The Effect of Four New Floodgates on the Flood Frequency in the Dutch Lower Rhine Delta

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Abstract: The Dutch Lower Rhine Delta, a transitional area between the Rivers Rhine, Meuse and the North Sea, is at risk of flooding induced by infrequent events of storm surges or fluvial floods, or the combination of both. To protect the delta from storm surges, it can be closed off from the sea by large dams and controllable storm surge barriers. Also, along the branches of the rivers controllable floodgates are operated to regulate the fluvial discharge. A former study quantified the flood frequency derived from three different sources that potentially may cause a flood and indicated that high water levels was mainly caused by the simultaneous occurrence of storm surges and Rhine floods. In the present water operational management system, the Haringvliet gates and the Maeslant Storm Surge Barrier with the Hartel Storm Surge Barrier should be closed in time when the simultaneous extreme event occurs, and therefore the extreme fluvial flow that accumulates during the closure would result in a very high water level within the delta area. Moreover, this frequency will increase significantly in the context of climate change. As a suggested adaptation measure, a controllable floodgate is proposed in Pannerdensch Canal and the other three floodgates in Merwede, Drechtse Kil and Spui are designed in the East and South of Rotterdam and Dordrecht. These floodgates are expected to decrease the potential extreme water levels which are driven by the simultaneous extreme events. This study will investigate the operational management of these four gates, and further apply a large number of scenarios of the simultaneous extreme event to estimate the effect on the flood frequency in the delta. The results can assist to make better decisions in the adaptation of the present operational water management system.

Key words: the Lower Rhine Delta, flood frequency, floodgate, the operational water management system

1. INTRODUCTION

Flood risk is very critical to the development of the Dutch Lower Rhine Delta. Infrequent storm surges or upstream river floods, or more infrequent simultaneous occurrence of both have the potential to strike the delta and then cause serious damages. For example, the storm in 1953 caused more than 1800 casualties and around 600-900 million Euros economic loss.

Flood risk is estimated by the well known Source-Pathway-Receptor-Concept approach. This approach can be summarised as: First, the flood sources are investigated before failure probabilities of the flood defence system are calculated. Failure modes are applied to identify the initial conditions for flood propagation and finally, potential economic loss in the delta is quantified.

The flood source that makes the highly urbanized cities of Rotterdam and Dordrecht at risk comes from the high water level peak height associated with the hydrograph in front of the flood defence system. The information on the high water level and hydrograph is the base for the scenario-based flood risk calculation process. Zhong *et al*., (2013) quantified the flood frequency in Rotterdam and Dordrecht under three flood sources: 1. storm surges from the sea; 2. River Rhine floods; 3. the combination of both. A large number of stochastic scenarios for each flood source were generated to drive a 1-D hydrodynamic model associated with the present operational water management system. The 1-D hydrodynamic model is able to simulate these scenarios and results in water level peak heights associated with hydrographs in Rotterdam and Dordrecht. The simulations highlighted that all the high water levels were driven by the simultaneous occurrence of storm surges and Rhine floods.

The Dutch water boards maintain high-level design water levels for the design, construction and maintenance of the flood defence systems in the delta. The design water level corresponds to a fixed low exceedance probability. For example, the design water level in Rotterdam is 3.6 m MSL corresponding to the exceedance probability 10^{-4}, which also means a flood event with a peak water level exceeding 3.6 m MSL should occur only once every 10,000 years (Ministerie van Verkeer & Waterstaat., 2007).

The flood defence system has to cope with the design water level. However, the climate change would increase the design water level by increasing the flood frequency curve (Zhong *et al*., 2013). The potential increase of the design water level stimulates the adaptation measures for the flood defence system. Moreover, the future local economy and urbanization development will also require adaptation measures for reducing the frequency of the high water levels.

Much attention used to be paid on the strength improvement of the dikes or levees and in this way upgrading the flood defence system. However, recently the development of active hydraulic structures like storm surge barriers and floodgates trigger the investigation of new active structures as a key adaptation measure for the flood defence system (Second Delta, 2008). The new structures will be operated in combination with the existing ones to regulate the flood water in a proper way as an operational water management system. The main function of the system is to decrease the potential extreme water levels and then to keep the delta flood-proof.

This study will focus on the simultaneous occurrence of storm surges and Rhine floods and explore a suggested adaptation measure to protect the highly important economic center containing the cities of Rotterdam and Dordrecht in the delta. In the adaptation measure four flexible floodgates are proposed and coupled in the present operational water management system. The operational management goal of these floodgates is to deal with the above flood source. Their effect on the flood frequency will be quantified. The results will assist the policy decision makers in their search for the most appropriate adaptation measures in the delta.

2. THE PRESENT OPERATIONAL WATER MANAGEMENT SYSTEM

The Dutch Lower Rhine Delta is a system of inter-connected rivers, canals, reservoirs, and adjustable structures (see Fig. 1 (Left)). The hydrodynamic characteristics of the delta as captured in a strongly simplified 1-D hydrodynamic model (see Fig 1 (Right)) are mainly governed by the discharge of the rivers Rhine (Lobith: node 14), Meuse (Borgharen: node 1) and by sea levels (Hook of Holland: node 36 and Haringvliet: node 29). The sea level at Haringvliet is assumed to be the same as at Hook of Holland in the hydrodynamic model. There are four locations under investigation within the delta: Rotterdam (node 24), Dordrecht (node 22), Hollandsch Diep (node 26) and Haringvliet (node 27).

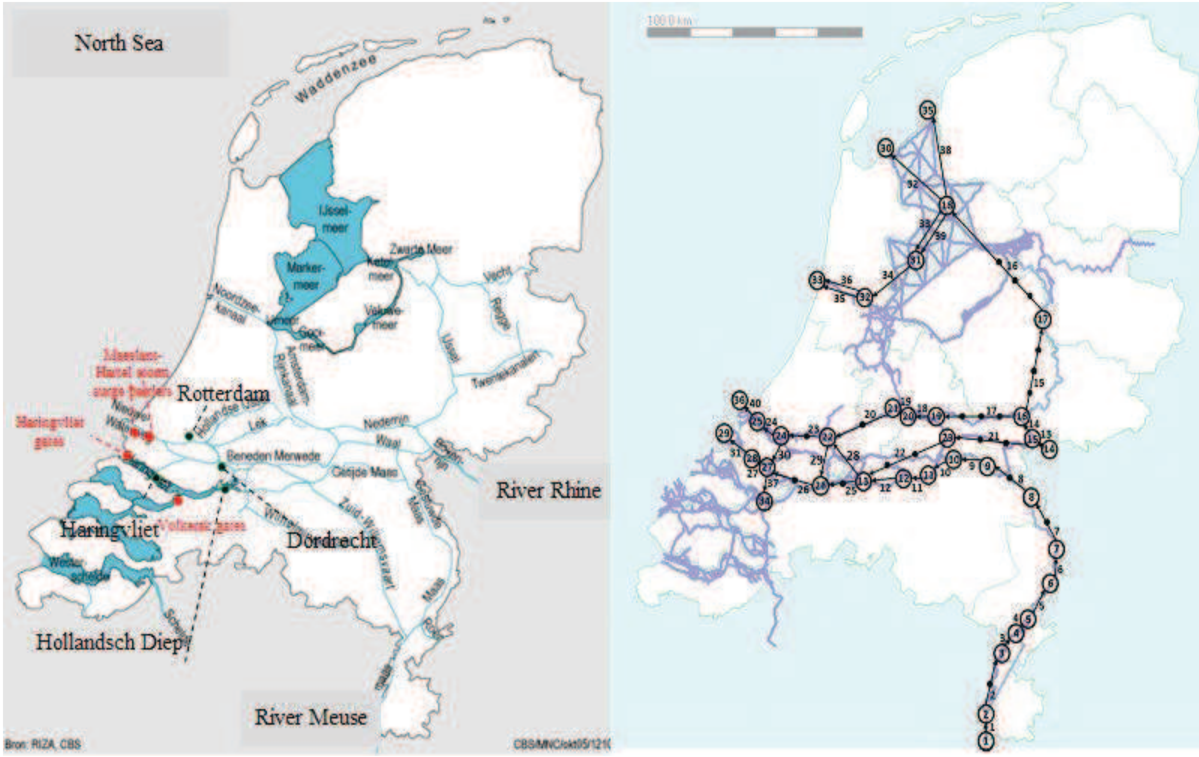

Figure 1. (Left) Description of the Rhine delta with existing operated structures and (Right) overview of the simplified 1-D hydrodynamic model (van Overloop, P.J, 2011).

The 1-D model is used to run stochastic scenarios of simultaneous occurrence of storm surges and Rhine floods and results in the peak water levels and accompanying hydrographs at investigated locations within the delta (van Overloop, P.J, 2011). Tortosa (2012) calibrated and validated this simplified model using simulation results of an accurate high-order numerical model over the period 1970 to 2003 and its accuracy is sufficient for this research.

The Haringvliet sluices are between the estuary of the Haringvliet and the North Sea. It consists of seventeen discharge sluices (each 56.5 m wide) and is located at the mouth of the former Haringvliet-estuary. Each discharge sluice has two gates. Therefore it can turn water from seaside as well as from riverside. The gate can be partially lifted making different discharges through the sluices possible. It prevents rise of the water levels in the Rhine-Meuse delta due to high water levels at the North Sea by closing off the mouth of the Haringvliet estuary. It keeps the Haringvliet fresh by preventing water flowing into the Haringvliet from the North Sea and it keeps the water level at Moerdijk above 0 m MSL;	
The Volkerak sluices are between Hollandsch Diep and Volkerak. Water can be discharged from the Hollandsch Diep to the Volkerak by means of 4 discharge gates each of 30 m width. The crest of these gates is at -4.25 m MSL, while the maximum opening is 1.50 m MSL;	

The Maeslant storm surge barrier is between New Waterway ("Nieuwe Waterweg") and the North Sea. The Maeslant barrier is capable of closing off the New Waterway. The structure consists of two gates that, when it has to close off the New Waterway, are floated out their dry docks and sunk down to the bottom of the canal. The Maeslant barrier therefore prevents the rising of the water levels in the lower Dutch Rhine delta behind the barrier, due to high water levels at the North Sea, by closing of the New Waterway;	
The Hartel storm surge barrier is also between the New Waterway and the North Sea. It has two gates, which can be lowered to close off the Hartel canal. Similar to the Maeslant barrier, the Hartel barrier prevents an increase in the water levels of the lower Dutch Rhine delta area caused by high water levels at the North Sea by closing off the Hartel barrier;	

Figure 2. The main existing structures within the delta (van Overloop, P.J, 2011).

The present operational water management system includes the existing main active hydraulic structures as indicated in Fig. 1 (Left) which are the Maeslant storm surge barrier, Hartel storm surge barrier, Haringvliet gates and the Volkerak gates. The present operational management is based on the rules of the national water board and modeled by flows derived from their discharge-water level relation in combination with these control rules. The details of these existing structures are listed in Fig. 2. In the model calculations it is assumed that the operation of these structures never fails.

When storm surges from the North Sea and Rhine floods occur simultaneously, the Haringvliet gates and the Maeslant Storm Surge Barrier with the Hartel Storm Surge Barrier are designed to close the delta in time, and then the large fluvial flows accumulate during the closure duration and hence may result in extreme water levels within the delta area. Zhong *et al*., (2013) computed the flood frequency curves in Rotterdam and Dordrecht under this condition (see Fig. 3).

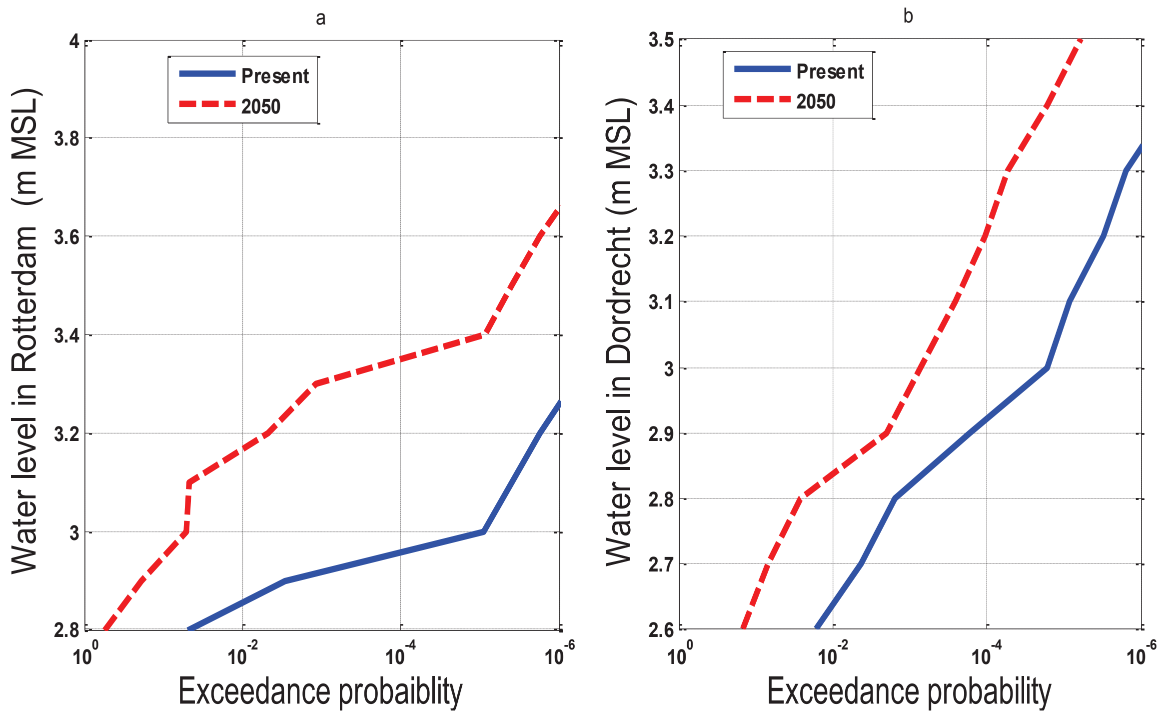

Figure 3. The flood frequency curves due to the simultaneous occurrence of storm surges and Rhine floods in a. Rotterdam. b. Dordrecht (Zhong et al., 2013).

The present design water levels for the investigated locations are available by the recent publication of the Ministry of Infrastructure and the Environment of the Netherlands (Ministerie van Verkeer & Waterstaat., 2007) in Table 1.

Table 1. The present design water levels for the investigated locations

Location	The present design water level (m MSL)	Associated with the frequency
Haringvliet	2.7	1/ 4,000
Hollandsch Diep	2.8	1/ 4,000
Rotterdam	3.6	1/10,000
Dordrecht	3.0	1/2,000

The present operational water management system can cope with the present design water levels. The present flood frequency curves (solid line in Fig.3) show that the official design water level 3.6 m MSL in Rotterdam and 3.0 m MSL in Dordrecht correspond to the exceedance probability of less than 10-6 and 10-5 which are far lower than the official value 10-4 and 5×10-4 respectively. Thanks to the operation of the existing hydraulic structures, the flood frequency complies with the required norm for safety in the present.

The present operational water management system needs adaptations for the future. Due to climate change the future flood frequency curves (dashed line in Fig.3) are much higher than the present curves. The exceedance probability of the present design water level in Dordrecht corresponds to 7.22×10-4, which is higher than 5×10-4. The present system cannot maintain the present design water level for the future flood safety. In other words, the present design water level increases based on the definition of the exceedance probability of 5×10-4. This requires adaptation of the flood defence system in the delta. The question is now if the adaptation of the operational water management system can maintain the present design water levels for the future flood safety?

3. THE ADAPTATION OF THE OPERATIONAL WATER MANAGEMENT SYSTEM

As a suggested adaptation measure, one active floodgate is proposed in the Pannerdensch Canal. The costs for the fourth gate are estimated at 800 M euro (de Jong, R, 2010). Three new active floodgates in Merwede, Drechtse Kil and Spui are designed at the Eastern and Southern side of the cities Rotterdam and Dordrecht. These three new structures are inspired by the research of Delft University of Technology on 'Open and Closed Rhine'. The estimation of the cost of these three gates is 500 M euro each (estimate from 'Open and Closed Rhine'). These structures are designed as floodgates instead of barriers, and therefore these controllable gates can be set on any gate heights in order to better optimistically control the flows instead of being completely open or closed like barriers. These new structures are shown in Fig. 4.

Figure 4. The Rhine delta with four new operated floodgates (van Overloop, P.J, 2011).

These four new controllable structures are expected to lower the potential extreme water levels resulting from these simultaneous extreme events in Rotterdam and Dordrecht. The floodgates are designed to close when the water level in Rotterdam and Dordrecht exceeds a reference water level and the water level in Rotterdam and Dordrecht is lower than the water level in Hollandsch Diep and Haringvliet. During the simultaneous occurrence of storm surges and Rhine floods, these three floodgates work together with the Maeslant barrier and Hartel barrier as a surrounding wall to protect Rotterdam and Dordrecht from the threat of extreme water levels. But the Rhine flow water can still flow into this area via the Lek-Nederijn branch. The designed Pannerdensche gate aims to direct water towards the Waal instead of the Lek- Nederrijn branch. It is expected that the water level in Rotterdam and Dordrecht can be kept low by operation of these four floodgates.

The method of operating these new floodgates is very similar to the present feedback control of the existing controllable structures. The operational control method is shown in Fig.5.

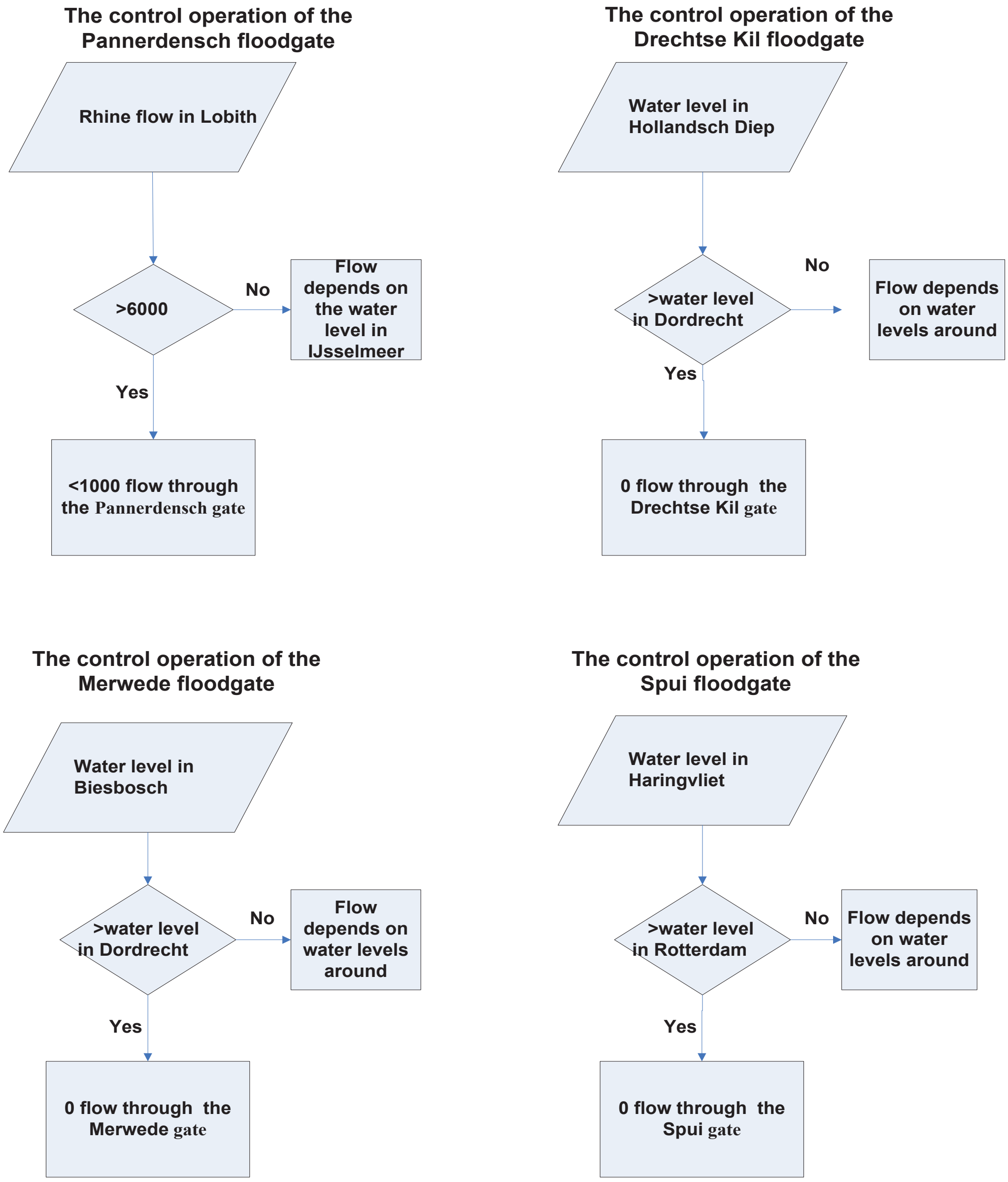

Figure 5. The operational control method for 1. Pannerdensch floodgate; 2. Merwede floodgate; 3. Drechtse Kil floodgate; 4. Spui floodgate.

4. RESULTS

A large number of stochastic scenarios of the source for potential flooding have been generated with the aim of testing the effect of the four new floodgates on reducing extreme water levels in Rotterdam and Dordrecht. These stochastic scenarios are used to drive a 1-D hydrodynamic model associated with the operational water management system. The model is able to run these scenarios into the peak water levels associated with hydrographs in target locations within the delta. These peak water levels are statistically analyzed and transformed into the flood frequency curves. The calculation process is illustrated in Zhong et al., (2013).

To investigate the effect of each floodgate and distinguish the importance for each floodgate, the operational water management system is tested for four situations: 1. the present; 2. the present with the Pannerdensch floodgate; 3. the present with Merwede, Drechtse Kil and Spui floodgates; 4. the present with the above four floodgates. For each situation the frequency results are shown in Fig. 6-9 for each target location.

In addition, the effect of the future climate change scenario is assessed. In the year 2050 the mean sea level rise is assumed to be 0.35 m (van den Hurk et al., 2006) and the peak Rhine discharge increases by 10% reference to the year of 2000 (Jacobs et al., 2000).

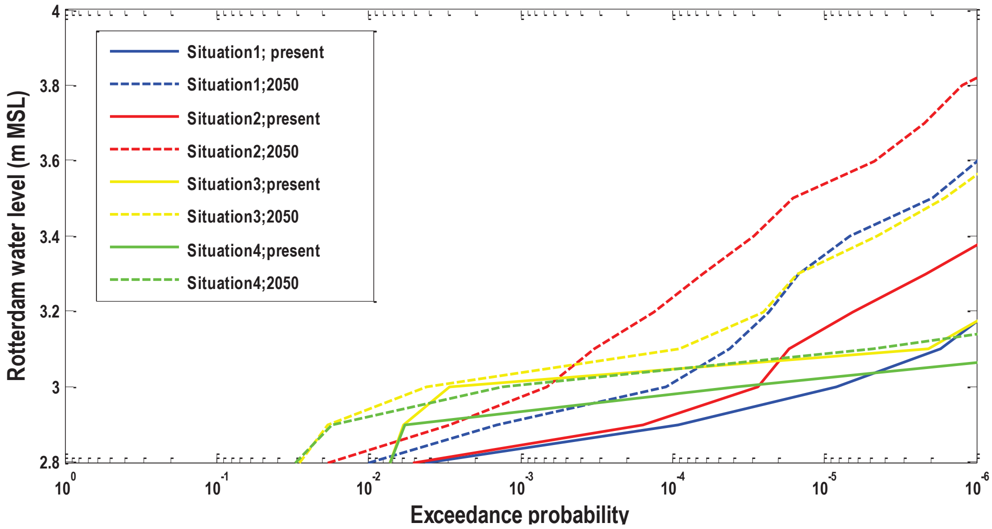

Figure 6. The flood frequency curves due to the simultaneous occurrence of storm surges and Rhine floods in Rotterdam.

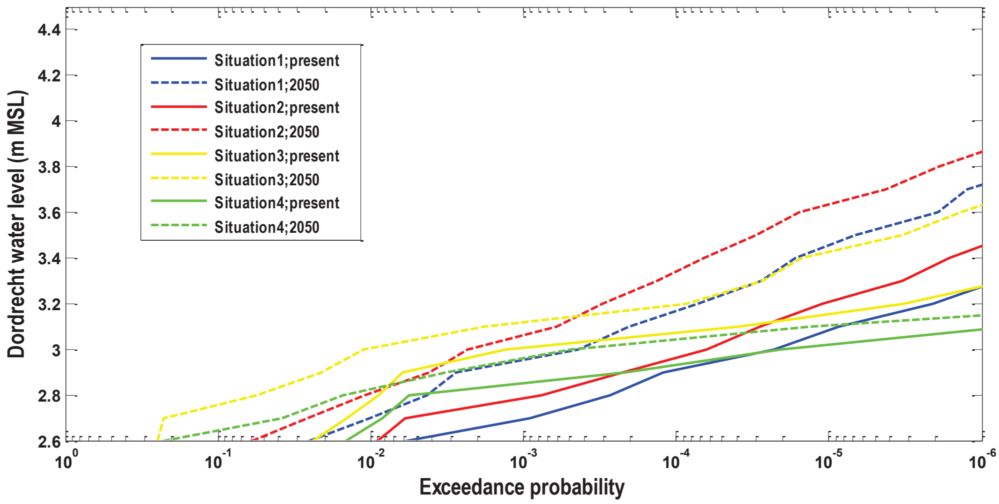

Figure 7. The flood frequency curves due to the simultaneous occurrence of storm surges and Rhine floods in Dordrecht.

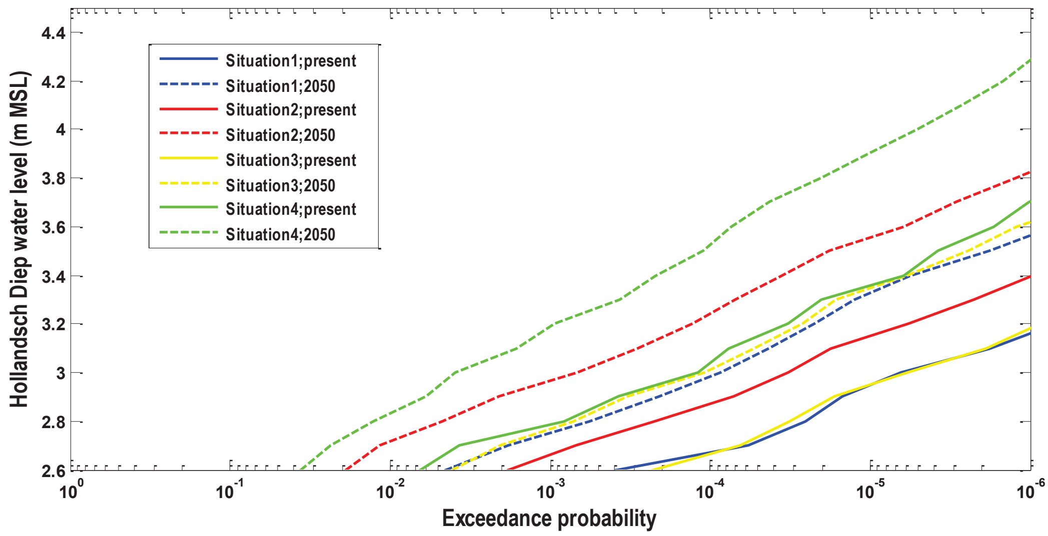

Figure 8. The flood frequency curves due to the simultaneous occurrence of storm surges and Rhine floods in Hollandsch Diep.

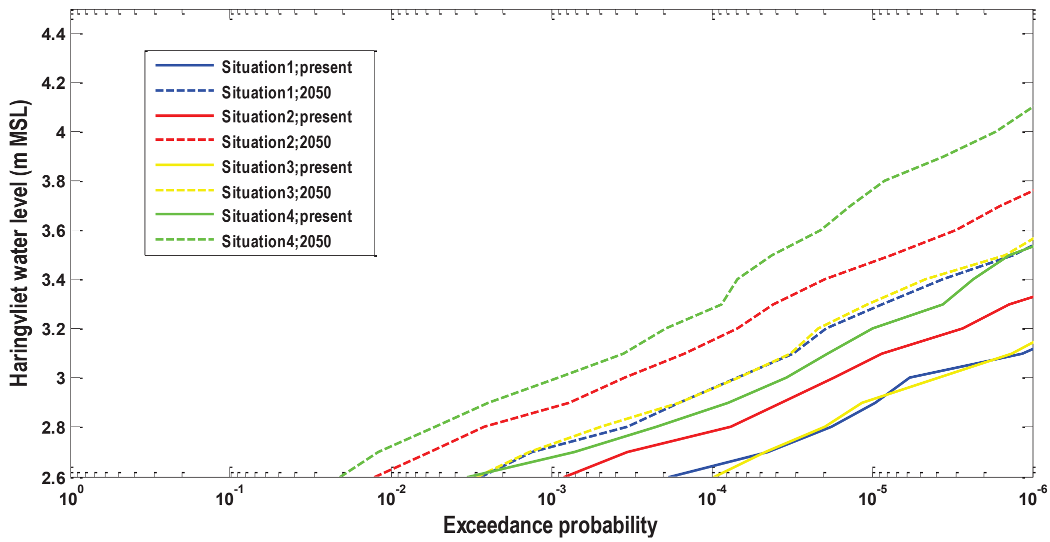

Figure 9. The flood frequency curves due to the simultaneous occurrence of storm surges and Rhine floods in Haringvliet.

From the above figures, we can conclude that:

1. The operation of the Pannerdensch floodgate itself cannot reduce the flood frequency in Rotterdam and Dordrecht; on the contrast it will increase the flood frequency largely in all the investigated locations.
2. The operation of the other three floodgates in Merwede, Drechtse Kil and Spui can reduce the flood frequency with a small amount in Rotterdam and Dordrecht, however, the flood frequency will increase as well in Hollandsch Diep and Haringvliet.
3. The operation of the above four floodgates together can reduce the flood frequency significantly in Rotterdam and Dordrecht. The water level in Rotterdam and Dordrecht are kept much lower than the present design water level even for the most serious simultaneous extreme events in future. However, this operation definitely increases the flood frequency in Hollandsch Diep and Haringvliet largely (see green line in Figure 8 and 9), as most flooding water is delivered to these places. It should be mentioned here that this area has a much lower economic value and enforcements to the dikes and levees are much easier to implement compared to the highly urbanized Rotterdam and Dordrecht area.

4. To look into the climate scenario of 2050, the increase in the mean sea level and the peak Rhine discharge will increase the flood frequency in all four situations. With the suggested adaptation measure Rotterdam and Dordrecht can cope with the future climate change.

5. CONCLUSIONS AND FURTHER RECOMMENDATIONS

This article explores the operational management of four new floodgates to be established in the delta of the Netherlands, and further estimates the new flood frequency in the Dutch Lower Rhine Delta if these floodgates were to be constructed. With the help of a new operational water management system, Rotterdam and Dordrecht can cope with the future climate change and become safer.

Further recommendations for future research are:

1. In this research the possible failure of the gates has not addressed. This needs to be included in future results, with the goal to see how much the benefit of the new structures and the new operational system regarding the flood frequencies reduces. If this is significant there may be a need to improve the operational system further or to propose very robust and possibly redundantly designed new structures.
2. The frequencies results indicate that the feedback control method applied to the four floodgates is straightforward and successfully decrease the extreme water levels in Rotterdam and Dordrecht. However, the control parameters are chosen rather arbitrarily. For example, 1000 m^3/s is allowed to flow through the Pannerdensch floodgate when Rhine flow in Lobith exceeds 6000 m^3/s. The control parameters could be optimized in order to further reduce the flood frequency in the delta.
3. The operational management does not take forecasting information into account. In reality, forecasting of storm surges and Rhine floods is available and can be incorporated in the operational water management system. Moreover, a centralized Model Predictive Control which uses the forecasting information and better meteorological, hydrological and hydrodynamic models is available (van Overloop *et al.*, 2010). It is expected that the application of the advanced operational management in the existing and new controllable structures can further lower the flood frequency in the delta. However, at present, the computational burden is a big barrier for estimating the effect of the advanced operational management on the flood frequency reduction in the delta.
4. The operation of the Pannerdensch floodgate allows most of the Rhine flood flow in Lobith to go to the Waal River and therefore the capacity of the Waal River is vital for the new operational water management system. This article assumes the capacity of the Waal is kept as the present and ignores the important linkage between the operational rule of the Pannerdensch floodgate and the capacity of the Waal River. These will be taken into consideration in further studies. Turning to the capacity of the Waal River, the present project ‘Room for the Rhine’ aims to increase the capacity of the Waal River for high Rhine discharges.
5. The new operational water management system avoids extreme water levels in the highly urbanized Rotterdam and Dordrecht by allowing high water levels in Hollandsch Diep and Haringvliet where mostly farmlands are located. The benefit comes from the fact that damage induced by flooding in the low value areas is much lower than the high value areas. Given good forecasting and evacuation measures, it is expected that human losses can be avoided. However, more detail on the damage analysis is required for the support of this strategy.

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