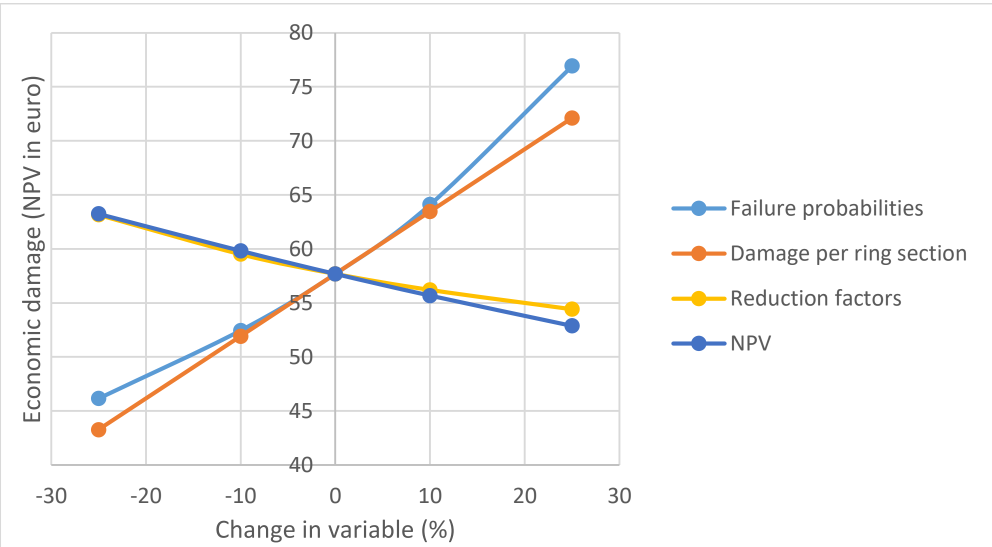


Figure 28 Sensitivity diagram for the economic damage

Sensitivity optimum for the probability of deployment

In the cost-benefit analysis the probability of deployment is derived from the emergency plan, whereby deployment is considered to take place when the water levels corresponding to phase 1 are estimated to occur. For the Vecht this corresponds with a probability of 1/1.9 year. However, it is possible that deployment will take place more or less often. To assess the effects on the final results the minimal total costs for five different deployment probabilities are calculated for the Vecht, namely once every year, 1.9 years (reference situation), 5 years, 10 years, and 20 years.

The results, in Figure 29, show that a lower probability of deployment gives less total costs. This means, for example, that when the measures are deployed once per 20 years, the total costs are lower than when the measures are deployed once per year. This seems logical, but an interesting point is that while the NPV of costs decrease, the amount of measures increase. The sum of the deployment costs with a probability of deployment with 20 years is greater than the sum of one yearly deployment, but the costs are spread over more years. This illustrates that when measures are deployed less often (once every 20 years) it is wise to prepare the deployment of more measures.

This statement is backed up by the results for the sensitivity of the capacities. The optimum for once every 20 years requires more capacity, namely 296,000 sandbags instead of 53,000 sandbags, 667,000 m3 sand instead of 114,000 m3 sand, and 350 men instead of 65 men, with respect to the once in a year deployment.

When projected to the cost-benefit relations, this means that the line for the investment costs becomes flatter when the measures are deployed less often. This can be seen by comparing the cost-benefit relations for the deployment once every 1.9 year, the reference situation, and deployment every 20 years, which are shown in Figure 30 and Figure 31.

The conclusion can be made that the optimum is very sensitivity to the (chosen) probability of deployment. Therefore, it is important to clearly determine when or at which water level it is necessary to active the deployment of measures. Thereby the forecasting of the water levels is also of major importance.

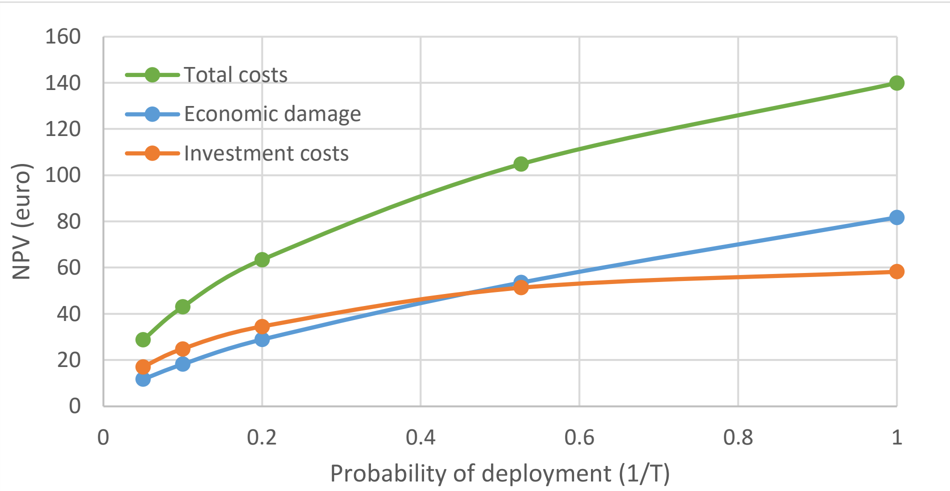


Figure 29 Sensitivity minimal total costs for probability of deployment

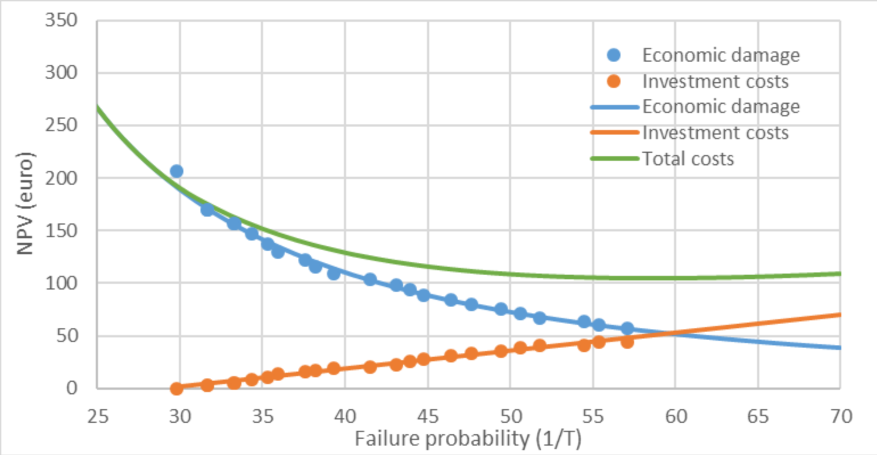


Figure 30 Cost-benefit relations for the Vecht with deployment every 1.9 years

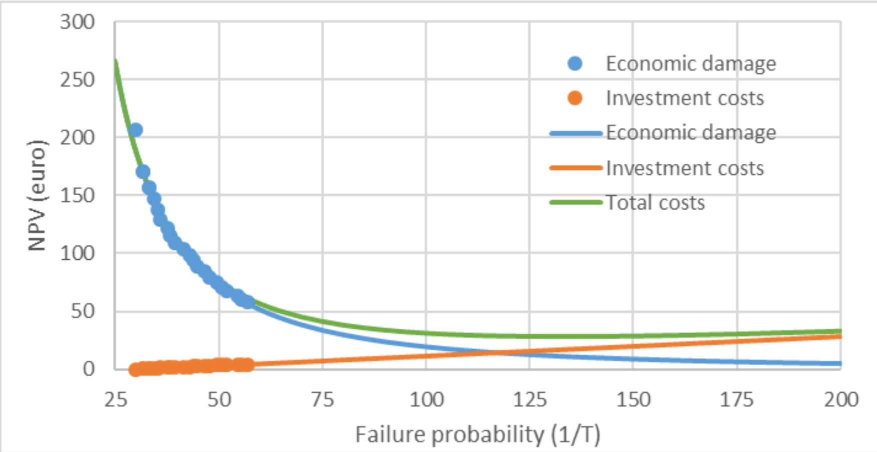


Figure 31 Cost-benefit relations for the Vecht with deployment every 20 years

Sensitivity optimum for the reduction factors

The reduction factor for the measures reduces the failure probability for the selected dike stretch, which results in a lower expected damage. Uncertainty occurs for the reduction factor because they are derived from another study for solely dike ring 53, namely Lendering (2014). Besides the used values are averages from multiple dike locations. In reality the reduction factor of a measure differs for each dike location. So a big assumption is taken in the performed cost-benefit analysis. The sensitivity of the optimum for the reduction factor is analysed to assess the effects of this assumption.

The results are given in Figure 32. They show that when the reduction factor decreases, the total minimal costs of the optimum increase. This means that when the measures are less effective than previously assumed, the total costs will be higher. The same occurs the other way around, when the measures are more effective, the total costs will be lower.

The minimal total costs vary because the investment cost and the economic damage change. The change in these costs becomes clearer when expressed in percentage, as in Figure 33. When the reduction factor decreases the investment costs also decreases, and vice versa. The economic damage shows the same behaviour, but the change in economic damage is larger than that of the investment costs. However, the change in investment costs and the capacity quantities are both relatively small.

In general, the NPV of the minimal total costs, i.e. optimum point, is sensitive for the reduction factor, but less than could be expected. The percentage change in the reduction factor is much higher than the percentage that occurs in the total costs. For example, a reduction factor change of -25% increases the total costs with 3.1%, and the investment costs with only 1.6%.

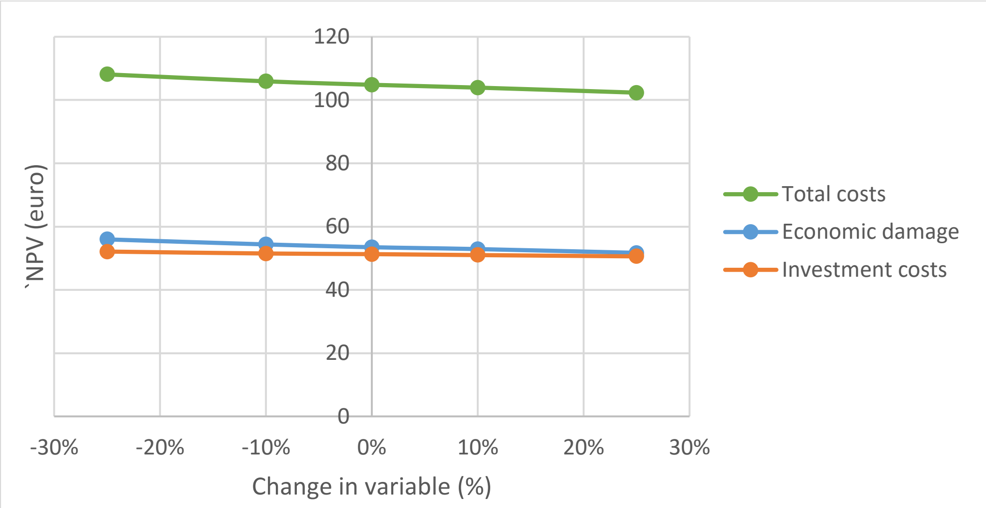


Figure 32 Sensitivity minimal total costs for the reduction factor of measures

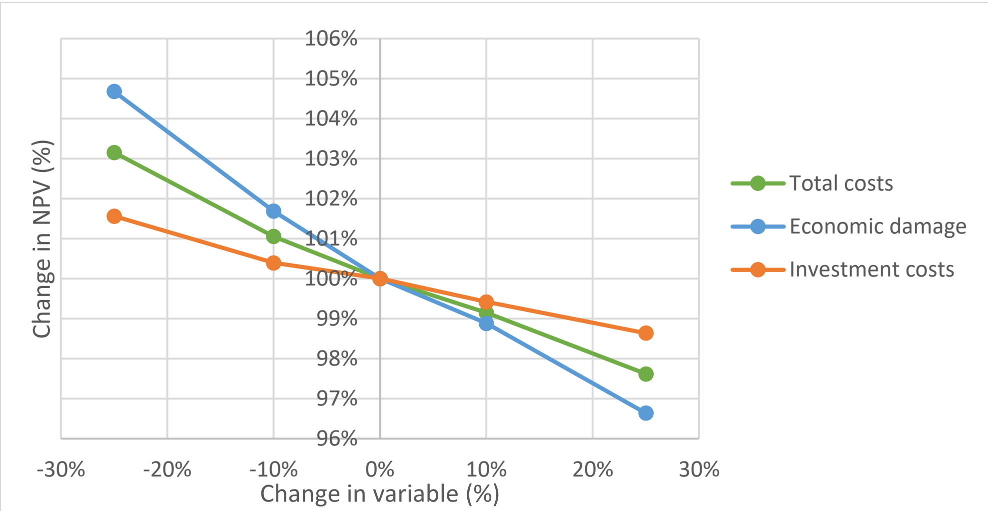


Figure 33 Sensitivity minimal total costs for the reduction factor of measures in percentages

6| Discussion

This research reaches its objective by answering the four research sub-questions regarding the study area, problem analysis, coincidence probabilities, and the cost-benefit analysis. Multiple assumptions and choices are made to answer these questions. These assumptions and choices are described in this chapter.

Problem analysis

Exclusion of water defence structure

The problem analysis firstly described the threats for the water safety. Hereby the focus was on the water systems and the dike stretches rather than on the water defence structures. The structure Ramspol, for example, plays an important role for the water safety during storm. When Ramspol fails the wave set-up at Ketelmeer is not blocked anymore and the failure probabilities for the dike stretches alongside the lake will definitely increase. The failure of structures is not included in this research because it is unclear what type of temporal measures can be taken for structures, and what the effects of these measures are.

When the structures are included the results for the cost-benefit will change. For example, there are multiple structures along the IJssel which have high failure probabilities and also high consequences. These structures are located near Deventer. Investing in measures for these structures will give a high reduction in risk, which means that the benefits will probably exceed the costs. In that case more investment should be made in the temporal measures to reach the minimal total costs.

Temporal control measures versus emergency measures

Another interesting issue is the overlap between the temporal control measures and the emergency measures during emergency situations. The starting point of this research was to only focuses on the temporal control measures for the dike locations that do not meet their norms, but these measures are exactly the same type as the measures for emergency situations. Nevertheless, the temporal measures and the emergency measures are seen as independent from each other by WDO Delta. In some situations, it can even be wiser to take measures for dike locations that do meet the norm but have a higher risk than insufficient locations with lower risks. The overlap between these situations is further confirmed within the cost-benefit analysis. Namely, in the cost-benefit analysis the measures are taken for the dike stretches with the highest risk reduction, the dike information about meeting the norms or not is completed abandoned.

Coincidence probabilities

Copula-based method and its interpretation

The coincidence probabilities between the three systems IJssel, Vecht and Zwarte Meer are determined with a copula-based assessment. Although this method is applied on several hydrological issues within other studies, the method is not very common and the researcher had no experience with it. This makes it hard to verify the performed steps and the results as almost no comparisons can be made. Also the interpretation of the results can possibly be improved when more guidance is available.

The issue of interpretation is reflected by the results for the fitting of copulas, which are not very straightforward. None of the three copula stand out when looking at the fitting results, while the choice of copula has major consequences for the final coincidence probabilities. This is illustrated in section 4.7 where the conditional probabilities for the Gumbel copula are much higher than those derived from the Frank copula.

Used data

Further, there used data is not ideal. For the storm surges the national wind data is used because the water levels and wind data within the study area are not available for long time spans. Although the verification of the daily and annual data between the national wind data and the water levels at Ramspol show a positive relation, it would be better to use the actual water levels or wind conditions in Zwarte Meer.

A similar issue is that for the data used for the IJssel and Vecht. The water levels are used for these systems because they have a long historical data set, but normally the discharges are used for data analysis instead of the water levels at a specific location because discharges are more reliable. For the discharge the water levels in a cross-section can vary over time due to change in the profile of the river. So when the water levels are used this means that change in water levels at the measured location do not necessarily give correct representations of the change in water levels downstream. This issue is not the case when discharges are used.

Cost-benefit analysis

The cost-benefit analysis is performed to provide more insight in the consequences and the possibilities of decreasing the consequences by deployment of temporal measures. To achieve this a few basic assumptions are made for the model, but there also are some greater issues which are discussed below.

Variable costs and benefits

The first issue arises by the fact that both the costs and the benefits are variable for the deployment of temporal measures. The costs are variable because there is a choice in type of measure. Each measure has different costs. But each measure also has different benefits; the failure reduction for one measure is greater than for the other. Besides, the failure reduction differs per dike location. In the model the choice is made for a pre-set failure reduction factor for each measure by the use of Lendering (2014). This resulted in a fixed reduction of the risk. Also the costs are pre-set for each measure in units of euro/100m with the information of WDO Delta. In reality the risk reduction and the costs are not fixed, but differ for each location. However, the sensitivity analysis showed that investment costs for the optimum point is not extremely sensitive to a change in failure reduction factors. Which means that the impact of this assumption is limited.

Probabilities of deployment values may differ

Another issue arises for the probability of deployment that is used to express the total deployment costs as yearly costs. The measures are deployed when a certain water level is estimated or occurs at an upstream location. The probability of this event is seen as the probability of deployment. In the model the probability of deployment is set per water system. However, as the dike location have different failure probabilities which occur at different water levels, each location also has an own moment at which the measure should be taken. This means that each location can have a different probability of deployment, i.e. some measures are more often deployed than others. In addition, the probabilities of deployment are currently derived from the water levels corresponding to phase 1 of the emergency plan. The actual water level wherefrom the measures are deployed can differ. Because the minimal total costs show to be very sensitive to change in the probability of deployment, the final outcome for the minimal total costs can differ a lot from the current results when other probabilities of deployment are used.

Infinite amount of measures can be deployed
Furthermore, the resulting cost-benefit relations for the systems can continue up to infinity. In other words, the lines for the expected damage and the investment costs can continue over the full range of the x-axis. This means that there is no limited reduction in failure probability. In reality there is a limit in reduction, at a certain moment it is simply not possible to take more measures. This limit might be logistic with respect to the amount of material and manpower, but it can also be spatial in the sense that at every location a temporal control measure is taken. However, it is unclear when this limit is reached and therefore it is not taken into account.

Measures assessed per dike stretch
Also the measures are assessed per dike stretch, but for consecutive dike stretches it could be relative easy and cheaper to implement the measure for multiple dike stretches as a single measure. In addition, the dike stretch approach makes it so that the model can only cope with singular dike breaches. Within a scenario approach it would be possible to derive the probability that multiple dike stretches fail during the same event. With the dike stretch approach this is not included in the values of the failure probability.

Dike reinforcements are not included
Dike reinforcement projects that are finished or will be finished are not included in the cost-benefit analysis. This means that the failure probability of the dike stretches remains the same over the full 30 years that are used for the NPV calculation. In reality there are dike stretches which are reinforced over the time, and as their failure probabilities decrease it would not be necessary to take measures at these dike stretches. When these dike reinforcements projects would be included in the cost-benefit analysis the total costs for the period of 30 years, from 2020-2050, would become lower.

Other types of measures
One of the smaller issues is the limited amount of type of measures available in the model. There are more types of measures that can be deployed but the capacity requirements for these measures are not quantified, so they are not usable in the model. By expanding the possible measures in the model a more comprehensive analysis can be performed.

Other
This study focused on the preparation for the deployment of temporal control measures. The time-phased forecasting and the execution of plans are not included. However, when focussing on preparation it is wise to think about how these preparations affect the execution, and vice versa.

Shared or separated stocks
For example, it might be necessary due to logistic limitations and response times to store the materials very near to the dikes. This would make it harder to create a shared stock which can be used for the deployment of measures for either one of the water systems. Equipment and manpower on the other hand are easier to share between the systems. When it is not possible to create a shared stock, this means that at least the materials should be prepared for each single system on its own. Which makes it more costly than when materials can be shared between the systems.

Appearances to inhabitants
Another aspect for the execution of temporal control measures is the appearance it gives to inhabitants. As mentioned before, the temporal control measures are of the same type as the emergency measures. When temporal control measures are deployed in an early stage, for the

inhabitants it might appear to be an emergency situation. Whereby in an emergency situation they would have been informed by the crisis organisation, this would not be the case now. To prevent panic it is needed to inform the inhabitants about the reason for the temporal control measures and their effects. Or to make it more simple it might be helpful to implement the deployment of temporal control measures in the earlier stages of the emergency plan. This brings us back to the discussion between the overlap between control measures and emergency measures. This issue should be further discussed within the organisation of the water board.

7| Conclusions

The problem for water board Drents Overijsselse Delta is that a temporal solution needs to be determined for several dike locations that currently do not meet the norms. This problem is caused by the fact that dikes are not reinforced instantly, but that the dike improvements are spread out over a timespan of several decades, up to 2050. The water board needs to take temporal control measures in order to fill this gap and protect their citizens. As the sources and expenses for the measures are not endless, it was necessary to provide more insight in the consequences and the logistics aspects that arise when measures are deployed. This gave the following objective.

> *Determining the optimal capacity for temporal control measures for dikes in case of extreme water levels by quantifying the coincidence probability of extreme water levels and performing a cost-benefit analyses.*

The objective is formulated into four sub-questions and a main research question, which are answered below.

1. *How does the water system in the IJssel-Vecht delta function?*

The first sub-question is answered in Chapter 2. The complex IJssel-Vecht delta is shaped by the convergence of the IJssel, Vecht and Zwarte Meer. These three systems are controlled by five main structures, whose functions are, simple put, to separate the water systems from each other. Further the IJssel-Vecht delta of WDO Delta is divided by the water systems into four dike rings, wherefrom dike ring 53 carries the greatest risk.

2. *What are the threats in the IJssel-Vecht delta and how are they currently dealt with?*

The second sub-question is answered in Chapter 3. The physical threats are caused by high discharges from the IJssel and Vecht, and by storm surges from the lake area. Multiple projects are (being) executed or planned in order to increase the water safety, but still a water safety policy with temporal measures is required to deal with extreme water levels until the projects are finished. While it is possible and required to define a clear protocol for the primary defences structures that do not meet their norm, there is no such protocol available.

3. *What are the coincidence probabilities of extreme water levels for the three water systems in the IJssel-Vecht delta?*

The third sub-question is answered with the use of a copula-based assessment in Chapter 4. The results showed that there is a significant correlation between the annual maximum water levels of the IJssel and Vecht, for both the occurrence dates and the magnitudes. The correlation between the IJssel and Vecht is also reflected in the bivariate and trivariate copulas, and therefore in the final coincidence probabilities.

Focusing on the IJssel and Vecht, the results show that the coincidence probability of high water level events is highest in the month January and February. This finding can be translated to logistic aspects by stating, for example, that during the summer months it is not necessary to have capacity ready for temporal control measures. The probability that in a single year the high water levels in the IJssel and Vecht occur in the same period of 5 days is at least a factor 14 to 19 higher than when independence is assumed. The exact value of the factor depends on the return periods of the water levels.

The coincidence probabilities are used to derive the conditional probabilities. The conditional probabilities show that, in general, the probability of simultaneous deployment of temporal control measures for both IJssel and Vecht is relatively low. For example, when it is assumed that temporal measures are deployed for the IJssel with a return period of 1000 years and for the Vecht with a return period of 100 years, the worst probability is that in one out of twelve times it necessary to deploy measures in both systems at the same time.

4. *What is the relation between risk reduction and investment costs for the deployment of temporal control measures in the IJssel-Vecht delta?*

The fourth sub-question is answered by the use of an econometric model based on a risk approach. The balance between risk reduction and investment costs is represented by a so-called optimum point. This the point at which the summation of the economic damage and the investment is minimal, i.e. the minimum total costs. If more measures are taken, the investments are higher than the reduction in damage. And if less measures are taken, the expected damage becomes greater than the reduction in investment costs.

For the IJssel the minimum total costs are reached at a total cost with a NPV of 100 million euro with investment costs with an NPV of 56 million euro, whereby the failure probability is reduced up to 1/275 years by the deployment of temporal measures. To give an indication of the magnitude of the measures, the required amount of sandbags would be about 1.9 million, the amount of sand 1.8 million m3, and the maximum amount of manpower approximately 1570 men. The high required capacity shows that investing in temporal measures to increase the water safety is worth doing until it practically is not possible anymore. This is caused by the fact that the consequences are much higher than the investments.

For the Vecht the minimum total costs are reached at a total cost with a NPV of 105 million euro with investment costs of 51 million euro, whereby the failure probability is reduced up to 1/59 years by the deployment of temporal measures. A total amount of 87,000 sandbags, 190,000 m3 sand and 105 men are required to deploy the measures. The capacity requirement for the Vecht are more realistic than those for the IJssel.

For Zwarte Meer the minimum total costs are reached at an NPV of 4.4 million euro with investment costs of 0.7 million euro, whereby the failure probability is reduced to 1/469 years by the deployment of temporal measures. A total amount of 7,000 sandbags, 3,600 m3 sand and 6 men are required to deploy the measures. The minimum total cost is reached very soon after the reference situation. Only a few measures are required to reach the optimum point, because the failure probability is already high and the economic damage in the area is relatively low.

When the above capacities are prepared for the three water systems the IJssel-Vecht delta is protected against threats in the most economic optimal way, at least according to the applied theory with all its assumptions. Because the total costs and optimum point showed to be very sensitive to the discount rate of the NPV and the probability of deployment.

❖ *What is the optimal capacity that should be reserved to balance the expenditures for temporal control measures and the flood damage due to extreme water levels in the IJssel-Vecht delta?*

The answer to the main question is shaped by the answers on the sub-questions. The IJssel-Vecht delta is shaped and threated by the three water systems the IJssel, Vecht and Zwarte Meer. Therefore, it is necessary to reserve capacity which can deal with these threats and reduce their flood damage.

The results from the coincidence probabilities showed that the probability of simultaneous deployment of temporal control measures for the IJssel and Vecht is low, and even lower for other combinations. This means that when capacity can be shared between the systems it is only necessary to prepare capacity for the water systems that requires the most capacity. However, as discussed in Chapter 6, logical limitations and response times might make it necessary to prepare the materials for each single system on its own.

The required materials and capacities for the system are presented in the answer on sub-question 4. When summing the indicative materials this means that a total of 1,994,000 sandbags and 1,993,600 m3 sand are required as capacity. These high amounts are caused by the results for the IJssel, which needs 1,900,000 sandbags and 1,800,000 m3 sand according to its optimum point. The total amount of men required for the whole area is determined by the requirement for the IJssel, namely 1570 men.

Focusing on the objective, the capacity for the temporal control measures for dikes is determined by deriving the coincidence probabilities of extreme water levels with a copula-based assessment and by performing a cost-benefit analyses on the three water systems IJssel, Vecht and Zwarte Meer. In other words, the objective is reached. Hereby the copula-based assessment provides insight into coincidence probabilities of multiple systems, which distinguishes itself by being helpful for the operational issues instead of the norms for dike reinforcements. In addition, the cost-benefit model provides the possibility to quantify the duty of care (‘zorgplicht’) of the water boards for a single system. The duty of care is a grey area in which the water boards carry the responsibility to do whatever is possible to increase the safety for their inhabitants.

8| Recommendations

Based on this research multiple recommendations are made.

Develop protocols for deployment of temporal control measures

The research showed that it is wise to take temporal control measures until a certain point is reached. Mainly for the IJssel this point will not be reached soon, which means that the water board cannot start soon enough with developing protocols for dike locations with high risk along the IJssel. This process should start with prioritization; which location have the highest risk? When deciding for which dike locations a protocol will be developed it is needed to include the planning for dike reinforcement projects in the decision-making. After the prioritization of locations, it should be assessed which measure is most suitable and effective for that specific location.

It is advised to write protocols in series for each separate location, starting with the dike locations with the highest priority. To increase the water safety as soon as possible the protocols can be developed one after the other, but of course when a new protocol is developed it should be tuned with the others.

Determine the position of temporal control measures in the organisation

The protocols for the deployment of temporal control measures are needed to increase the safety of the dikes that are currently insufficient and which will be reinforced in the coming decades. For a successful performance of the deployment and to justify the deployment it is necessary to implement the protocols rightfully in the organisation. It should be determined where in the organisation the temporal control measures are implemented. They can be added to the early stages of the emergency plan, but they can also be regarded as completely independent. In both cases they have effect on the decisions and actions that are taken emergency situations.

Other methods for coincidence probabilities

A wide literature study resulted in the choice for a copula-based assessment to derive the coincidence probabilities for the simultaneous occurrence of extreme water levels in the study area. Although the copula method is used in other hydrological studies it is not very common which makes it hard to verify and interpret the results in the correct way. It may be likely that there are other (statistical) methods to derive the probability of simultaneous occurrence of extreme water levels. For example, the copula-based assessment uses historical data, but maybe a Monte Carlo simulation with the use of a model like SOBEK would also be an option. It is recommended to search for alternative methods in the field of data analysis.

Cost-benefit model improvements

Although the econometric model for the cost-benefit analysis is helpful in its current state it contains multiple assumptions. If used for further analysis, it is recommended to improve some of these assumptions.

Currently the measures are deployed per water system when a water level fitting to the first emergency phase occurs at a certain upstream location. The actual water level wherefrom the measures are deployed can differ. Because the minimal total costs show to be very sensitive to change in the probability of deployment, the final outcome for the minimal total costs can differ a lot from the current results when other probabilities of deployment are used.

Within the cost-benefit model the current state of the dikes is used. Aspects that changes over time like the dike reinforcement projects, ground settlement and economic growth are not included. As these aspects can have a high influence on the results it would be wise to include them. For example, when it is known that several dike locations are reinforced in several years, it would be illogical to reserve capacity for these locations for the coming eighteen years fitting to the current failure probabilities. The same accounts when an industrial area is being developed. This increases the consequences and calculating with the current state will result in an underestimation of required capacity.

Further, in the model a limited amount of type of measures is available. The cost-benefit model can be improved by quantifying the capacity requirement for more measures. By expanding the possible measures in the model, the measures can be compared and a more comprehensive analysis can be performed. Hereby it is also required to quantify the reduction factors for reduction in failure probability.

Insights over values

Lastly, it should be mentioned that a cost-benefit analysis should not be seen as the only deciding force. The advantages are that it gives an indication of the magnitudes of the challenge that lays ahead for the deployment of temporal control measures, but apart from the assumptions it contains, a cost-benefit analysis is always incomplete and the results have a wide margin. Besides some effects like the image towards the inhabitants cannot be expressed. So it is recommended to not cling to much to the values that are presented in this research, but pay attention to insights it presents.

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Appendix A: Projects flood protection

The projects for the IJssel are part of the Room for the River Programme. The goal of this programme is to give the river more room to be able to manage higher water levels. At more than 30 locations in The Netherlands, measures are taken to give the river space to flood safely. Moreover, the measures are designed in such a way that they improve the quality of the immediate surroundings. The Room for the River programme will be completed by approximately 2016. An overview of the projects along the IJssel is given in Figure A-1. (Rijkswaterstaat, 2016)

Also for the Vecht and the Zwarte Meer projects are going to be or are already performed. An overview of the planning and locations of these projects are presented in Figure A-2 and Figure A-3.

Figure A- 1 Room for the River projects

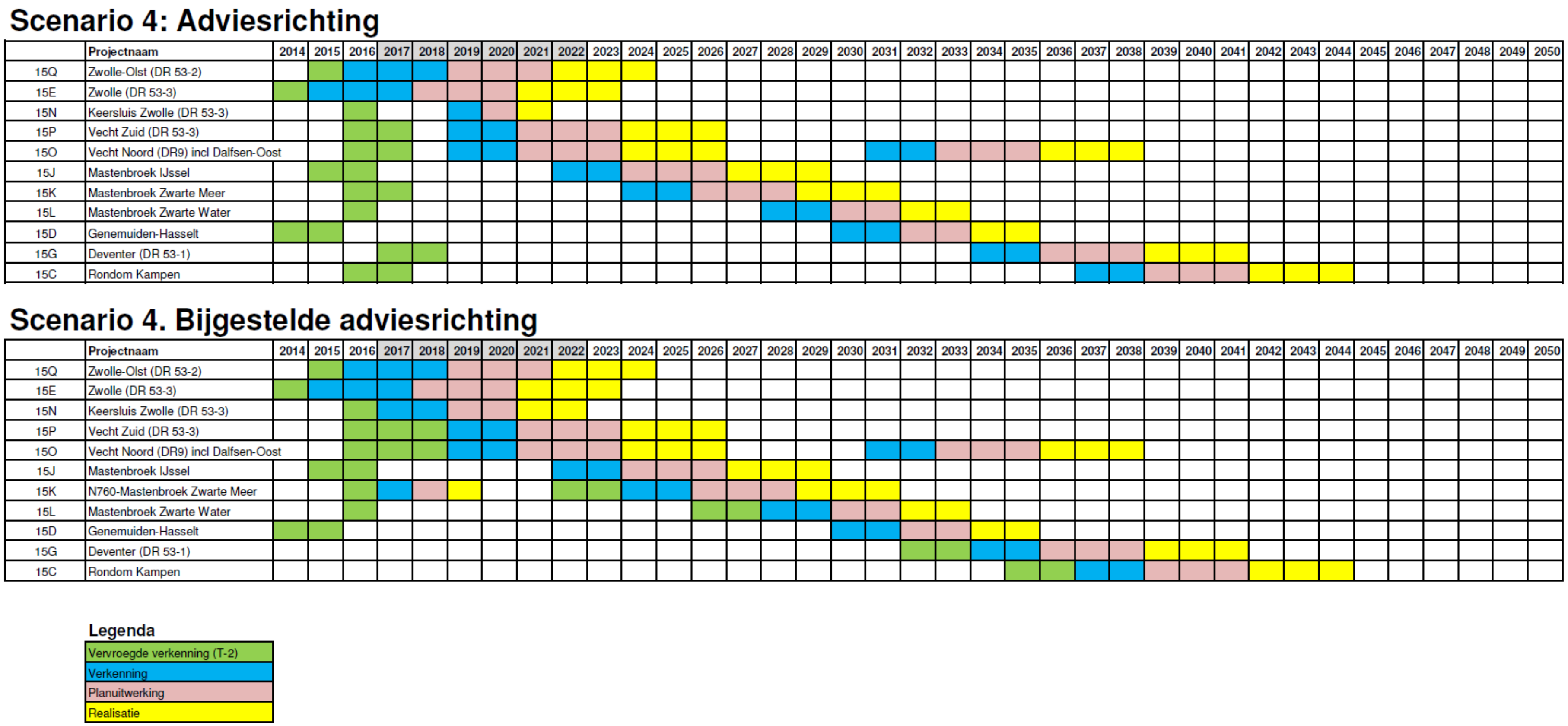

Figure A- 2 Planning projects

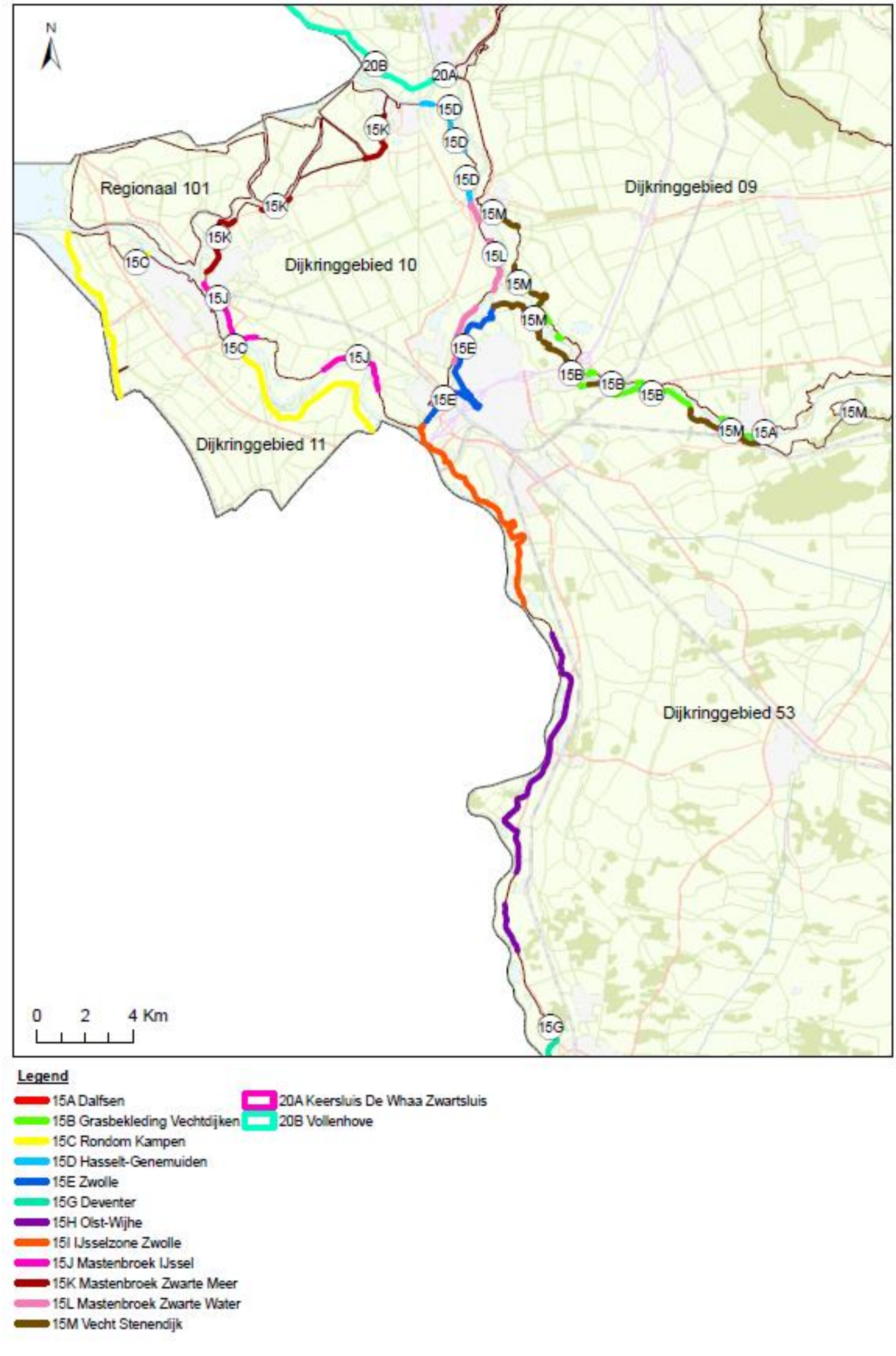

Figure A- 3 Location of projects

Appendix B: Emergency plan summary

The water board distinguishes four emergency plans; water surplus and shortage, high outer waters, technical failure of purification works, and water quality. The first plan regards issues due to water in the polder itself and the second plan regards issues caused by the waters outside the dike ring. The focus is on the latter. High outside water levels are caused by high river discharges, storm surges, or combinations of the two. Another reason is obstruction of flow, for example by ice formation. The emergency plan for high outer waters is summarized in this appendix.

Organisation

The organisation for emergencies is divided into four parties, as presented in the Figure 34. The field staff ('veldmedewerkers') take care of the actual deployment of the measures. The 'Waterschap Actieteam ('WAT') is responsible for the source control. It develops scenarios, determines the response measures, and coordinates the deployment of measures.

The 'Waterschap Operationeel Team ('WOT') is responsible for the effect control. The WOT develops control tactics based on the available information, scenarios, and resources. By doing this the WOT is the link between WAT and 'Waterschaps Beleidsteam ('WBT'). In addition, the WOT communicates with the external parties.

The WBT is responsible for the overall performance of the emergency organisation. It is concerned with the policy and political factors of the emergency plan and therefore determines the strategy for the performance of the water board. Also the WBT is responsible for the regional administrative coordination, and the coordination with the water operators and other governmental authorities.

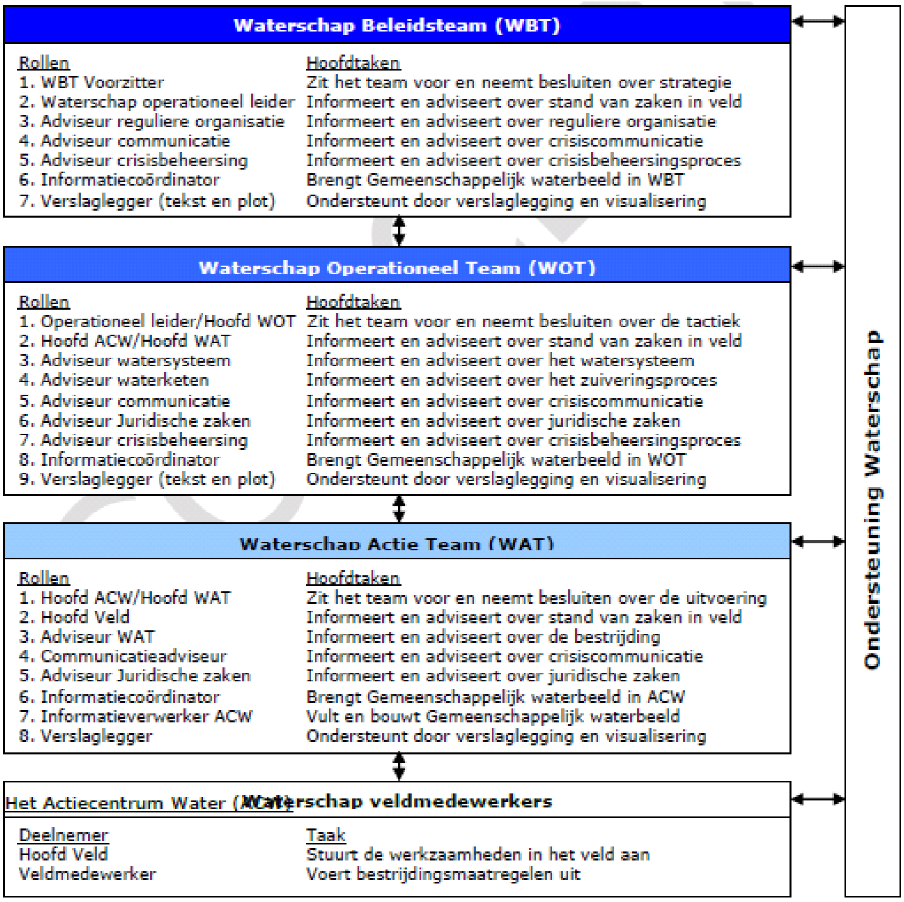

Figure B- 1 Emergency organisation, source: (WDO Delta, 2015)

Phases

The emergency plan is divided into four phases. These phases are based on the need for coordination. This need is dependent on the level of threat, the amount of administrative involvement, the financial consequences, and the required communication to media and inhabitants. Table 19 shows these phases, in addition it shows which parties are involved, the threat level, administrative involvement, and the trigger for up scaling to the next phase.

The phases of the emergency organisation of the water board correspond to the 'Gecoordineerde Regionale Incidentbestrijding Procedure (GRIP)' of the safety region IJsselland. GRIP is used to determine the regional coordination and upscaling levels for the emergency services. More information about the safety regions is found in the next part. Furthermore, Appendix B: 'Emergency plan phases –water levels' shows the water levels at multiple locations that correspond to the phases.

Table B- 1 Phases emergency plan, source: (WDO Delta, 2015)

Fase	Actieve teams	Dreigingsniveau	Bestuurlijke betrokkenheid	GRIP	Trigger opschaling GRIP
Regulier	Reguliere bedrijfsvoering (wachtdienst)	incident af te handelen binnen de dagelijkse routine	- Geen	*0*	*Motorkapoverleg*
1	WAT ACW	calamiteit met beperkte impact op de omgeving	- Voorzitter OT wordt geïnformeerd - Voorzitter BT wordt geïnformeerd	*1*	*Bronbestrijding, zeer beperkte effecten*
2	WAT+ WOT ACW	calamiteit met grote impact op de omgeving	- Voorzitter BT wordt geïnformeerd	*2*	*Bron- en effectbestrijding, grote effecten*
3	WAT+ WOT+ WBT ACW	calamiteit met zeer grote impact en bedreigend voor mens en milieu	- Lokaal bestuurlijke dillema's	*3*	*Grote impact op bevolking, veel aandacht politiek/ bestuurlijk/ media*
4	WAT+ WOT+ WBT ACW	calamiteit is gebiedsgrens overschrijdend	- Regionaal bestuurlijke dillema's	*4* *5* *Rijk*	*Gemeentegrens-overschrijdende effecten eventuele schaarste* *Bovenregionaal (meerdere veiligheidsregio's)* *Nationaal incident*

After the emergency situation has passed there are some aspect that need to be dealt with. One of these is the recovery of the damage to the flood defences and the water treatment plants. Also, care is needed for the employees that are exposed to shocking events. Further, an evaluation of the performance by the emergency organisation should be undertaken, and the legal and financial matters should be settled.

Safety region IJsselland

The safety regions are in charge of the regional disaster and emergency management, which makes them the most important partner for the water board. Safety regions are a coalition of the fire brigade, medical services (GHOR), police, and municipalities for a specific region. The safety region IJsselland is responsible for the area of water board Drents Overijsselse Delta.

At a certain point the safety region establishes the 'Regionale Coordinatiecentrum'. The objective of this centre is to provide a quick coordination of the responsibilities and activities. It consists of a regional policy team ('regionaal beleidsteam (RBT)') and a regional operational team ('regionaal operationeel team (ROT)'). Whereby the RBT leads the administrative aspects and the ROT do the actual performances.

Water levels per GRIP phase

The water levels for locations in the water system for each GRIP-phase are shown on the next pages.

IJssel

Table B- 2 Emergency phases IJssel

Coördinatiefasen voor de IJssel								
		Toetspeil 2011 [m +NAP]		Coördinatiefasen				
Km (RWS)	**Plaats en hectometer WGS**	**1/1250**	**MHW**	**fase 0**	**fase 1**	**fase 2**	**fase 3**	**fase 4**
862	Lobith (n.v.t.)	1/1250	+18.00	+14.00	+16.15	+16.90	+17.65	-
945	Deventer (53-10,2)	1/1250	+7.90	+5.80	+6.80	+7.15	+7.45	-
957	Olst (53-22,0)	1/1250	+6.80	+4.90	+5.90	+6.15	+6.45	-
980	Katerveer (53-45,5)	1/1250	+4.70	+2.65	+3.60	+3.95	+4.35	-
981	Spooldersluis (10-0,4)	1/2000	+4.70	+2.65	+3.60	+3.95	+4.35	-
996	Kampen (10-14,4)	1/2000	+3.10	+1.00	+1.90	+2.25	+3.00	-

Vecht

Table B- 3 Emergency phases Vecht

Coördinatiefasen voor de Vecht								
		Toetspeil 2011 [m +NAP]		Coördinatiefasen				
Km (RWS)	**Plaats en hectometer WGS**	**F**	**MHW**	**fase 0**	**fase 1**	**fase 2**	**fase 3**	**fase 4**
34.55	Instr. Ommerkanaal (53-123,0)	1/1250	+5.46	+3.80	+4.20	+4.60	+5.00	-
39.10	Stuw Vilsteren (53-117,6)	1/1250	+4.80	+3.00	+3.40	+3.80	+4.20	-
41.0	Waterkering Hessum (53-116,0))	1/1250	+4.70	+2.50	+2.90	+3.30	+3.70	-
45.30	Vechtbrug Dalfsen (53-26.2)	1/1250	+4.43	+2.20	+2.60	+3.00	+3.40	-
49.20	Vechterweerd (53-106.0)	1/1250	+3.60	+1.40	+1.80	+2.20	+2.60	-

Table B- 4 Emergency phases Zwarte Water

Coördinatiefasen voor het Zwarte Water								
		Toetspeil 2011 [m +NAP]		Coördinatiefasen				
Km (RWS)	**Plaats en hectometer WGS**	**F**	**MHW**	**fase 0**	**fase 1**	**fase 2**	**fase 3**	**fase 4**
18	Genemuiden (10-29,4)	1/2000	+1.80	+0.40	+0.70	+1.00	+1.30	-
10	Hasselterdijk (10-49,0)	1/2000	+2.00	+0.50	+1.00	+1.40	+1.80	
1,0	Zwolle (10-45,2)	1/2000	+2.20	+0.50	+1.00	+1.40	+1.80	

Storm surge

Table B- 5 Emergency phases Vossemeer

Coördinatiefasen voor het Vossemeer								
		Toetspeil 2011 [m +NAP]		Coördinatiefasen				
Km (RWS)	**Plaats en hectometer WGS**	**F**	**MHW**	**fase 0**	**fase 1**	**fase 2**	**fase 3**	**fase 4**
WGS 11	Vosserwaard (11-7,0)	1/2000	+2.80	+0.80	+1.60	+1.95	+2.60	-
WGS 28	Roggebotsluis (11-4,2)	1/2000	+3.20	+1.00	+1.90	+2.25	+3.00	-

Table B- 6 Emergency phases Ketelmeer

Coördinatiefasen voor het Ketelmeer								
		Toetspeil 2011 [m +NAP]		Coördinatiefasen				
Km (RWS)	**Plaats en hectometer WGS**	**F**	**MHW**	**fase 0**	**fase 1**	**Fase 2**	**fase 3**	**fase 4**
990	Kampen (10-14,4)	1/2000	+3.10	+1.00	+1.90	+2.25	+3.00	-
991	Wilsum (991)	1/2000	+3.60	+1.40	+2.30	+2.65	+3.40	-

Table B- 7 Emergency phases Zwarte Meer

Coördinatiefasen voor het Zwarte Meer								
		Toetspeil 2011 [m +NAP]		Coordinatiefasen				
Km (RWS)	**Plaats en hectometer WGS**	**F**	**MHW**	**fase 0**	**fase 1**	**fase 2**	**fase 3**	**fase 4**
	Vollenhove (09-0,2)	1/2000	+1.60	+0.70	+0.80	+0.90	+1.20	-
	Zuiderzeepolder (104)	1/500	+1.10	+0.70	+0.80	+0.80	+1.10	-
	Kampereiland (101)	1/500	+1.05	+0.60	+0.70	+0.80	+1.05	-
	Mandjeswaard (102)	1/500	+1.05	+0.60	+0.70	+0.80	+1.05	-
	Pieper (103)	1/500	+1.05	+0.60	+0.70	+0.80	+1.05	-
	Polder de Koekoek (105)	1/100	-0.55	-	-	-	-	-

Appendix C: Validation wind data

The use of the national wind data is validated by assessing the correlation between the wind data and the water levels at Ramspol for the period 1990-2016. The daily maxima, minima and mean of the wind speeds and the water levels are given in Figure C-1. The annual maxima, minima, and mean are shown in Figure C-2. The correlation results for the daily maxima and annual maxima are given in Figure C-3 and C-4.

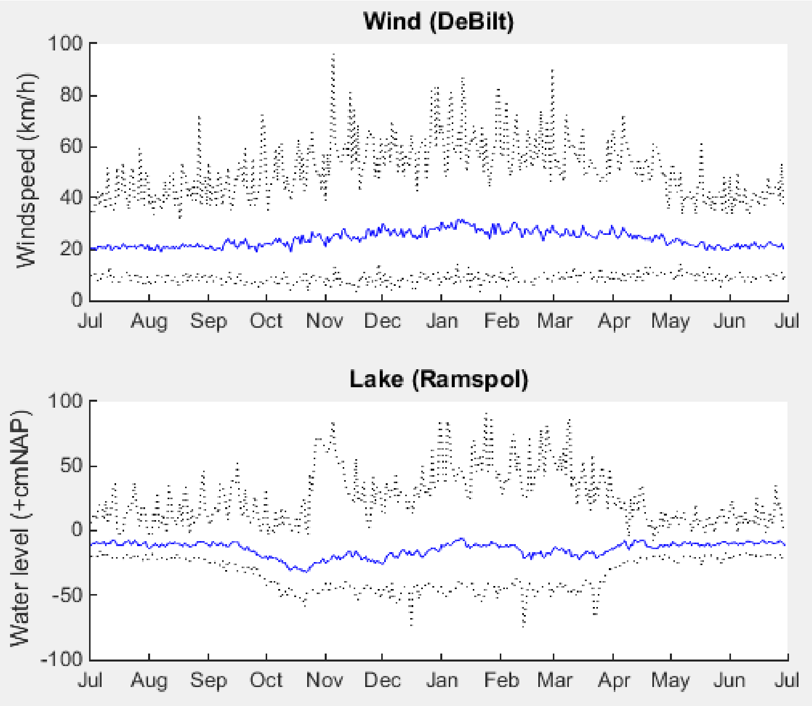

Figure C- 1 Daily maxima, minima and mean of wind speeds at De Bilt and water levels at Ramspol

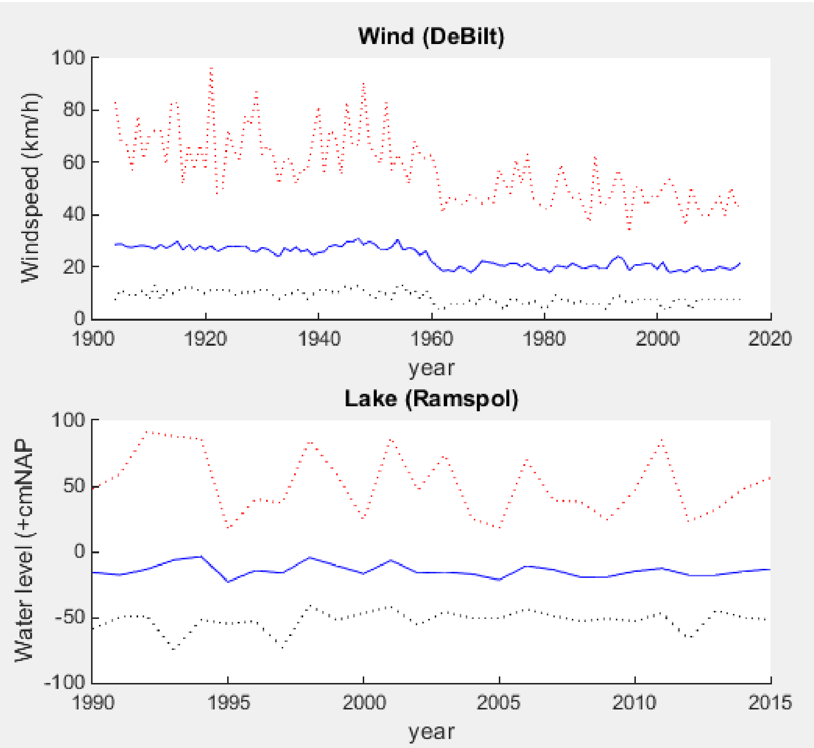

Figure C- 2 Annual maxima, minima and mean of wind speeds at De Bilt and water levels at Ramspol

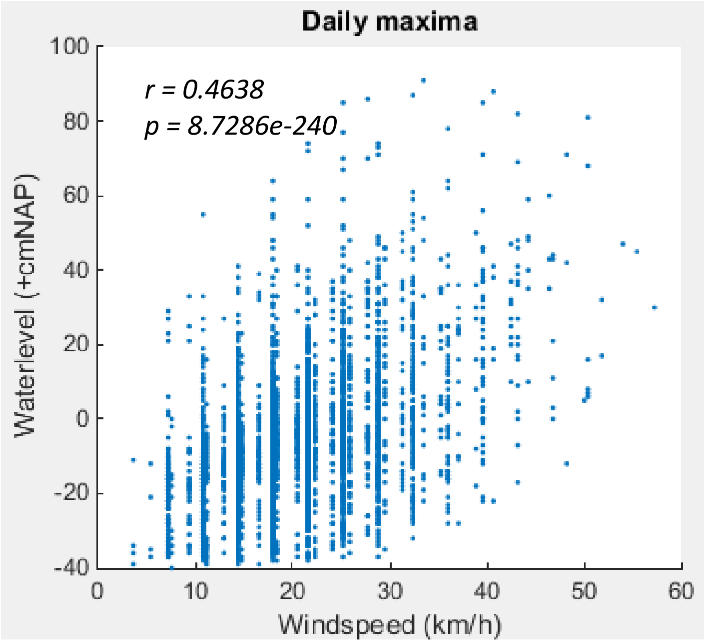

Figure C- 3 Pearson correlation for daily maxima

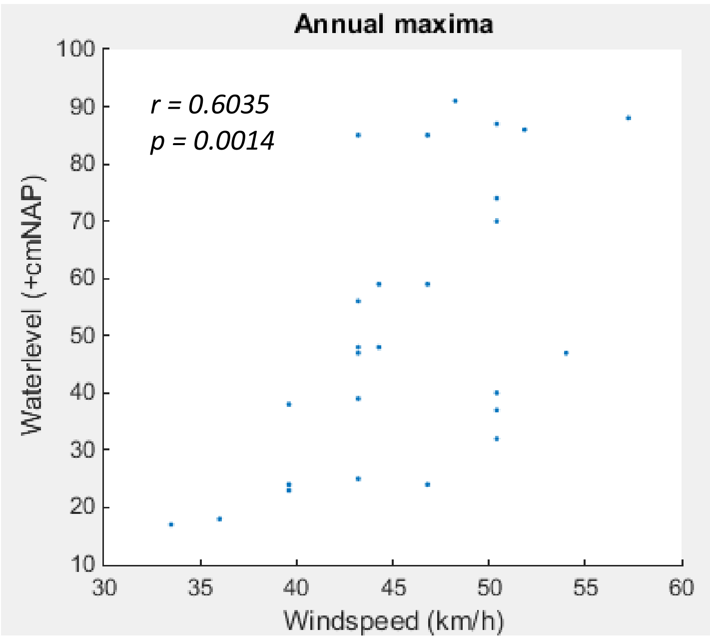

Figure C- 4 Pearson correlation for annual maxima

Appendix D: Copula-based assessment – selected data

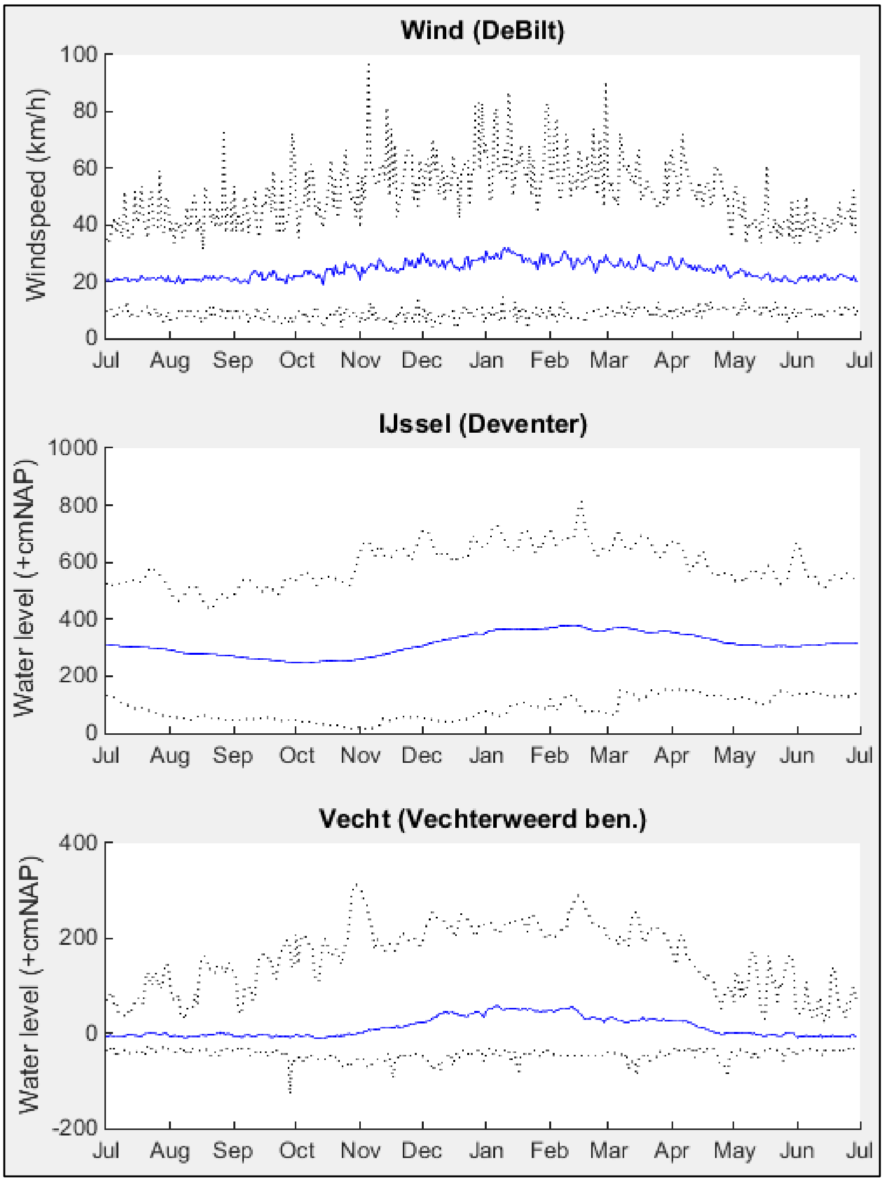

Figure D- 1 Daily maxima, minima and mean for the wind speed and water levels

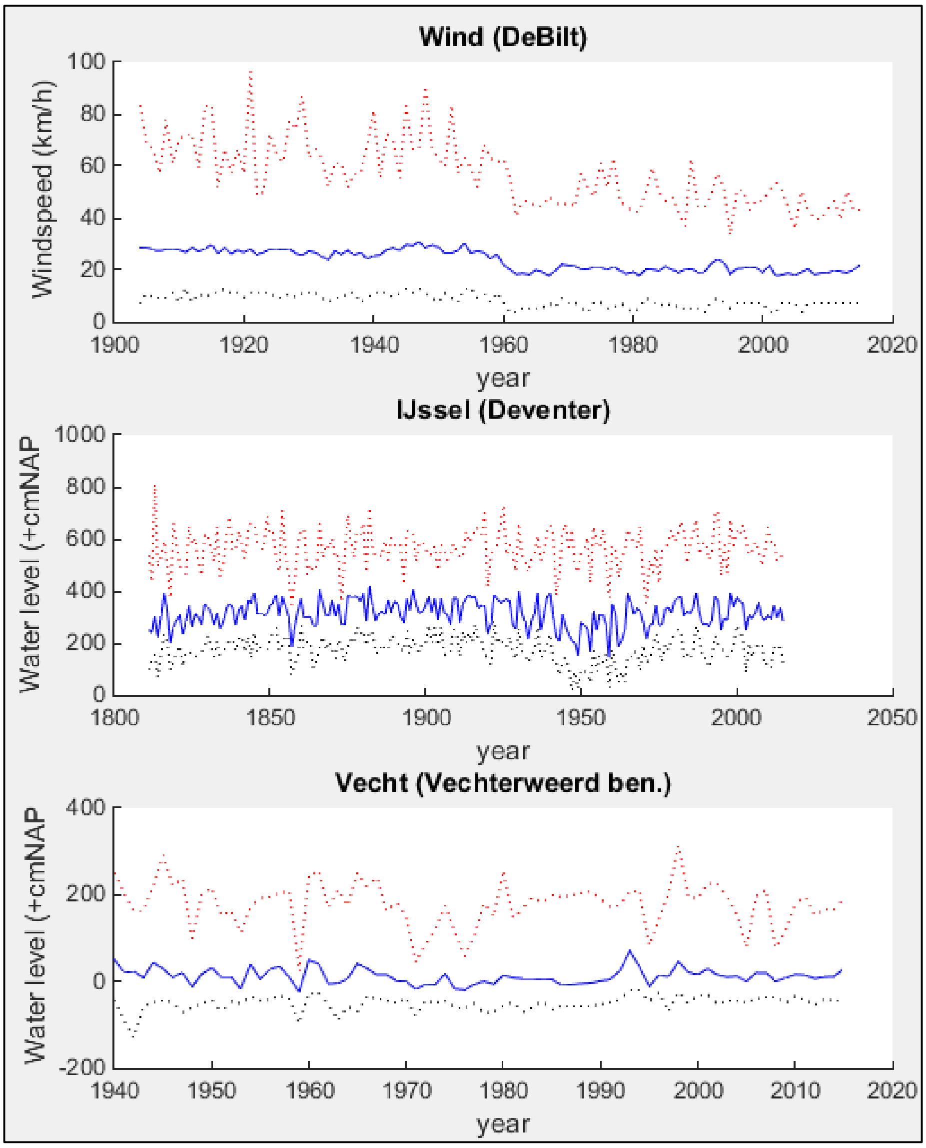

Figure D- 2 Annual maxima, minima and mean for the wind speed and water levels

Appendix E: Copula-based assessment - coincidence probabilities

Table E- 1 Exceedance probabilities bivariate cases

Gumbel	**Vecht**				
IJssel	3000	2000	1000	100	10
3000	4.58E-06	6.24E-06	1.04E-05	5.02E-05	1.75E-04
2000	6.24E-06	8.53E-06	1.44E-05	7.16E-05	2.57E-04
1000	1.04E-05	1.44E-05	2.47E-05	1.30E-04	4.95E-04
100	5.02E-05	7.16E-05	1.30E-04	8.49E-04	4.15E-03
10	1.75E-04	2.57E-04	4.95E-04	4.15E-03	2.91E-02
Gumbel	**Wind**				
IJssel	3000	2000	1000	100	10
3000	1.61E-07	2.39E-07	4.70E-07	4.39E-06	4.00E-05
2000	2.39E-07	3.55E-07	6.99E-07	6.55E-06	5.97E-05
1000	4.70E-07	6.99E-07	1.38E-06	1.29E-05	1.19E-04
100	4.39E-06	6.55E-06	1.29E-05	1.24E-04	1.16E-03
10	4.00E-05	5.97E-05	1.19E-04	1.16E-03	1.11E-02
Gumbel	**Wind**				
Vecht	3000	2000	1000	100	10
3000	4.80E-07	6.93E-07	1.29E-06	9.86E-06	6.73E-05
2000	6.93E-07	1.00E-06	1.88E-06	1.44E-05	9.97E-05
1000	1.29E-06	1.88E-06	3.53E-06	2.77E-05	1.95E-04
100	9.86E-06	1.44E-05	2.77E-05	2.32E-04	1.78E-03
10	6.73E-05	9.97E-05	1.95E-04	1.78E-03	1.52E-02

Table E- 2 Exceedance factors bivariate cases

	Vecht				
IJssel	3000	2000	1000	100	10
3000	41.2	37.4	31.3	15.1	5.2
2000	37.4	34.1	28.8	14.3	5.1
1000	31.3	28.8	24.7	13.0	5.0
100	15.1	14.3	13.0	8.5	4.2
10	5.2	5.1	5.0	4.2	2.9
	Wind				
IJssel	3000	2000	1000	100	10
3000	1.4	1.4	1.4	1.3	1.2
2000	1.4	1.4	1.4	1.3	1.2
1000	1.4	1.4	1.4	1.3	1.2
100	1.3	1.3	1.3	1.2	1.2
10	1.2	1.2	1.2	1.2	1.1
	Wind				
Vecht	3000	2000	1000	100	10
3000	4.3	4.2	3.9	3.0	2.0
2000	4.2	4.0	3.8	2.9	2.0
1000	3.9	3.8	3.5	2.8	2.0
100	3.0	2.9	2.8	2.3	1.8
10	2.0	2.0	2.0	1.8	1.5

Table E- 3 Exceedance probabilities trivariate cases

		Wind				
IJssel	**Vecht**	3000	2000	1000	100	10
3000	3000	5.55E-09	7.64E-09	1.31E-08	7.22E-08	3.31E-07
	2000	7.64E-09	1.05E-08	1.81E-08	1.01E-07	4.66E-07
	1000	1.31E-08	1.81E-08	3.12E-08	1.76E-07	8.30E-07
	100	7.22E-08	1.01E-07	1.76E-07	1.05E-06	5.24E-06
	10	3.31E-07	4.66E-07	8.30E-07	5.24E-06	2.76E-05
2000	3000	7.64E-09	1.05E-08	1.81E-08	1.01E-07	4.66E-07
	2000	1.05E-08	1.45E-08	2.50E-08	1.41E-07	6.57E-07
	1000	1.81E-08	2.50E-08	4.33E-08	2.47E-07	1.17E-06
	100	1.01E-07	1.41E-07	2.47E-07	1.49E-06	7.51E-06
	10	4.66E-07	6.57E-07	1.17E-06	7.51E-06	4.03E-05
1000	3000	1.31E-08	1.81E-08	3.12E-08	1.76E-07	8.30E-07
	2000	1.81E-08	2.50E-08	4.33E-08	2.47E-07	1.17E-06
	1000	3.12E-08	4.33E-08	7.53E-08	4.37E-07	2.11E-06
	100	1.76E-07	2.47E-07	4.37E-07	2.69E-06	1.39E-05
	10	8.30E-07	1.17E-06	2.11E-06	1.39E-05	7.63E-05
100	3000	7.22E-08	1.01E-07	1.76E-07	1.05E-06	5.24E-06
	2000	1.01E-07	1.41E-07	2.47E-07	1.49E-06	7.51E-06
	1000	1.76E-07	2.47E-07	4.37E-07	2.69E-06	1.39E-05
	100	1.05E-06	1.49E-06	2.69E-06	1.78E-05	9.94E-05
	10	5.24E-06	7.51E-06	1.39E-05	9.94E-05	6.07E-04
10	3000	3.31E-07	4.66E-07	8.30E-07	5.24E-06	2.76E-05
	2000	4.66E-07	6.57E-07	1.17E-06	7.51E-06	4.03E-05
	1000	8.30E-07	1.17E-06	2.11E-06	1.39E-05	7.63E-05
	100	5.24E-06	7.51E-06	1.39E-05	9.94E-05	6.07E-04
	10	2.76E-05	4.03E-05	7.63E-05	6.07E-04	4.22E-03

Table E- 4 Exceedance factors trivariate cases

		Wind				
IJssel	**Vecht**	3000	2000	1000	100	10
3000	3000	149.8	137.5	117.8	65.0	29.8
	2000	137.5	126.3	108.5	60.4	28.0
	1000	117.8	108.5	93.6	52.9	24.9
	100	65.0	60.4	52.9	31.6	15.7
	10	29.8	28.0	24.9	15.7	8.3
2000	3000	137.5	126.3	108.5	60.4	28.0
	2000	126.3	116.3	100.1	56.2	26.3
	1000	108.5	100.1	86.7	49.5	23.5
	100	60.4	56.2	49.5	29.8	15.0
	10	28.0	26.3	23.5	15.0	8.1
1000	3000	117.8	108.5	93.6	52.9	24.9
	2000	108.5	100.1	86.7	49.5	23.5
	1000	93.6	86.7	75.3	43.7	21.1
	100	52.9	49.5	43.7	26.9	13.9
	10	24.9	23.5	21.1	13.9	7.6
100	3000	65.0	60.4	52.9	31.6	15.7
	2000	60.4	56.2	49.5	29.8	15.0
	1000	52.9	49.5	43.7	26.9	13.9
	100	31.6	29.8	26.9	17.8	9.9
	10	15.7	15.0	13.9	9.9	6.1
10	3000	29.8	28.0	24.9	15.7	8.3
	2000	28.0	26.3	23.5	15.0	8.1
	1000	24.9	23.5	21.1	13.9	7.6
	100	15.7	15.0	13.9	9.9	6.1
	10	8.3	8.1	7.6	6.1	4.2

Table E- 5 Coincidence probabilities bivariate cases

	Vecht				
IJssel	3000	2000	1000	100	10
3000	2.99E-06	4.08E-06	6.83E-06	3.28E-05	1.14E-04
2000	4.08E-06	5.58E-06	9.43E-06	4.68E-05	1.68E-04
1000	6.83E-06	9.43E-06	1.62E-05	8.50E-05	3.24E-04
100	3.28E-05	4.68E-05	8.50E-05	5.55E-04	2.72E-03
10	1.14E-04	1.68E-04	3.24E-04	2.72E-03	1.91E-02
	Storm				
IJssel	3000	2000	1000	100	10
3000	1.88E-08	2.80E-08	5.50E-08	5.14E-07	4.68E-06
2000	2.80E-08	4.16E-08	8.19E-08	7.67E-07	7.00E-06
1000	5.50E-08	8.19E-08	1.61E-07	1.52E-06	1.39E-05
100	5.14E-07	7.67E-07	1.52E-06	1.45E-05	1.36E-04
10	4.68E-06	7.00E-06	1.39E-05	1.36E-04	1.30E-03
	Storm				
Vecht	3000	2000	1000	100	10
3000	6.11E-08	8.83E-08	1.65E-07	1.26E-06	8.57E-06
2000	8.83E-08	1.28E-07	2.39E-07	1.84E-06	1.27E-05
1000	1.65E-07	2.39E-07	4.50E-07	3.53E-06	2.49E-05
100	1.26E-06	1.84E-06	3.53E-06	2.96E-05	2.26E-04
10	8.57E-06	1.27E-05	2.49E-05	2.26E-04	1.94E-03

Table E- 6 Coincidence factors bivariate cases

	Vecht				
IJssel	3000	2000	1000	100	10
3000	194.8	176.8	148.1	71.2	24.8
2000	176.8	161.4	136.3	67.7	24.3
1000	148.1	136.3	116.9	61.4	23.4
100	71.2	67.7	61.4	40.1	19.6
10	24.8	24.3	23.4	19.6	13.8
	Storm				
IJssel	3000	2000	1000	100	10
3000	1.4	1.4	1.4	1.3	1.2
2000	1.4	1.4	1.4	1.3	1.2
1000	1.4	1.4	1.4	1.3	1.2
100	1.3	1.3	1.3	1.2	1.2
10	1.2	1.2	1.2	1.2	1.1
	Storm				
Vecht	3000	2000	1000	100	10
3000	4.3	4.2	3.9	3.0	2.0
2000	4.2	4.0	3.8	2.9	2.0
1000	3.9	3.8	3.5	2.8	2.0
100	3.0	2.9	2.8	2.3	1.8
10	2.0	2.0	2.0	1.8	1.5

Table E- 7 Coincidence probabilities trivariate cases

		Storm				
IJssel	**Vecht**	3000	2000	1000	100	10
3000	3000	1.13E-10	1.56E-10	2.67E-10	1.47E-09	6.75E-09
	2000	1.56E-10	2.14E-10	3.68E-10	2.05E-09	9.49E-09
	1000	2.67E-10	3.68E-10	6.36E-10	3.59E-09	1.69E-08
	100	1.47E-09	2.05E-09	3.59E-09	2.14E-08	1.07E-07
	10	6.75E-09	9.49E-09	1.69E-08	1.07E-07	5.63E-07
2000	3000	1.56E-10	2.14E-10	3.68E-10	2.05E-09	9.49E-09
	2000	2.14E-10	2.96E-10	5.10E-10	2.86E-09	1.34E-08
	1000	3.68E-10	5.10E-10	8.82E-10	5.03E-09	2.39E-08
	100	2.05E-09	2.86E-09	5.03E-09	3.04E-08	1.53E-07
	10	9.49E-09	1.34E-08	2.39E-08	1.53E-07	8.20E-07
1000	3000	2.67E-10	3.68E-10	6.36E-10	3.59E-09	1.69E-08
	2000	3.68E-10	5.10E-10	8.82E-10	5.03E-09	2.39E-08
	1000	6.36E-10	8.82E-10	1.53E-09	8.90E-09	4.30E-08
	100	3.59E-09	5.03E-09	8.90E-09	5.48E-08	2.82E-07
	10	1.69E-08	2.39E-08	4.30E-08	2.82E-07	1.55E-06
100	3000	1.47E-09	2.05E-09	3.59E-09	2.14E-08	1.07E-07
	2000	2.05E-09	2.86E-09	5.03E-09	3.04E-08	1.53E-07
	1000	3.59E-09	5.03E-09	8.90E-09	5.48E-08	2.82E-07
	100	2.14E-08	3.04E-08	5.48E-08	3.63E-07	2.02E-06
	10	1.07E-07	1.53E-07	2.82E-07	2.02E-06	1.24E-05
10	3000	6.75E-09	9.49E-09	1.69E-08	1.07E-07	5.63E-07
	2000	9.49E-09	1.34E-08	2.39E-08	1.53E-07	8.20E-07
	1000	1.69E-08	2.39E-08	4.30E-08	2.82E-07	1.55E-06
	100	1.07E-07	1.53E-07	2.82E-07	2.02E-06	1.24E-05
	10	5.63E-07	8.20E-07	1.55E-06	1.24E-05	8.60E-05

Table E- 8 Coincidence factors trivariate cases

		Storm				
IJssel	**Vecht**	3000	2000	1000	100	10
3000	3000	795	730	625	345	158
	2000	730	671	576	321	148
	1000	625	576	497	281	132
	100	345	321	281	168	83
	10	158	148	132	83	44
2000	3000	730	671	576	321	148
	2000	671	617	532	299	140
	1000	576	532	460	263	125
	100	321	299	263	158	80
	10	148	140	125	80	43
1000	3000	625	576	497	281	132
	2000	576	532	460	263	125
	1000	497	460	400	232	112
	100	281	263	232	143	74
	10	132	125	112	74	41
100	3000	345	321	281	168	83
	2000	321	299	263	158	80
	1000	281	263	232	143	74
	100	168	158	143	95	53
	10	83	80	74	53	32
10	3000	158	148	132	83	44
	2000	148	140	125	80	43
	1000	132	125	112	74	41
	100	83	80	74	53	32
	10	44	43	41	32	22

Appendix F: Model inputs for Drents Overijsselse Delta

Table F- 1 Failure probabilities per failure mechanism dike ring 9 Vollenhove

Vak nr.	Faalkans (per jaar) per faalmechanisme				
	Overloop en golfoverslag	Macrostabiliteit binnenwaarts	Opbarsten en piping	Beschadiging bekleding en erosie dijklichaam	**Gecombineerd**
1	1/510*	-	-	-	-
2	>1/100*	-	-	-	-
3	1/310.000*	-	-	-	-
4	1/1.300	-	-	-	**1/1.300**
5	1/120	-	-	-	**1/120**
6	1/980*	-	-	-	-
7	1/1.200*	-	-	-	-
8	1/1.400*	-	-	-	-
9	1/2.400	-	1/17.000	-	**1/2.200**
10	1/6.600*	-	-	-	-
11	1/850	-	-	-	**1/850**
12	1/580	-	-	-	**1/580**
13	1/140.000	-	-	<1/1.000.000**	**1/140.000**
14	1/87.000	-	-	<1/1.000.000	**1/87.000**
15	1/110.000**	<1/1.000.000	1/610	1/59.000	**1/600**
16	1/240.000	-	1/1.300	<1/1.000.000**	**1/1.300**
17	1/330.000	<1/1.000.000	1/1.700	<1/1.000.000	**1/1.700**
18	1/110.000	-	1/2.000	1/730.000**	**1/2.000**
19	1/820.000	-	1/4.400	<1/1.000.000	**1/4.400**
20	1/200.000	-	1/4.400	<1/1.000.000**	**1/4.300**
21	<1/1.000.000	-	1/2.100	<1/1.000.000**	**1/2.100**
22	1/66.000	-	1/7.900	<1/1.000.000	**1/7.100**
23	1/410.000	-	1/7.300	<1/1.000.000	**1/7.200**
24	1/290.000	-	-	<1/1.000.000	**1/280.000**
25	1/1.700	1/120.000	1/1.200	-	**1/740**
26	<1/1.000.000	-	-	-	**<1/1.000.000**
27	1/34.000	-	-	-	**1/34.000**
28	1/4.400	-	1/1.400	-	**1/1.100**
29	1/1.800	-	-	1/380.000	**1/1.800**
30	1/5.900	-	-	-	**1/5.900**
31	1/8.600	-	1/7.600	1/88.000	**1/4.000**
32	1/6.700	<1/1.000.000	1/1.500	1/7.300	**1/1.100**
33	1/110.000	-	-	-	**1/11.000**
34	1/79.000	-	1/1.200	-	**1/1.200**
35	1/2.600	<1/1.000.000	-	-	**1/2.600**
36	1/11.000	-	-	-	**1/11.000**
37	1/43.000	-	-	-	**1/43.000**
38	<1/1.000.000	-	-	-	**<1/1.000.000**
39	1/43.000	-	1/4.600	-	**1/4.200**
40	1/16.000	<1/1.000.000	1/3.100	-	**1/2.600**
41	1/6.500	-	1/1.200	-	**1/1.100**
42	1/3.000	-	1/5.100	-	**1/2.000**
43	1/150.000	-	1/2.200	<1/1.000.000**	**1/2.200**
44	1/440.000	-	-	<1/1.000.000	**1/440.000**
45	<1/1.000.000	-	-	-	**<1/1.000.000**
46	<1/1.000.000	-	1/10.000	-	**1/10.000**
47	1/530.000	<1/1.000.000	-	-	**1/470.000**
48	1/130.000	-	-	<1/1.000.000	**1/120.000**
49	<1/1.000.000	-	-	<1/1.000.000	**<1/1.000.000**
50	<1/1.000.000	-	-	<1/1.000.000**	**<1/1.000.000**
51	<1/1.000.000	-	<1/1.000.000	-	**<1/1.000.000**
Overstromingskans	**1/120**	**1/110.000**	**1/140**	**1/6.100**	**>1/100**

Table F- 2 Economic damage per ring section dike ring 9 Vollenhove

Ring-deel	Breslocatie	buitenwaterstand		
		tp-1d	tp	tp+1d
1	Oudleusen schade (miljoen €) aantal slachtoffers	1 0	5 0	25 0
2	Dalfsen schade (miljoen €) aantal slachtoffers	195 0 - 5	335 0 - 10	525 5 - 25
3	Na Dalfsen schade (miljoen €) aantal slachtoffers	415 0 - 10	655 0 - 30	850 5 - 40
4	Hessenpoort schade (miljoen €) aantal slachtoffers	425 0 - 10	660 5 - 30	865 5 - 40
5	Bomhofsplas schade (miljoen €) aantal slachtoffers	295 0 - 10	415 5 - 15	630 5 - 30
6	Hasselt schade (miljoen €) aantal slachtoffers	305 5 - 20	480 5 - 30	650 5 - 40
7	Veldiger-binnenland schade (miljoen €) aantal slachtoffers	550 10 - 45	955 15 - 85	1305 25 - 125
8	Zwart Sluis schade (miljoen €) aantal slachtoffers	105 0 - 5	385 0 - 10	510 5 - 15
9	Zwarte Meer schade (miljoen €) aantal slachtoffers	5 0	10 0	15 0
Max. scen.	1 t/m 9 schade (miljoen €) aantal slachtoffers	-	-	1705 30 - 145

Table F- 3 Failure probabilities per failure mechanism dike ring 10 Mastenbroek

Vak nr.	Faalkans (per jaar) per faalmechanisme			
	Overloop en golfoverslag	Macrostabiliteit binnenwaarts	Opbarsten en piping	**Gecombineerd**
1	1/32.000	-	-	1/32.000
2	1/9.700	-	1/5.600	1/4.000
3	1/16.000	-	1/920	1/910
4	1/6.000	-	-	1/6.000
5	1/13.000	-	1/10.000	1/6.000
6	1/16.000	-	1/270.000	1/16.000
7	1/3.800	-	1/4.200	1/2.300
8	1/21.000	-	-	1/21.000
9	1/9.200	-	-	1/9.200
10	1/300.000	-	-	1/300.000
11	1/14.000	-	-	1/14.000
12	1/36.000	-	1/54.000	1/23.000
13	1/21.000	-	-	1/21.000
14	1/18.000	-	-	1/18.000
15	1/18.000	-	-	1/18.000
16	1/17.000	1/18.000	1/9.800	1/6.100
17	-	-	-	-
18	1/10.000	-	-	1/10.000
19	1/34.000	<1/1.000.000	-	1/34.000
20	<1/1.000.000	-	-	<1/1.000.000
21	<1/1.000.000	-	-	<1/1.000.000
22	<1/1.000.000	-	-	<1/1.000.000
23	1/830.000	-	-	1/830.000
24	<1/1.000.000	1/9.900	-	1/9.800
25	1/840.000	-	1/670	1/670
26	1/880.000	-	-	1/880.000
27	1/480.000	-	-	1/480.000
28	1/800.000	-	-	1/800.000
29	1/15.000	-	-	1/15.000
30	1/95.000	-	-	1/95.000
31	1/980.000	-	-	1/980.000
32	<1/1.000.000	-	-	<1/1.000.000
33	1/720.000	-	-	1/720.000
34	<1/1.000.000	-	-	<1/1.000.000
35	<1/1.000.000	-	-	<1/1.000.000
36	1/740.000	-	-	1/740.000
37	<1/1.000.000	-	-	<1/1.000.000
38	<1/1.000.000	-	1/12.000	1/12.000
39	<1/1.000.000	-	-	<1/1.000.000
40	1/400.000	1/9.100	-	1/8.900
41	<1/1.000.000	-	-	<1/1.000.000
42	1/460.000	-	-	1/460.000
43	<1/1.000.000	1/11.000	1/2.200	1/1.900
44	<1/1.000.000	-	<1/1.000.000	1/600.000
45	<1/1.000.000	-	1/21.000	1/21.000
46	<1/1.000.000	-	1/2.400	1/2.400
47	<1/1.000.000	-	1/17.000	1/17.000
48	1/810.000	-	1/4.500	1/4.500
49	<1/1.000.000	-	-	<1/1.000.000
50	<1/1.000.000	-	-	<1/1.000.000
51	<1/1.000.000	-	-	<1/1.000.000
52	-	-	-	-
53	-	-	-	-
54	-	-	-	-
55	-	-	-	-
Overstro-mingskans	1/2.800	1/2.900	1/310	1/210

Table F- 4 Economic damage per ring section dike ring 10 Mastenbroek

Ring-deel	Breslocatie	buitenwaterstand		
		tp-1d	tp	tp+1d
RD01	IJssel 981_3 schade (miljoen €) aantal slachtoffers	1335 15 - 115	2155 25 - 235	2245 25 - 245
RD02	IJssel 985_2 schade (miljoen €) aantal slachtoffers	1535 15 - 150	2135 25 - 220	2215 25 - 230
RD03	IJssel 993_2 schade (miljoen €) aantal slachtoffers	1415 15 - 140	2035 25 - 210	2145 25 - 230
RD04	IJssel 995_8 schade (miljoen €) aantal slachtoffers	945 10 - 70	1590 15 - 155	1990 20 - 200
RD05	IJsselmuiden-spoorlijn schade (miljoen €) aantal slachtoffers	565 5 - 45	1240 15 - 130	1400 15 - 155
RD06	IJsselmuiden schade (miljoen €) aantal slachtoffers	-	195 0 - 15	-
RD07	GDGS schade (miljoen €) aantal slachtoffers	45 0 - 5	155 0 - 10	-
RD08	GOGS schade (miljoen €) aantal slachtoffers	15 0 - 5	30 0 - 5	-
RD09	VEGS schade (miljoen €) aantal slachtoffers	165 0 - 10	210 0 - 15	-
RD10	ZW-Genemuiden schade (miljoen €) aantal slachtoffers	-	-	30 0 - 5
RD11	NW-Genemuiden schade (miljoen €) aantal slachtoffers	-	-	45 0 - 5
RD13	Genemuiden schade (miljoen €) aantal slachtoffers	70 0 - 5	110 0 - 5	200 0 - 10
RD14	ZW Vecht 12_7 schade (miljoen €) aantal slachtoffers	590 5 - 35	995 10 - 75	1175 10 - 100
RD15	ZW Vecht 265_12 schade (miljoen €) aantal slachtoffers	830 5 - 55	1035 10 - 80	1200 10 - 105
RD16	Voorsterhaven schade (miljoen €) aantal slachtoffers	-	120 0 - 5	-
Max Scen.	Maximaal scenario schade (miljoen €) aantal slachtoffers	-	-	2285 35 - 305

Table F- 5 Failure probabilities per failure mechanism dike ring 11 IJsseldelta

Vak nr.	Faalkans (per jaar) per faalmechanisme				
	Overloop en golfoverslag	Macrostabiliteit binnenwaarts	Opbarsten en piping	Beschadiging bekleding en erosie dijklichaam	**Gecombineerd**
1	1/2.500	-	1/75.000	<1/1.000.000	1/2.400
2	1/8.200	-	-	<1/1.000.000	1/8.200
3	1/10.000	-	-	<1/1.000.000	1/10.000
4	1/13.000	-	-	<1/1.000.000	1/13.000
5	1/93.000	-	-	-	1/93.000
6	1/400.000	-	-	-	1/400.000
7	<1/1.000.000	-	-	-	<1/1.000.000
8	<1/1.000.000	-	-	-	<1/1.000.000
9	1/950.000	-	<1/1.000.000	<1/1.000.000	1/860.000
10	1/870.000	-	1/590.000	<1/1.000.000	1/360.000
11	1/120.000	-	-	<1/1.000.000	1/110.000
12	1/200.000	-	<1/1.000.000	-	1/200.000
13	1/50.000	-	-	-	1/50.000
14	1/13.000	-	-	-	1/13.000
15	1/2.900	-	-	-	1/2.900
16	1/9.800	-	-	-	1/9.800
17	1/18.000	-	-	-	1/18.000
18	1/5.800	-	1/7.200	-	1/3.700
19	1/12.000	-	1/25.000	-	1/8.700
20	1/6.300	-	1/30.000	-	1/5.700
21	1/1.200	-	-	-	1/1.200
22	1/2.500	-	-	-	1/2.500
23	1/5.200	-	-	-	1/5.200
24	1/4.400	-	-	-	1/4.400
25	1/3.700	-	-	-	1/3.700
26	1/3.800	1/410.000	-	-	1/3.800
27	1/8.300	-	-	-	1/8.300
28	1/4.400	-	-	-	1/4.400
29	1/11.000	-	1/50.000	-	1/9.000
30	1/3.600	-	1/5.300	-	1/2.400
31	1/3.700	-	1/110.000	-	1/3.600
32	1/4.000	<1/1.000.000	1/80.000	-	1/3.800
33	1/12.000	-	-	120.000	1/11.000
34	1/8.100	-	-	-	1/8.100
35	1/7.700	-	1/25.000	-	1/6.200
36	1/4.800	-	1/140.000	-	1/4.700
37	1/1.900	-	-	-	1/1.900
38	1/3.100	-	-	-	1/3.100
39	1/1.500	-	-	-	1/1.500
40	1/900	-	-	<1/1.000.000	1/900
41	1/450	-	-	-	1/450
42	1/4.500	<1/1.000.000	1/11.000	-	1/3.400
43	1/1.600	-	1/8.000	-	1/1.500
44	1/1.000	-	1/3.900	-	1/890
Overstro-mingskans	1/370	1/310.000	1/1.400	1/110.000	1/370

Table F- 6 Economic damage per ring section dike ring 11 IJsseldelta

RD		tp-1d	tp	tp+1d	tp+2d
1	**Zandjes**				
	schade (miljoen €)	115	180	490	680
	aantal slachtoffers	0 - 5	0 - 5	5 - 30	10 - 50
1	**Zandjes – met bypass**				
	schade (miljoen €)		215		730
	aantal slachtoffers		0 – 10		15 - 66
2	**Kampen-Noord**				
	schade (miljoen €)	240	310	425	570
	aantal slachtoffers	0 - 10	5 - 15	5 - 25	10 - 40
2	**Kampen-Noord – met bypass**				
	schade (miljoen €)		310		570
	aantal slachtoffers		5 - 15		10 - 40
3	**Kampen-Zuid**				
	schade (miljoen €)	785	1345	1475	
	aantal slachtoffers	10 - 85	20 - 185	25 - 215	
3	**Kampen-Zuid - met bypass**				
	schade (miljoen €)		1040	1320	
	aantal slachtoffers		20 - 195	30 – 290	
4	**Zalk**				
	schade (miljoen €)	1375	1540	1800	
	aantal slachtoffers	15 - 125	15 - 150	20 - 190	
4	**Zalk – met bypass**				
	schade (miljoen €)		825	970	
	aantal slachtoffers		10 - 75	10 – 100	

Table F- 7 Failure probabilities per failure mechanism dike ring 53 Salland part 1

Vak nr.	Lengte dijkvak [m]	Faalkans (per jaar) per faalmechanisme				
		Overloop en golfoverslag	Macrostabiliteit binnenwaarts	Opbarsten en piping	Beschadiging bekleding en erosie dijklichaam	**Gecombineerd**
1	2100	1/1.700				1/1.700
2	300	1/3.400				1/3.400
3	500	1/4.000*				1/4.000
4	1500	1/2.100				1/2.100
5	1800	1/6.800				1/6.800
6	700	1/1.700			<1/1.000.000	1/1.700
7	500	1/8.200		1/260.000		1/8.100
8	700	1/1.900		<1/1.000.000		1/1.900
9	600	1/2.100				1/2.100
10	700	1/1.100			1/23.000	1/1.100
11	1300	1/670				1/670
12	800	1/1.200			1/69.000	1/1.200
13	1200	1/1.900		1/570.000		1/1.900
14	300	1/1.900		1/480.000		1/1.900
15	1200	1/4.000				1/4.000
16	600	1/3.900				1/3.900
17	600	1/7.200				1/7.200
18	300	1/6.200				1/6.200
19	700	1/6.300		1/3.100		1/2.100
20	2000	1/3.100		1/1.600		1/1.100
21	2100	1/3.200		1/850		1/710
22	1300	1/38.000		1/8.300		1/7.800
23	800	1/6.000		1/1.500	<1/1.000.000	1/1.200
24	1600	1/1.100		1/3.500		1/900
25	600	1/1.300		1/1.000		1/600
26	1200	1/740		1/440		1/330
27	1200	1/1.800			1/14.000	1/1.600
28	1400	1/3.300		1/7.200		1/2.300
29	1300	1/4.300		1/290	1/330.000	1/280
30	1500	1/2.400				1/2.400
31	2200	1/3.800		1/310		1/300
32	1800	1/3.800		1/11.000		1/3.000
33	1400	1/5.300	1/54.000	1/1.200		1/1.000
34	900	1/610		1/2.200		1/490
35	200	1/4.800				1/4.800
36	100	1/7.700		1/2.800	1/140.000	1/2.200
37	1400	1/7.000				1/7.000
38	900	1/1.600		1/930		1/630
39	1700	1/1.100		1/780	1/19.000	1/500
40	1300	1/1.500		1/2.300		1/950
41	1300	1/1.600		1/86.000		1/1.600
42	100	1/2.600		1/1.100		1/790
43	1700	1/2.600				1/2.600
44	300	1/18.000				1/18.000
45	300	<1/1.000.000				<1/1.000.000
46	1100	1/1.600				1/1.600
47	800	1/13.000				1/13.000
48	1100	1/10.000			<1/1.000.000	1/10.000
49	2200	1/1.500				1/1.500
50	500	<1/1.000.000	<1/1.000.000			<1/1.000.000
51	1100	1/5.900		1/11.000	1/29.000	1/3.500
52	400	1/380.000		1/2.600		1/2.600
53	1400	1/98.000		1/1.200		1/1.200
54	900	1/330.000		1/29.000		1/27.000

Table F- 8 Failure probabilities per failure mechanism dike ring 53 Salland part 2

Vak nr.	Lengte dijkvak [m]	Faalkans (per jaar) per faalmechanisme				
		Overloop en golfoverslag	Macrostabiliteit binnenwaarts	Opbarsten en piping	Beschadiging bekleding en erosie dijklichaam	**Gecombineerd**
55	1000	1/97.000				1/97.000
56	1400	1/44.000			<1/1.000.000	1/44.000
57	2400	1/290.000				1/290.000
58	200	<1/1.000.000				<1/1.000.000
59	3200	1/160.000				1/160.000
60	800	1/400.000				1/400.000
61	1200	1/100.000			<1/1.000.000	1/100.000
62	400	1/380.000			<1/1.000.000	1/380.000
63	1200	1/230.000		1/490		1/490
64	800	1/260.000				1/260.000
65	2900	1/4.000				1/4.000
66	2600	1/5.400				1/5.400
67	2100	1/6.300*				1/6.300
68	400	1/38.000*				1/38.000
69	1000	1/150.000*				1/150.000
70	1400	1/89.000*				1/89.000
71	1400	1/62.000				1/62.000
72	400	1/73.000	1/13.000	1/2.400		1/2.000
Overstromings-kans		**1/370**	**1/10.000**	**>1/100**	**1/5.500**	**>1/100**

Table F- 9 Economic damage per ring section dike ring 53 Salland

Ringdeel	Doorbraaklocatie	Buitenwaterstand		
		tp-1d	tp	tp+1d
1	**Deventer** schade (miljoen €) aantal slachtoffers	 580 5 - 30	 1440 10 - 80	 3170 20 – 180
2	**Deventer Noord** schade (miljoen €) aantal slachtoffers	 185 0 - 5	 1130 5 - 55	 3315 25 - 215
3	**Olst** schade (miljoen €) aantal slachtoffers	 5620 50 - 475	 6465 65 - 580	 7065 70 – 640
4	**Wijhe** schade (miljoen €) aantal slachtoffers	 5390 50 - 455	 6270 60 – 565	 6885 70 - 630
5	**Windesheim** schade (miljoen €) aantal slachtoffers	 5625 55 - 495	 6425 65 - 590	 7060 75 - 665
6	**Zwolle Zuid-West** schade (miljoen €) aantal slachtoffers	 4555 40 - 360	 5740 55 – 510	 6290 65 - 590
7	**Zwolle Noord-West** schade (miljoen €) aantal slachtoffers	 3465 30 - 255	 4765 40 - 375	 5560 55 - 515
8	**Zwolle IJsselkanaal** schade (miljoen €) aantal slachtoffers	 440 0 - 10	 1000 5 - 45	 1545 10 - 90
9	**Zwolle Holterbroek** schade (miljoen €) aantal slachtoffers	 590 5 - 45	 1140 10 - 90	 1615 25 - 135
10	**Langenholte** schade (miljoen €) aantal slachtoffers	 1215 10 - 95	 1615 15 - 135	 1940 20 - 170
11	**Berkum** schade (miljoen €) aantal slachtoffers	 1600 15 - 125	 2000 20 - 175	 3035 30 – 250
12	**Marshoek** schade (miljoen €) aantal slachtoffers	 1945 20 - 165	 3065 30 - 255	 3900 35 - 305
13	**Rechteren** schade (miljoen €) aantal slachtoffers	 15 0 - 5	 270 0 - 5	 1745 15 – 140
Max	**RD01 t/m RD13** schade (miljoen €) aantal slachtoffers			 9255 100 - 895