

## MOVEABLE FLOOD BARRIERS IN THE RHINE-MEUSE ESTUARY

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**ABSTRACT:** It is possible to reduce flood risk in estuaries without having to drastically modify the river banks by levees or to block shipping routes and ecological flows by dams. 'Storm surge barriers' close off a river mouth at times of high sea water levels, but keep the river open during calmer times. 'Moveable river flood barriers' direct a river towards less urbanised parts of the delta. It is likely that with climate change and continuing economic growth more of these barriers will be built worldwide.

The influential Dutch state commission the 'Delta Commission' has adopted an idea by Delft University of Technology to flood-proof the Dutch Rhine-Meuse delta by a number of existing and new moveable barriers. These will direct high water flows in desired directions, particularly at times when a storm at sea coincides with high river discharges. This would create a historically complex system of flood defenses, thus needing thorough modelling and more detailed design to evaluate benefits and costs. This paper will compare a number of alternatives as follows: locate the various barriers on different locations, see where additional river widenings would be possible, calculate the remaining required levee modifications (dictated by Dutch national flood law) as a function of sea level rise, determine the effects on urbanisation of the river banks, on shipping, and if possible also on ecological flows. This comparison will in this paper not lead to the 'best configuration', but to valuable insight in the system. It appears that improving the high water prediction errors and the location, failure probability, operating regimes and architecture of the barriers will increase benefits and reduce costs of the entire flood protection system.

This paper follows from a multidisciplinary, explorative and practically-oriented research project (11 different researchers and consultants) conducted under the Dutch 'Hotspot Rotterdam - Knowledge for Climate' programme in 2010.

Key Words: Flood Risk, Flood Works, River Engineering, Hydraulic Engineering, Urbanism



Figure 1: idea by Delft University of Technology as adopted by the national 'Delta Committee 2008'

## 1. A SYSTEMS APPROACH

In spring 2008, Delft University of Technology wrote a report for the national 'Second Delta Committee'. The report included a colorful drawing of an option for the long-term flood safety of Rotterdam and the Drecht Cities (Kok 2008). The Delta Committee used this image to illustrate their 'closable-but-open' recommendation for the Rhine estuary and explicitly recommended further research in the near future (Delta Committee 2008, Stive 2011).

Meanwhile the study 'Rhine estuary closeable but open – a multidisciplinary exploration' has been carried out for the research programmes 'Rotterdam Climate Proof' and 'Knowledge for Climate', conducted by the same researchers that made the initial drawing for the Delta Committee. Six specialized reports together with an integration report were the result of this study (Kok, Rijcken 2010).

The recommendation for a closable-but-open Rhine estuary, as formulated by the Delta Committee, represents a vision and the accompanying image showed an idea. In accordance to this vision and initial idea, this multidisciplinary exploration has set two goals. The first is to study the effectiveness of the idea, and the second is to gain insight in the influence of new movable flood barriers on the interplay between the components of the Rhine-Meuse estuary as an 'integrated system'. These different components are: the flood risks of the inner and the outer dike (unembanked) areas, shipping, and the spatial development of the levees and the unembanked areas (with a focus on the highly urbanized Rotterdam and Drecht Cities region). The method chosen to achieve these goals includes five particular alternatives. These alternatives are all variations on the initial idea of a 'closable-but-open Rhine-Meuse estuary', on either the seaside or on both the sea and riverside, and researching them will address goal one. However, studying the alternatives will primarily serve the second goal: to develop a systematical approach to the case (fig. 2).

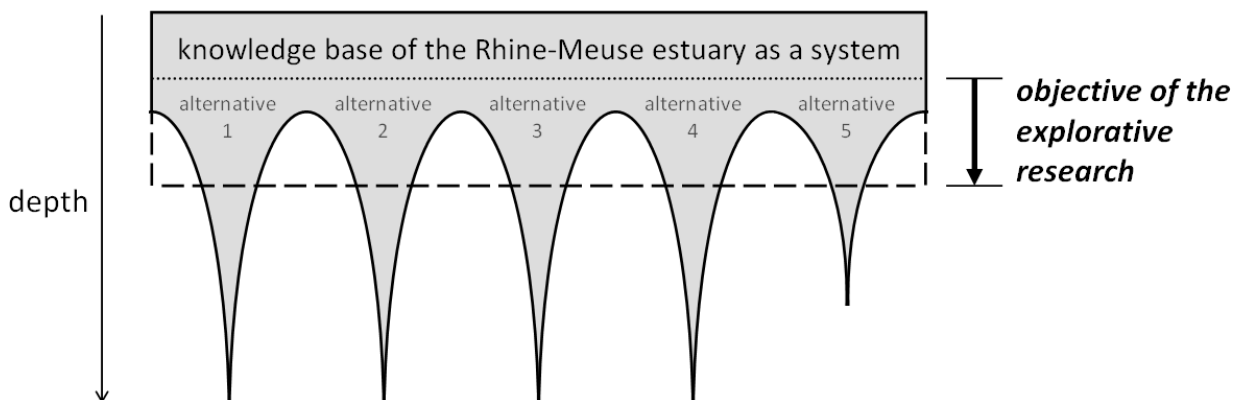


Figure 2: using alternatives to increase insight in the system components interplay

The starting point of this systems approach is the existing geometry of the entire unembanked area (dry and wet) together with the adjacent dikes (levees). To this geometry, additional 'means' can be added. First, the movable flood barriers, such as the existing barriers in the Europoort and the new barriers as suggested in the recommendation by the Delta Committee. These objects can direct the water in desired directions under different hydraulic conditions. Second, it is possible to alter the existing geometry by connecting it to an adjacent system like the basins in Zeeland (in the south) or creating an entire new outer dike waterway in the current inner dike area. Both these additions will be called 'means' in the systems approach used in this research; see figure 3. The approach revolves around the national Dutch flood law (TAW 1998) and is based on probabilistic engineering, design theory and multi-criteria methodologies (Van Dantzig 1956, Vrijling 1997 and 2005, Walker 2000, de Jong 2002).

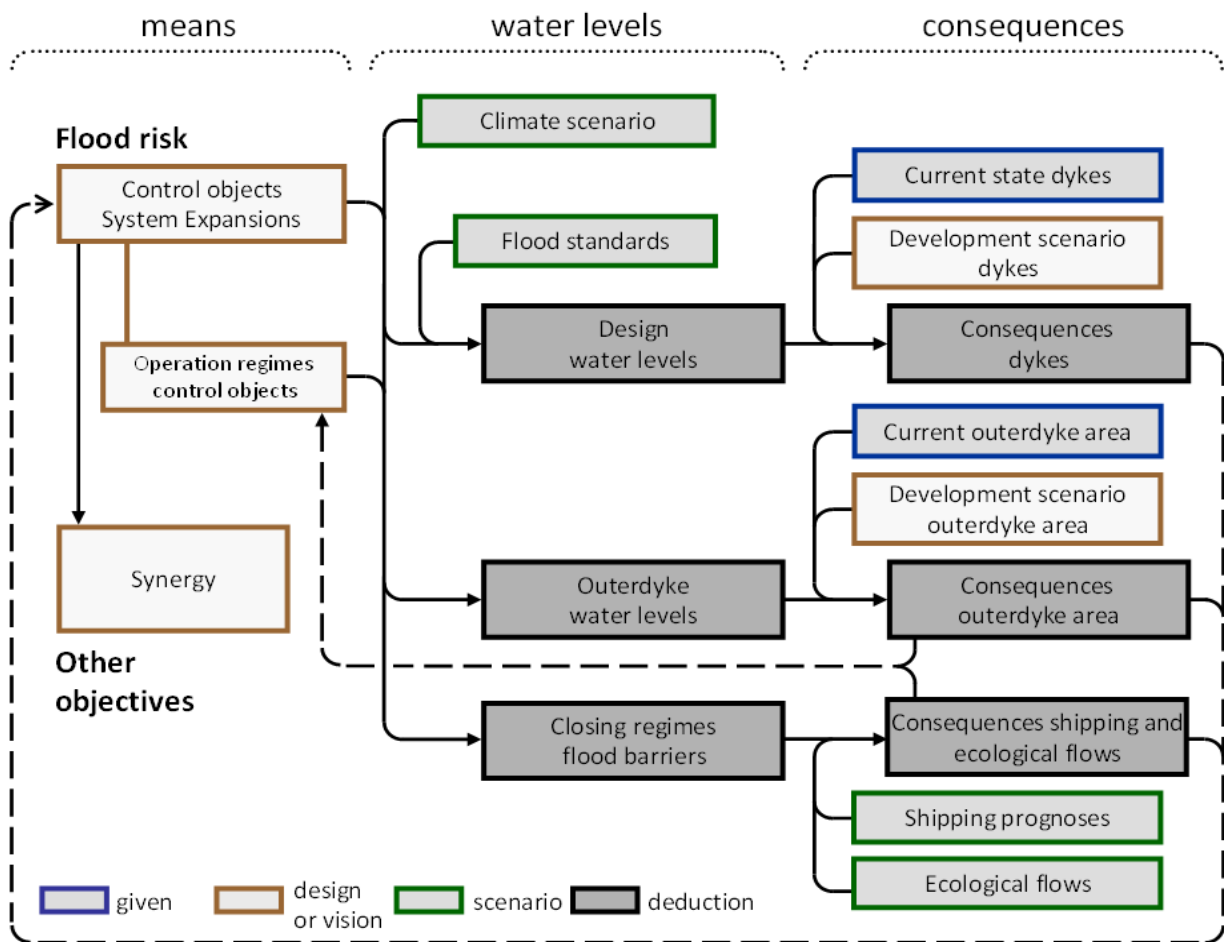


Figure 3: the systems approach developed and used in this multidisciplinary research

Water levels follow from the alternatives, including 'closing regimes' of the movable barriers, and from national flood protection standards and climate change scenarios. These water levels, and also the closing frequencies of the barriers, are the crucial link between the alternatives and the consequences of the alternatives on the levees, the unembanked area, and shipping. Just as shipping can be perceived as a network of 'flows' of ships through the system, also the ecological 'flows' play a part in the systems approach. The ecological flows have not been explicitly studied in the current research, nor have related goals such as freshwater supply and transportation infrastructure, but they have to be taken into account for a complete systems approach.

The consequences do not only depend on the water levels and closing frequencies but also on shipping prognoses and the urban or spatial developments of the levees and the unembanked areas. Finally, an integrated image of the various consequences offers two important 'feedback loops' in the systematical approach. The first are suggestions for other alternatives, such as an additional system expansion or to omit of one of the movable barriers. The second is the alteration of the closing regime for one of the movable barriers or for all the barriers together. These closing regimes deserve special attention since they are an influential and at the same time the most flexible parameter of the alternatives. The regime for the existing Europoort storm surge barriers for example, is ordered to be reconsidered by the national government every five years (Muntinga 2006).

## 2. MEANS

The report 'multifunctional movable barriers' describes the research on the hydraulic as well as the architectural aspects of movable flood barriers for sea and river. It concludes that these objects can fit nicely in the various types of the Dutch water landscape. They also offer plenty of opportunities to integrate with secondary functions and they can be designed to be 'flexible', sustainable and even 'displacable'. Research on building costs shows that the four movable barriers in the initial plan can cost around 850 million euro all together.

The failure probability per closing request of a movable barrier is of significant importance to the design water levels (dictated by national flood standards) and with that to the consequences for the levees. The specialized report 'First exploration flood safety Rijnmond-Drecht Cities', made by HKV consultants, shows how two Maeslant barriers with each an probability of failure of once every two-hundred closing requests, can result in a combined probability of 1/10.000. A failure probability of 1/1000 in one single barrier can be a feasible technical challenge by making a 'fundamental redesign of the control and decision system' (Rijcken and Kok 2010).

The reports 'First exploration flood safety' by HKV consultants, and 'Nature and environment', written by RIVM (Rijcken and Kok 2010), look more closely into the spatial matters of the new waterway the 'New Lek', into the widening of the New Merwede and into water storage southbound in Zeeland ('system expansions', see the two examples in figure 4). Proposed new river the 'New Lek' is feasible, but will have a high impact and high costs. Like the widening of the Nieuwe Merwede, it can generate new nature but at higher costs than creating the same amount of nature elsewhere (without water safety as primary goal). The area around the New Merwede is dominated by the Natura 2000 legislation, which will create difficulties for the possible relocation of levees.

The report 'Urbanism and multifunctional levees' suggests an interesting third spatial measure in the east of the Rhine-Meuse estuary: creating a bypass along the eastside of Werkendam. This can affect the surrounding water levels similar to widening the Merwede.

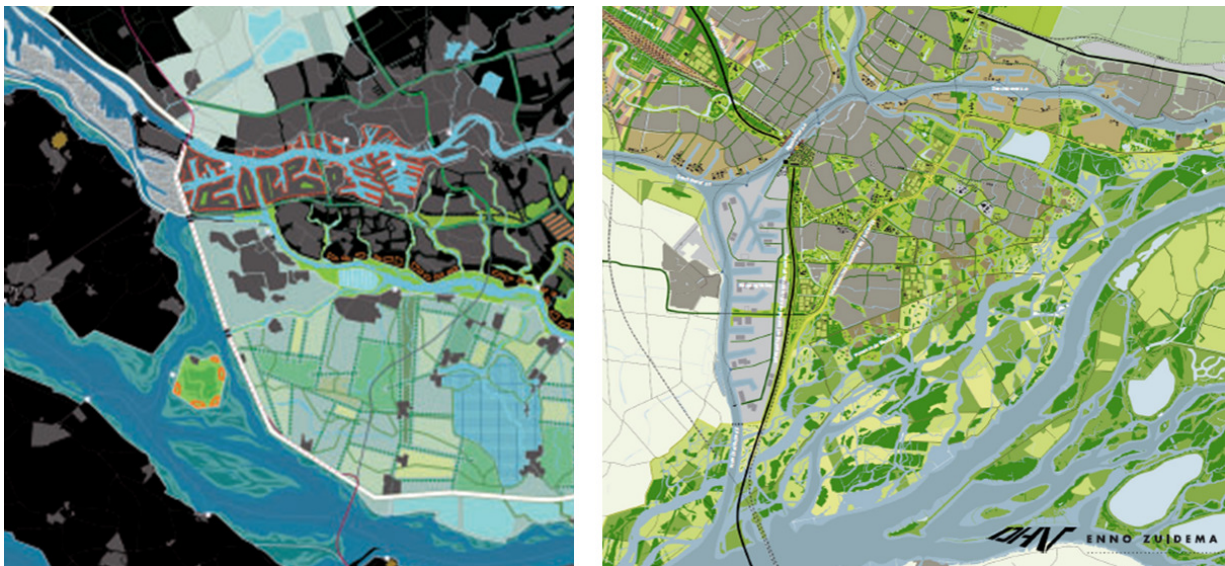


Figure 4: means: 'system expansions'. The drawings show a new river under Rotterdam (left - concept by Kuijper Compagnons) and widening the Nieuwe Merwede (right – concept by DHV and Enno Zuidema, EO Wijers 2009)

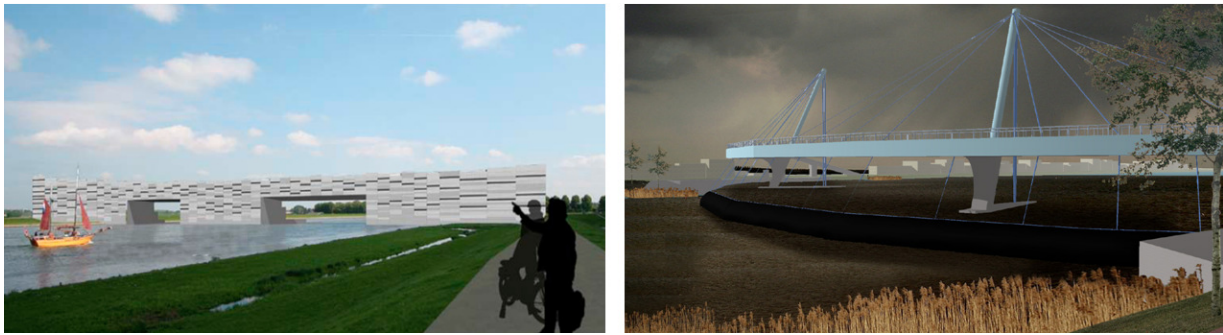


Figure 5: means: 'control objects'. River barriers by students Anna Dijk (left) and Floris van der Ziel (right)

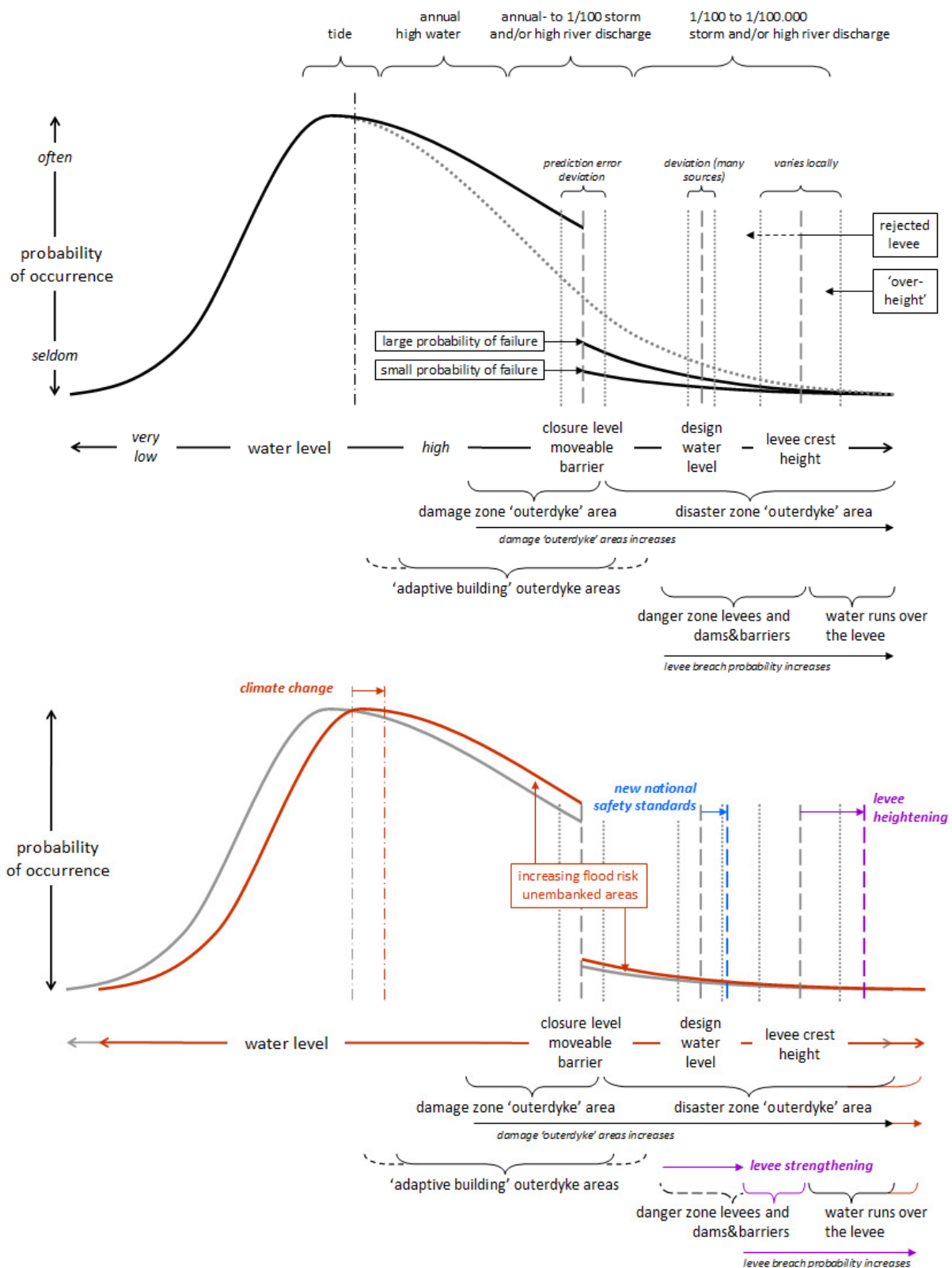
### 3. WATER LEVELS

Design water levels are the levels that the Dutch levees need to withstand according to nationally set legal standards (TAW 1998) (also see figures 7a and 7b). The image of the initial plan, as presented in the report by the Delta Committee, suggests that the design water levels within the 'ring' of movable barriers and levees, will not go up, despite the effects of climate change. The report 'First exploration water safety Rijnmond-Drecht Cities' researches this statement for the climate scenarios 'KNMI-G+' and 'Delta Committee 2008' and worked with the five alternatives (Rijcken and Kok 2010). It appears that in an open or closable-open system the daily water levels will increase in accordance with the sealevel rise in the areas dominated by sea, and the area dominated by both sea and rivers. Calculations have been made for six cities to show the design water levels in the two climate scenarios and in the five alternatives (see figure 6 for the current situation under climate change). A smaller failure probability of the Europoort barrier in Rotterdam will be able to maintain the current normative water levels in the 'G+' scenario'. The Merwede barrier (which does not yet exist) would do the same in Dordrecht when combined with water storage in Zeeland. The barriers in Spui and Dordtse Kil appear ineffective in the 'G+' scenario as well as the 'Delta Committee 2008' scenario if combined with sufficient water storage in Zeeland.

With a sealevel rise of 1.30 meter, as stated in the 'Delta Committee 2008 scenario', it will no longer be possible to keep the design water levels equal to the current ones in a closable-but-open system, not



Figure 6: Increase of 'hydraulic load levels' (design water levels also incorporating the wave run) under the 'G+' - climate scenario in 2100 (65 cm sea level rise and 12,5% more river discharge), without additional moveable river barriers, at a failure rate of the Europoort barrier of 1/100, under the current safety standards.



Figures 7a and 7b: schematic representation of the distortion of a normal distribution of water levels in an estuary by a moveable high water barrier (storm surge barrier or river barrier)

even with additional overflow-free and leak-free movable barriers with a probability of failure of 1/1000 and additional water storage in the South Western Delta (the characteristics of the 'AOR-PLUS-alternative'). These measurements can lower the design water levels with an extra 30 to 50 centimeter, but this will not be enough to compensate the sealevel rise of 1.30 meter.

This interdisciplinary exploration also uses results on water levels and risks in unembanked areas from the parallel study 'water safety unembanked areas' by Rotterdam Climate Proof and Knowledge for Climate (Veerbeek 2010). The largest urbanized areas are situated along the Nieuwe Maas, the Noord and the Beneden Merwede. It appears that the unembanked areas will flood more frequently and deeper with a closable-but-open system, when the critical closing levels of the barriers stay equal to the current closing level of the Europoort barrier. A smaller failure probability will hardly change this, because most damage occurs in the situation where the water level is high, but when the barrier is not closed yet. In the east of the Rijnmond, the area around Dordrecht, the unembanked areas can be protected by the new barriers. This will require a different closing regime from the current closing level of 2.90 meter for the Europoort barrier, since most of the unembanked areas in the Eastern Rijnmond are situated below 2.90 meter.

The duration of a storm appears to have a big influence on the calculations of the water levels. Water flows at junctions also provide uncertainties in the analyses, but using more advanced and accurate models can minimize these uncertainties (V&W 2007).

#### 4. CONSEQUENCES

The parallel Rotterdam Climate Proof research project 'water safety unembanked areas' provided information on the water levels of the unembanked areas as a basis for two studies within 'Rhine estuary 'closeable but open' – a multidisciplinary exploration'. First, 'Urbanism and multifunctional levees' by Delft University of Technology and second 'Nature and Environment' conducted by RIVM. The report 'First exploration flood safety Rijnmond-Drechtsteden' by HKV consultants, provided the locations of relative low levees to the group 'Urbanism and multifunctional levees', and it provided the closing frequencies per climate scenario to the study 'Shipping', done by Delft University of Technology and the Port of Rotterdam. A separate study conducted by ABF Research focused on the developments of the housing market in Rotterdam and the Drechtsteden, with a special attention for waterfront development. This study expects that each year around 1000 new houses will be built in the municipality of Rotterdam. A

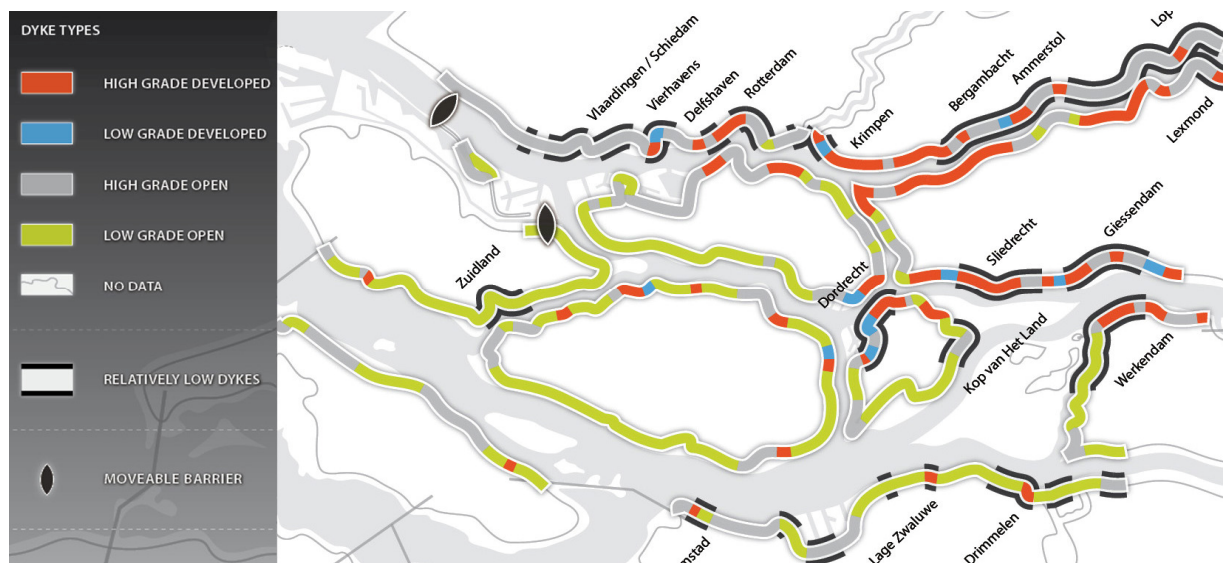


Figure 8: Dyke classification and dykes with relatively low crest height.

significant part of these will be located in unembanked areas, as the result of municipal policy and housing consumer preferences. For the rest of the region, comparable prognoses can be made.

The study 'Urbanism and multifunctional levees' categorized the levees in the Rhine – Meuse estuary in seven different types. Each of these has a different intensity of buildings and different costs for reinforcement (Stalenberg 2010). The unembanked areas were also divided in different categories. Two concluding maps show first of all where the relatively low levees are situated, and second where the most vulnerable unembanked areas can be found.

In this research the costs of reinforcing levees per alternative have been connected directly to the design water levels because it appeared too intensive to include the fragmented 'over-height' (and over-dimensioning) in the calculations. This provides a plausible maximum for the costs of the reinforcements of the levees with maintaining the current safety standards, over the entire 21st century. This number varies between 0.9 and 9 billion euro for the different alternatives and climate scenarios (based on current prices). The cost-indications are quite uncertain for different reasons, but show nevertheless that dispersion of the water level-rise is possible by use of movable barriers and water storage in Zeeland. Directing water flows towards areas where the fortification of the levees is less expensive (as for example for empty 'grass levees') has a positive effect on the total costs.

The parallel study 'water safety unembanked areas' shows that the yearly risk for outer-dike housing and infrastructure (the sum of probability times damage, for various 'return periods') can vary between 0.7 and 1.5 million euros per year for the coming century. Most of the damage is done by water levels that occur once every ten years, when the barriers are predominantly still open. Additional to this damage in costs is the environmental risk. Currently, a little over a 100 companies situated in unembanked locations with polluting materials in their subsoil or facilities, have a flood-risk of 1 to 1000. This number can increase to 350 sites in the upcoming century, according to the report 'Nature and Environment' within this research.

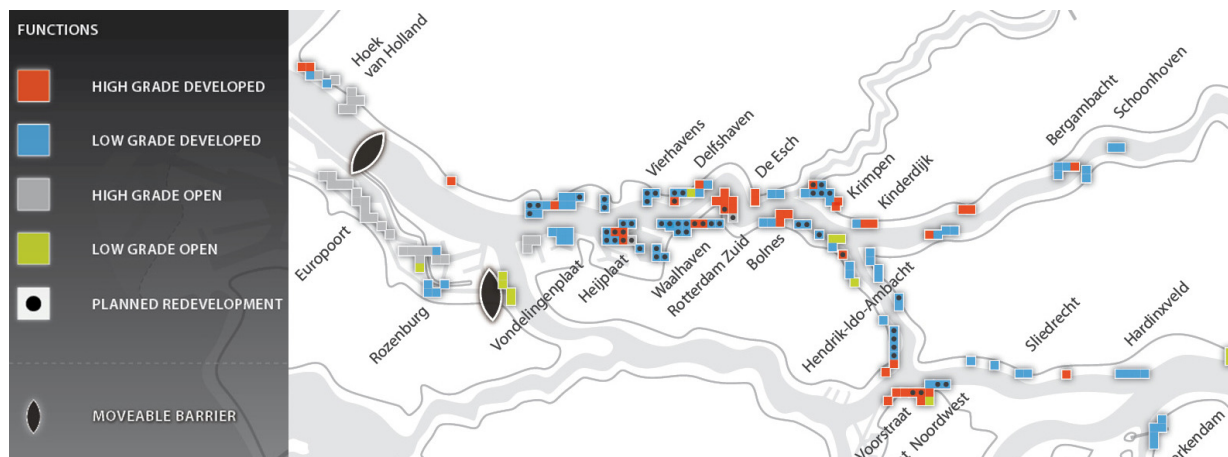


Figure 9: Outer dyke (unembanked) area classification (excluding agricultural and natural areas) in Rijnmond-Drechtsteden with a probability of over 1/100 of flooding in 2100, without additional moveable river barriers, under 65 cm sea level rise and 12,5% more river discharge, maintaining the current Europoort barrier failure rate (1/100) and closing regime (3,00 m).

The shipping report has calculated what the damage to the shipping industry would be, when it would not be able to operate for one entire day. This could have cost 1.8 million euros in 2007 for the inland shipping (of which three-quarter travels through the Hartelcanal and does not pass the Measlant barrier) and 0.75 million euros for sea shipping (all blocked by the Measlant barrier). In 2050 the cost for this last category would be the same as in 2007, but for the inland shipping the cost will increase with almost 50%. This sets the total amount of the damage when closing the port for 24 hours, to over 3 million euro (current prices). With the 'Delta Committee 2008' climate scenario, this situation of closing down the

shipping industry of the Rijnmond can occur once every year around 2050. In that case, the costs for the shipping industry will be bigger than the risk to the unembanked areas. This situation would have an extra impact on the shipping industry since the damage in unembanked areas will be less than now calculated, because of the development of 'adaptive building'. The damage to the shipping industry on the other hand, will be bigger because of the decrease of the reliability of the open hinterland connection and the image of the port of Rotterdam in general.

When climate changes and the closure levels of the barriers will remain the same, this will lead to a faster increase of damage to shipping than to damage in the unembanked areas. Fortunately, the closing regimes can be easily altered to maintain this balance. The costs for the inner dike safety will probably be dominant in the final decision process, but the shipping and unembanked areas are significant to the whole.

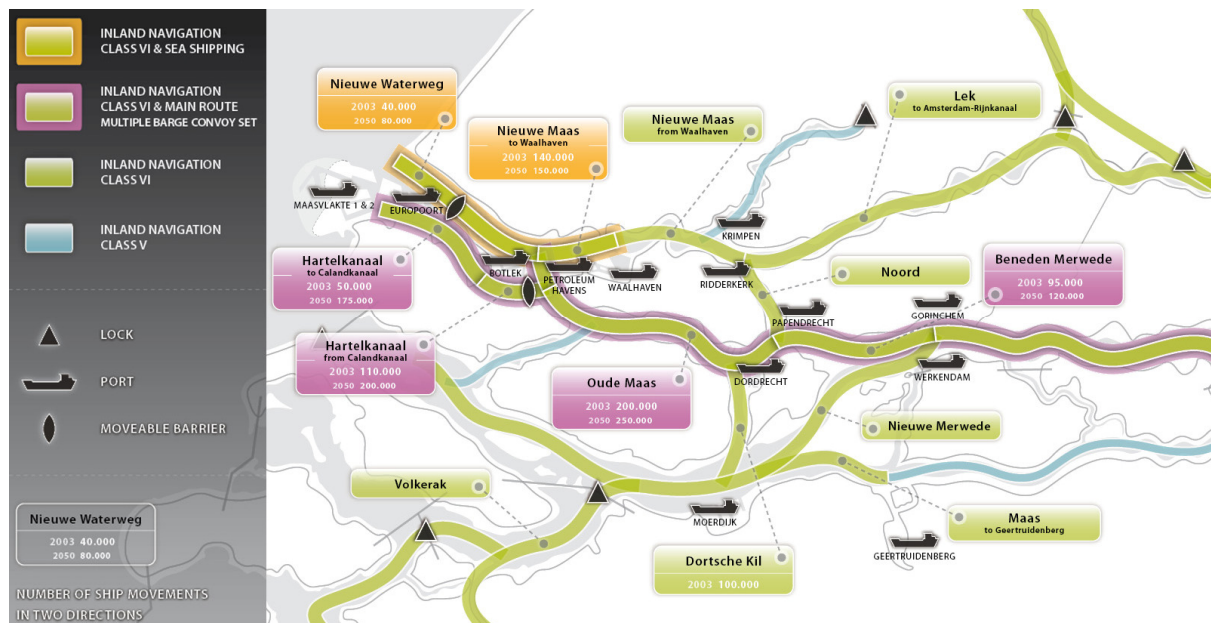


Figure 10: Shipping routes, shipping movements in 2003 and projections for the number of shipping movements for the year 2050, based on the Environmental Impact Report data of the second Maasvlakte.

The study 'Urbanism and multifunctional levees' recommends a number of alternative approaches besides the most general approach where costs are the main parameter for decision making. The 'dike-rings' IJsselmonde and the Island of Dordrecht are currently not a part of the 'Randstad' (the urban area stretching from Amsterdam to Rotterdam). To provide these dike-rings with the same flood safety standards as the Randstad would be a national statement to add these areas to the Randstad as a whole. Higher standards will probably once lead to the choice to close some of the rivers off with movable barriers or dams (closed, closable-open, or something in between). These objects and the levee on the south become a symbol for the extension of dike-ring 14, and for the Randstad 'embracing' IJsselmonde and Dordrecht. The barriers altogether will 'tame' the Nieuwe Maas, the Lek, the Noord and maybe even the Beneden Merwede. These waterways will become less wild and fluctuating and less used by heavy transport. It will give space for more recreation and urban 'intimate' use of the shores. The wins are not only expressed in quantitative features, such as the lower flood risks in the unembanked areas, but also qualitatively. Connections with the inner dike waterways will be easier, new marinas and residential water-areas can be built on locations where it previously had been impossible to develop, because of the environmental contours around hazardous shipping routes. A more intimate experience of the water of the Rijnmond will evolve, similar to which the Randstad has already grown accustomed to.

See the six underlying reports (Rijcken and Kok 2010) for more results and information.

## 5. CONCLUSIONS AND RECOMMENDATIONS

1. Was the idea as drawn in the Delta Committee report a good one? With 1.30 meter sealevel rise (as defined in the Delta Committee 2008 climate scenario), all four of the river-barriers, together with the 'Nieuwe Lek', will result in a lesser increase of the design water levels of 30 centimeter in Dordrecht and 10 centimeter in Rotterdam. Additionally, lowering the failure probability of the Europoort Barrier will result in a lesser increase of 10 centimeter in Dordrecht and 50 centimeter in Rotterdam. Measurements like additional water storage in Zeeland, lower probabilities of failure, less leaking and smarter control of the movable barriers can additionally decrease the rising design water levels up to 30 to 50 centimeter. All together, it will probably not be possible to maintain the current design water levels under a closable-but-open Rhine estuary in the region Rijnmond-Drechtsteden with the idea presented in the Delta Committee report when sealevel rises 1.30 meter. The increase of the design water levels can yet be slowed down significantly.

2. Increasing design water levels do not necessarily lead to reinforcements of the levees because the Deltaworks have provided a substantial (but fragmented) 'overheight' in the levee-system in the Western part of the Rhine estuary. Higher water levels will probably result in higher maintenance costs for the levees and lower water levels can transform a normal levee into a fashionable 'Delta Dike' (Stive 2011). Along the more urbanized sections, reinforcement of the levees will be an expensive undertaking, but it will be possible. There is for example space available to move the levee in the direction of the river, as has been done several times in the past. More research will need to focus not only on sections with or without 'overheight' but also with 'over-dimension' of the current levees.

3. Under the KNMI-G+-climate scenario the current design water levels in Rotterdam and Dordrecht can most probably be maintained until 2100, with the addition of extra water storage capacity in the South Western Delta, a Maeslant barrier with a failure probability of 1/1000 and an additional 'Merwede barrier'. The exact functioning of this barrier without the 'Nieuwe Lek' and the other three river barriers needs closer research. On the longer run, many solutions will be possible, all combinations of movable barriers on strategic locations, dams, additions to the system, and/or levee reinforcements. These can be conceived using 'road maps' and along 'timelines'.

4. A sealevel rise of 1.30 meter will lead to a closing frequency of 30 times every winter when the current closing regime of the Europoort barrier will be maintained for the Europoort barriers and the new barriers. This will lead to an unreliable shipping connection to the hinterland and unacceptable financial damage to the shipping sector. A sealevel rise of 60 centimeter will result in a closure frequency of once every year, which will probably be acceptable to the Port of Rotterdam and the shipping industry in general. Maintaining the current closing regimes at a sealevel rise of 1.30 meter, the movable barriers will not be able to prevent an increase of unembanked flooding with a factor 5 to 10, to 1 or 2 million euros a year. The unembanked areas can cope with more frequent flooding by adaptive measurements on different levels: buildings, building blocks or even enclosing an entire area with a new levee construction (for example when the adjacent levee needs fortification anyway). The shipping industry can look for new possible routes, like the Oude Maas or all the way south to Dordrecht. This would create the possibility to use lower closing levels for probable barriers in the Beneden Merwede, the Noord or the Oude Maas.

5. Unless a radical solution in favour of one of the interests would be adopted sometime during the 21st century, the Rhine-Meuse estuary system will have to ongoingly implement highly customized measures. Maintaining the flood safety of the region the coming centuries will mean keeping a delicate balance between complicated fortification of the urbanized levees, the flood risks for the inner and unembanked areas, the reliability for inland shipping, and ecological flows through the region. The movable barriers can coordinate this balance since their closing regimes can easily be altered at any given moment. They can favor either shipping or the unembanked areas. In the current situation for example, the closing frequency of the Europoort Barrier could still go up, as the average closing rate is still only once every 12 years. Control measurements like these provide time for the unembanked areas to adjust to higher water levels.

6. Currently, the objects that control water flows in the Rhine-Meuse estuary are either dams with gates (the Haringvliet dam and the Volkerak dam), or movable barriers like the Maeslant barrier. A new design that mediates between these two types of barriers could be an interesting alternative. This would be a barrier with a lower probability of failure but a high capacity for shipping passage, river discharge and ecological flows. When designed with care, an hydraulic engineering feat like this can blend in well with its urban or rural surroundings and provide additional value as it connects the opposite shores, creates new public space or serves as a landmark.



Figure 11a: schematic representation of the river water flows during a storm surge. The added effect of climate change and/or higher flood standards spreads out over different branches.



Figure 11b: vision for short term measures based on this research. The added effect of climate change and/or higher flood standards is directed towards the eastern and southern rural area, limiting the effects on the urbanised northern area.

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