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Kennis voor Klimaat

WATERVEILIGHEID BUITENDIJKS SYNTHESE

FLOOD RISK IN UNEMBANKED AREAS

SYNTHESIS

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SAMENVATTING

WATERVEILIGHEID BUITENDIJKS

Inleiding

Langs de rivieren in de regio Rijnmond-Drechtsteden liggen grote oppervlakken stedelijk gebied en havengebieden die niet door de rivierdijken worden beschermd. Dit zijn de buitendijkse gebieden. Vanwege sedimentatie liggen deze gebieden relatief hoog ten opzichte van de binnendijkse zones waardoor ze plaatselijk bestand zijn tegen overstroming. Additionele bescherming vindt hier van oudsher plaats door gronden voorafgaand aan de bouw verder op te hogen met zand. Op regionaal niveau leveren de Maeslant- en Hartelkering bescherming tegen een stormvloed vanuit de Noordzee.

Er bestaat geen uitgewerkt waterveiligheidsbeleid voor deze buitendijkse gebieden. De beleidsontwikkelingen die er zijn, richten zich met name op nieuwbouw en herstructurering. Desalniettemin kent het buitendijks gebied in Rijnmond-Drechtsteden vandaag de dag maar liefst 64.000 inwoners en zijn de aanwezige havens van cruciaal belang voor de economie van Nederland en de buurlanden.

Klimaat- en onderzoeksopgave

3 Klimaatverandering brengt zeespiegelstijging en verandering van de rivierafvoer met zich mee. Daarmee komt het huidige waterveiligheidsniveau onder druk te staan, zich uitend in een hoger risico door toename van zowel kans op als gevolgen van overstromingen. In een viertal onderzoeken is een uitgebreide analyse verricht op de consequenties van klimaatverandering voor de waterveiligheid van buitendijkse gebieden in de regio Rijnmond-Drechtsteden:

1. karakterisering van de overstromingen door waterdiepten en omvang van overstroming in kaart te brengen;
2. karakterisering van de overstromingen door overstromingssnelheden te beschouwen;
3. bepaling van directe schade door overstroming aan stedelijk gebieden (vastgoed en infrastructuur);
4. bepaling van de kwetsbaarheid van havengebieden.

Van elk deelonderzoek is een apart rapport beschikbaar. Daarnaast zijn de resultaten geïntegreerd in een vijfde rapport: de synthese.

Vanwege de onzekerheden in klimaatveranderingen/scenario’s zijn de consequenties in beeld gebracht door zowel uit te gaan van het relatief milde KNMI scenario (G+, 2050) en het extremere Veerman-scenario (1,3 meter zeespiegelstijging, 2100). Hierdoor komt de impact van klimaatverandering in bandbreedtes van tijd en omvang van overstroming tot uitdrukking.

Overstromingen
Vergelijking van de overstromingen in de huidige situatie, G+ en Veermanscenario brengen aan het licht dat het overstroomde oppervlak door klimaatverandering significant toeneemt in tijd en omvang. Overstromingsdiepten variëren hierbij van plaats tot plaats afhankelijk van de reeds aanwezige verschillen in maaiveldhoogte. Natuurlijke overstromingsgebieden (natuur- en recreatiegebieden) overstromen als eerste, gevolgd door stedelijke en havengebieden bij extreme omstandigheden (lees grotere herhalingstijden). De kans op overstroming die kenmerkend was voor extreme omstandigheden verschuift door klimaatverandering in een richting waarbij dezelfde extreme omstandigheden zich vaker gaan voordoen. Ten opzichte van de huidige condities, intensiveren de overstromingsfrequenties met factor 10 voor het G+ scenario en een factor 100 voor het Veerman scenario. Deze getallen blijken overigens sterk afhankelijk te zijn van de faalkans van de Maeslantkering. Aangezien de hoogwaters sterk afhankelijk zijn van de combinatie stormvloed en extreme rivierafvoer, leidt een verlaagde faalkans direct tot een verlaging van overstroomd oppervlakte en waterdiepte.

Stroomsnelheden
De stroomsnelheden van het water in de overstroomde gebieden blijken relatief laag te zijn, tot maximaal 0.5 m/s. In de hoofdstroom van de rivier en op de Maasvlakte (liggend in zee buiten de Maeslantkering) kunnen volgens inschatting hogere stroomsnelheden optreden. Hieruit valt te concluderen dat eventueel optredend instortingsgevaar van gebouwen en infrastructuur beperkt is.

Schade stedelijk gebied
De schade aan vastgoed en infrastructuur in stedelijk gebied is op basis van de overstromingskaarten bepaald. Voor het extreme Veerman scenario, neemt deze potentiële overstromingsschade toe met een ongeveer factor 4. Hierbij gaat het vooral om schade aan vastgoed en in minder mate aan infrastructuur. Overigens beweegt de schade zich van lage tot hoge herhalingstijden redelijk rechtlijnig; van abrupte schade toe- of afnamen is geen sprake. Wel zijn er een aantal opvallendheden te noemen. Zo blijken er verschillen tussen de verschillende klimaatscenario's te zijn wanneer naar de leeftijdsklassen van gebouwen wordt gekeken. In de huidige situatie blijkt vooral veel woningen van de leeftijdscategorie van 1980-2000 bouw getroffen te worden. In het Veerman scenario ligt de piek bij monumentale bouw van voor 1900; het cultureel erfgoed. Ook zijn er zowel in relatieve als absolute zin grote verschillen tussen gemeenten onderling. Een ander opvallend resultaat is dat de schade aan vastgoed voor bijna 50 procent te wijten is aan schade aan de inboedel.

Kwetsbaarheid haveninfrastructuur
Met het in kaart brengen van de kwetsbaarheid van de haveninfrastructuur is een start gemaakt met ontginning van een nieuw kennisgebied. Een belangrijke constatering is dat vooral de vitale infrastructuur voor elektriciteit, ICT en hoofdtransportroutes gevoelig blijkt te zijn voor overstroming. In minder mate geldt dit ook voor natte bulk (olie, gas en LPG). Uitval van deze havenfuncties kan effect sorteren tot ver over de Nederlandse grens. Maatschappelijk ontwrichting kan hierdoor het gevolg zijn. Voor de relatief nieuwe (hoger) aangelegde terreinen blijkt de kans hierop echter redelijk beperkt. Oudere gebieden zouden een grotere risico kunnen lopen, doordat deze lager liggen. Vergelijking van een worst case situatie bij één chemisch bedrijf met en zonder overstroming levert de conclusie op dat de aanwezigheid van water extra risico's brengt. Water kan als een transportmedium fungeren voor gevaarlijke stoffen waardoor risico's voor gezondheid en voor milieu groter worden.

Algemeen oordeel en vervolg
Algemeen kan worden geconcludeerd dat de kwetsbaarheid van buitendijkse gebieden in de huidige situatie voor frequent voorkomende overstromingen redelijk beperkt is, maar dat het gebied wel kwetsbaar is voor overstromingen die zich in extreme omstandigheden voor kunnen doen. Deze kwetsbaarheid neemt als gevolg van klimaatverandering toe. Deze conclusie en de fysieke kenmerken van het buitendijkse gebied pleiten voor een waterveiligheidsstrategie die niet louter gebaseerd is op preventie (voorkomen van overstroming), maar ook rekening houdt met ingecalculeerde overstromingen. In dat laatste geval bieden aanpassingen in de ruimtelijke ordening (aanleg vluchtwegen, hoogwaterbestendig bouwen) en in institutionele arrangementen (verzekeringen tegen overstromingen, plannen voor horizontale of verticale evacuatie) kansrijke perspectieven. Een bijzonder geval is het havengebied waar overstroming substantiële gevolgen (maatschappelijke ontwrichting) kan hebben voor het achterland, tot ver over de grens. Hier is nader onderzoek noodzakelijk om een beter beeld te genereren. Daaraan kan worden toegevoegd dat de kwetsbaarheid van de haven via minder desastreuze ingrepen als het omhoog verplaatsen (droog houden) van het elektriciteitsnetwerk mogelijk sterk kan worden verbeterd.

De resultaten van dit onderzoek leveren inzicht op over de waterveiligheid van buitendijkse gebieden in de regio Rijnmond-Drechtsteden. Daarmee fungeert het onderzoek als een belangrijke voedingsbodem voor de normeringsdiscussies rond waterveiligheid. Daarnaast levert de hoge mate van detail van de resultaten talrijke aangrijpingspunten voor de ontwikkeling van adaptatiestrategieën, zowel op regionale als lokale schaal. Hier liggen dan ook de opgaven en kansen voor nieuw te formuleren onderzoek en uitwerking van praktijkvoorbeelden.

Juiste perspectief
Het is belangrijk om de resultaten van dit onderzoek in het juiste daglicht te plaatsen. Daar waar dit onderzoek effecten benoemt van extreme overstromingen in het buitendijkse gebied, veroorzaken dezelfde klimatologische en hydrologische condities tegelijkertijd ook grote, zo niet grotere problemen voor de binnendijkse gebieden. In deze omstandigheden zouden de relatief hoog gelegen buitendijkse gebieden nog wel eens de letterlijke en figuurlijke veilige havens kunnen zijn voor de dieper gelegen poldergebieden achter de waterkeringen.

SYNTHESIS

FLOOD RISK IN UNEMBANKED AREAS

1. INTRODUCTION

The Rijnmond-Drechtsteden region in the Netherlands is a delta area, which consists of urban, port, and agricultural areas. The majority of these areas is protected by a system of dike rings. Yet, along the rivers, a substantial unembanked area is located often hosting urban and industrial areas. Many of these areas are relatively safeguarded against flooding because of their high level of elevation. This is caused by a process of sedimentation and additional manmade structures. Part of the area is protected against storm surges by a system of barriers that can be closed during a storm surge (see figure 1).

At present, no adequate flood risk policy is available for the unembanked areas. This extents to liability issues in relation to flood damages. In a way, the unembanked areas operate as free-zones in which homeowners and businesses are individually responsible for suffered flood impacts. At the moment, the Province of South Holland is developing a flood risk policy for the future location of vulnerable functions (e.g. power plants, hospitals) in the unembanked areas. For the moment, the existing building stock and infrastructure are excluded from these plans. Generally though, new constructions are validated against municipal zoning plans and regulations without a proper liability construction; so if you build a new building according to the zoning plan, any suffered flood damages will not be compensated by a third-party.

As for other delta areas, the potential consequences of climate change could increase flood risk significantly. The combination of sea level rise and increasing river discharge elevates water stages to a maybe unprecedented level. Furthermore, current climate change predictions differ substantially which decreases the confidence intervals on which current flood defence standards are based. This increases the residual risk of flooding which could force us to redesign current strategies.

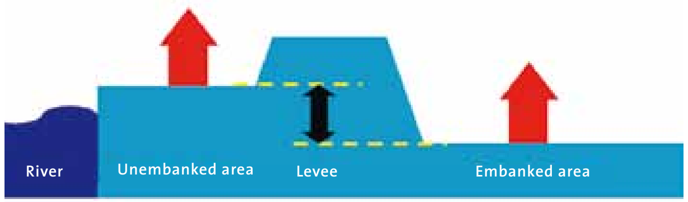


Fig. 1. Protection of unembanked area in Rijnmond-Drechtsteden by
1) higher elevation of ground (man made),
2) storm surge barrier (only the Maeslantkering is shown)

2. AIM AND OBJECTIVES

To cope with a potentially larger flood risk resulting from climate change, a better understanding is needed about the flood risk in the unembanked areas in the Rijnmond-Drechtsteden region. These insights are important to assess the hazard for the current urban and industrial extent as well as for future planning operations. This is especially prudent since the area is a major contributor to the Dutch economy and hosts a significant population. Within the Knowledge for Climate Program, a thorough study was performed on flood risk assessment for the unembanked areas of the Rijnmond-Drechtsteden region.

Central question: What are the consequences of climate change for flood risk of the unembanked area in the Rijnmond-Drechtsteden area?

Subquestions:

- What is the flood extent and what are the corresponding flow velocities and water depths in present and climate change scenario's?
- What are the characteristics of the direct damage resulting from these floods?
- What is the flood vulnerability of new developed port area?

Since flood risk can be subdivided into a hazard component (including the probability of the hazard) and an impact component, the study has been subdivided into four different sub categories. These consist of:

A. Flood extent and depth estimation for a wide range of return periods and with a high level of detail;
B. Analysis of flood velocities to identify additional hazard resulting from flooding within the study area;
C. Flood damage estimation focusing on the urbanized areas using a high level of detail in which urban differentiation is taken into account;
D. Flood vulnerability estimation focusing on newly developed port area.

Note that these studies provide a highly detailed but still incomplete picture of the potential consequences of flooding. Flood impacts consist of tangible and intangible consequences and in turn, the tangle consequences can be subdivided further into direct and indirect effects. Research on some of these areas is still in development, while others have been left outside the scope of this study because of limited resources. Nevertheless, this study could provide a solid framework for further analysis especially because of an excellent combination of breadth and depth.

Although these components have been written as independent chapters (and reports), they fit together and serve as a main reference for flood risk estimation for the Rijnmond-Drechtsteden area. Since many of the results of the first chapters serve as input for the subsequent chapters, the report should preferably be read in the proper order.

3. THE STUDY AREA

Figure 2 shows the study area which runs from the Maasvlakte in the North Sea (West) towards the Drechtsteden in the East. The Rijnmond area is located in between. This typical delta area is subjected to sea tides as well as discharge from the east by the main rivers Rhine en Meuse.

In this study only the area outside the primary flood defences is observed. This region consists out of highly dense urban areas (fig. 3), industrial and port areas (fig. 4), and (to a lesser extent) agricultural and natural areas. In total, more than 64,000 inhabitants are located here, while this number is expected to increase due to future urban (re)development. Furthermore, the case-study area hosts The Port of Rotterdam, which is the largest port of Europe. This makes the area an import economical hub which influence extents beyond the national Dutch boundaries.

Fig. 2 Case-study area. The red dots signify densely population areas. Fig. 3 River island in Rotterdam. Urban and economic functions, partly monumental Fig. 4 One of the oldest sections of the port of Rotterdam

Table 1. Base statistics about the study area

CATEGORY	AMOUNT
total area [ha]	40593
area water [ha]	16481
area land [ha]	24111
# inhabitants	64128
# municipalities	46
# neighborhoods	307
# housing units	30964
# houses	14844
# other buildings	12556
# power plants	4
# metro stations	3
# educational facilities	20
# police stations	6

Traditionally the flood risk in unembanked areas has been reduced by developing urban and industrial areas on elevated (manmade) grounds. Since 1997 the storm surge barrier Maeslantkering (near Hoek van Holland) is operational. Although this barrier performs primarily a formal role in the protection of the areas behind the levees, it also has a secondary and positive influence as it protects the unembanked areas along the rivers.

4. APPROACH AND METHODOLOGIES

The climate change scenarios that have been used to explore future flood risk cover the medium (2050) and long term (2100) as well as a moderate and extreme scenario for the increase of the river discharge and the sea level rise. These are respectively the G+ 2050 scenario (KNMI, 2009) and the Veerman scenario for 2100 (Deltacommissie, 2008).

Table 2 . Discharge and sea level rise for the applied scenarios

Climate scenario	Normative Rhine discharge at Lobith [m^3/s]	Normative Meuse discharge at Borgharen [m^3/s]	Sea-level rise after 2006 [m]
Current situation (2010)	16000	3800	0
KNMI '06 G+ (2050)	18000	4600	0,60
Veerman (2100)	18000	4600	1,30

Part A: flood extent and depth
Every flood risk study requires information on flood characteristics as input. With respect to vulnerability assessments the most important flooding characteristics are flood depth and flood extent. While the extent of the study area is large enough to apply a regional perspective, the level of detail used for the determination of flood maps applies a resolution of 5 meters which provides a very detailed view that connects to the scale level of individual buildings, roads, etc.

Part B: flow velocity
Damage to private properties and port infrastructure can be assessed using water depth maps. However, when flow velocities are high, part of the damage may also be due to these high flow velocities, and not solely due to large water depths. Estimates of flow velocities generally are obtained through measurements and hydraulic models. However, in the downstream river reaches near Dordrecht and Rotterdam, flow velocities only are measured in the channel. Hence, they provide no information on flow velocities at the adjacent quays. As the water depth maps that were developed as part of this project are based on GIS instead of a hydraulic model, they do not provide information on flow velocities either. It was therefore decided to collect information and knowledge on flow velocities in other potentially flooded areas that are located outside the dike ring. The information was then used to deduce estimates of flow velocities that are expected to occur at the quays in the tidal river area near Rotterdam.

Part C: flood damage

The generated data on flood extent, depth and velocity is subsequently used to determine the expected flood damages on individual feature level, thus providing detailed flood risk maps in which both the flood characteristics and the consequences are included. This is especially important in highly populated areas; the applied high level of detail could provide valuable information towards local retrofitting or other low level responses; sparsely populated area in which single assets are flooded might be served better by flood proofing measures on object level. On the other hand, damage 'hotspots' might be effectively protected by small scale (temporal) levee structures. Since space within cities is scarce and large scale interventions are difficult to implement, the approach seems crucial for future urban adaptation towards increasing flood risks. Finally, it is important to note the importance of uniformity. The study area covers 46 different municipalities that now can benefit from a single, uniformly applied flood risk assessment that fits the individual scale level of both smaller towns as well as metropolitan areas. This paves the road for an integrated approach that crosses administrative boundaries.

Part D: flood vulnerability of the port infrastructure

For the port area of Rotterdam, a study was performed focussing on the vulnerability of a range of port infrastructure categories to flooding. To date, only limited literature exists on this topic. In addition, the vulnerability of port infrastructure is case specific, which requires a case-by-case approach. The assessment was therefore based on expert knowledge resulting in a qualitative evaluation on flood vulnerabilities (up to a flood depth of 1 meter) of industries and port infrastructure. In a second part the study focuses on the significance of flood risk of chemical industry compared to the existing risk profile of the area. To test these outcomes a case study was performed for one hypothetical chemical plant within the port area of Rotterdam.

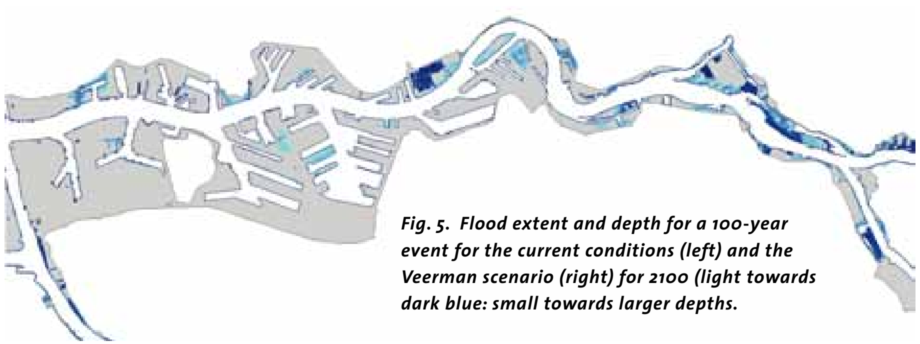
5. RESULTS AND CONCLUSIONS

Part A & B: Flood extent, depth and flow velocities

The initial results of parts A and B of this study assessed the flood extent, depths and flow velocities in the study area for the current situation as well as the two climate change scenarios. While the current flood extent is for 'extreme events' (e.g. a 1:10000 year flood) considerable, the flooded area increases significantly after application of the climate change scenarios. For the current probability distribution, the flood extent increases by about 30% for a 10,000-year event when compared to a 'frequent' 10-year event. Note that this does not imply that the occurring flood depths or velocities increase in a similar fashion. Because of the large variability in elevation levels, these differ substantially per location. Application of the climate scenarios drastically increased the flood extent; the shift in the probability distribution resulting from climate change moves these 'extreme events' into the realm of more frequent floods. This holds especially for the extreme 'Veerman'-scenario for the year 2100 and to a lesser extent for the G+ scenario for 2050. An illustration of the increase in flood extent is depicted in figure 5.

Generally, the estimated return periods for the two climate change scenarios are lowered by a factor 10; the flooding properties for a 10-year event in 2050 are about equal to a 100-year event in the current conditions while the flooding properties of a 10 years event in 2100 are about equal to a 100-year event in 2050. These estimates are strongly affected by the failure rate of the storm surge barrier. A reduced failure rate of the Maeslant storm surge barrier shows in 2010, 2050 and 2100 significant effects on the flood extent and flood depth in the Rotterdam area. This effect gradually diminishes when going further upstream (e.g. the Dordrecht area). Another factor influencing high water levels is the storm duration. Yet, calculations using a reduced storm duration of 29 hours instead of 35 for the extreme Veerman scenario for climate change only resulted in a reduction of up to 6cm in the observed water levels. Further study is required to investigate why this effect is limited. Finally, the effects of the proposed closable but open alternative from the Delta committee's report are limited; no significant reduction in flood extent and depths were found. This is primarily due to the failure rate of the storm surge barriers, which undermine the aim to develop bounded water levels for the area.

The spatial distribution of the flood extent is not uniformly distributed over the unembanked areas. Flooding for low return periods is limited to the natural floodplains while port areas and industrial areas suffer from flooding during higher return periods. The reason for this is the higher terrain elevation in the man-made areas. This can be especially observed in the port areas of Rotterdam where the newer western areas are raised above the original terrain elevation. These areas suffer less from flooding than some of the industrial sites found in the case-study area.



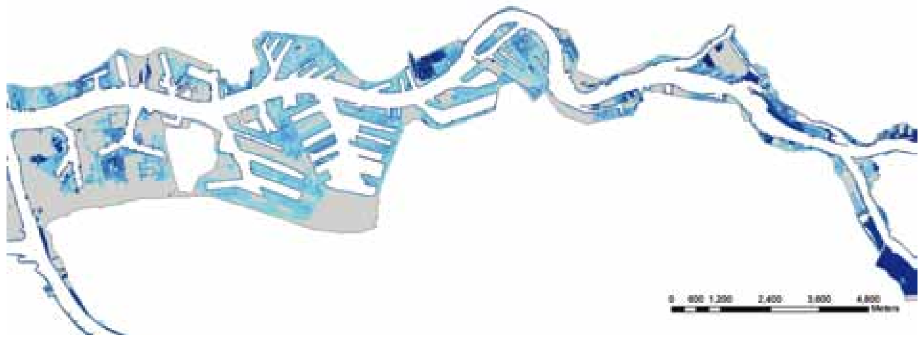


Fig. 5. Flood extent and depth for a 100-year event for the current conditions (left) and the Veerman scenario (right) for 2100 (light towards dark blue: small towards larger depths.

Apart from the flood extent and occurring depths, the expected flood velocities are important determinants for the subsequent flood damages and public safety. These are estimated to be relatively low: in the order of 0.1 to 0.25m/s during flooding. Within the main channels as well as in the Maasvlakte these might locally exceed 0.5 m/s. Note that the expected velocities do not necessarily represent the conditions for overland flow; these might be effectively lower because the higher roughness (e.g. built obstacles, vegetation) of the built-up areas. In exceptional cases though, flood velocities might be boosted when water is forced in between buildings or around obstacles.

Many of the outcomes are dependent on specific technical issues within the applied models including schematization and parameterisation. To assess the reliability of the outcomes a series of sensitivity tests have been performed. The applied model is highly sensitive to the level of detail used for the calculations. Resampling of flood extent and depth data from a cell resolution of $5x5m^2$ to a resolution of $25x25m^2$ has a strong effect on the flood extent. From this study an increase of flood extent of approximately 20% was found as a result of applying an averaging resampling technique. This would lead to overestimation of the flood exposure and possibly in the subsequent damage models. Therefore, all calculations have been made using the highest available level of detail ($5x5m^2$).

Part C: Flood vulnerability assessment urbanized area

The outcomes of part A and B have been used as input for the assessment of flood damages in the urban extent of the Rijnmond-Drechtsteden area. To gain some further insights in the spatial distribution of the flood extent, the number of flooded houses has been determined for the range of return periods and climate scenarios. While within a specific scenario no threshold effects can be identified (i.e. a step-wise increase of the number of flooded houses), the outcomes differ substantially between the applied scenarios. For instance, currently, a 10-year flood results in inundation of 385 housing units in the Rijnmond area. For the G+ scenario and the Veerman scenarios, these figures rise to 1050 and 2674 respectively. This rise extents into the estimation of direct flood damages for which the main outcomes are depicted in figure 6.

For the current conditions, the damage levels in urban areas are relatively low for frequent flooding while high for 'extreme events' (e.g.1:1000 years). Although the damage levels show a sharp increase, threshold effects are limited. Only beyond around the 4000-year mark a minor disproportional increase can be identified. Yet, the applied climate change scenarios cause the damage levels to shift substantially. The G+ scenario results in a damage increase between 89% and 139%. The Veerman 2100 scenario adds another increase ranging between 277% and 400%.

Since the combination of flood extent and spatial distribution of buildings and infrastructure causes a differentiation in susceptibility and the subsequent expected damages, flood damage assessment has been performed for housing and infrastructure individually. The outcomes show that flood damages for infrastructure are smaller than those for housing. These values range between 18% and 39% across different return periods and scenarios. Within the housing units, the expected damages have been further analyzed by assessing the contribution of individual damage components. One of the most important insights from this analysis is that the flood damages for housing are for about 50% composed of damages to the interior (furnishes).

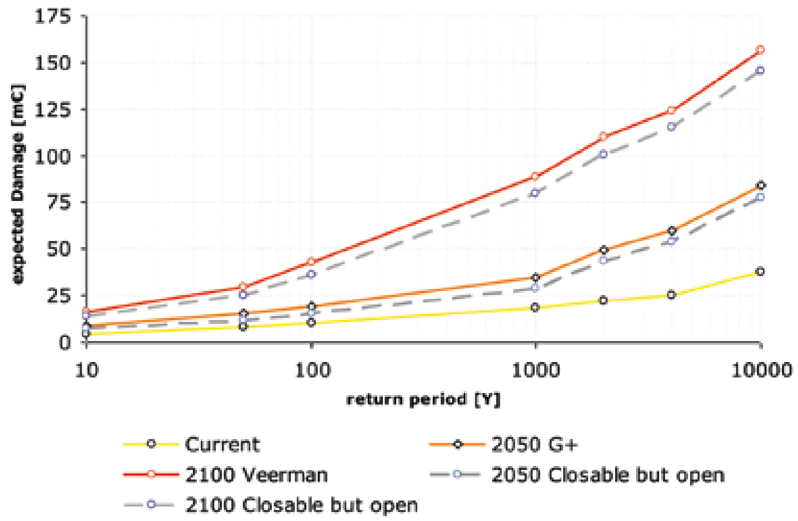


Fig. 6. Expected aggregate damages for the range of return periods and scenarios

The change of flood extent and flood depth causes different parts of the built-up areas to be flooded. The damage distribution over the age of the building stock shows that currently most of the exposed building stock was built during the 1980s. The applied climate change scenarios cause a shift in this distribution; the majority of flood damages is expected in the historic building stock built prior to 1900 (e.g. the historic centre of the city of Dordrecht). Most of the flood damages are located in specific spatial clusters instead of being sparsely distributed over the region. Nevertheless, these clusters shift in location for increasing return periods.

The aggregate and mean annual damage levels are somewhat different when averaging them out over the complete building stock in the unembanked area. For instance, the mean annual damage for the municipality of Rotterdam per housing unit is only € 3.7 per year. This is because only a limited subset of the total housing stock in the unembanked area is exposed to flooding. For other municipalities these figures differ. The maximum mean annual damage per housing unit is currently found in Bergambacht (€ 613.9 per year). Application of the climate change scenarios makes these figures shift substantially. While for Bergambacht the figure almost remains constant, for Dordrecht the mean annual damage per housing unit shifts form € 5.4 per year to € 56.4 per year, increasing more than tenfold.

For the assessment a range of sensitivity studies have been performed to gain insight in the effects of individual parameters in the model. Apart from the similar results found for the resampling of small flooded cells into larger ones (as in part A and B), one of the major refinements came from identifying individual housing characteristics that might reduce the sensitivity to flooding. Elevated ground floors and entrances were identified in many individual buildings and resulted in a maximum decrease in expected damages of 44%. Note that this reduction has been incorporated in the presented estimates.

Part D: Flood vulnerability assessment port area

The results of the qualitative assessment of port infrastructure in the port of Rotterdam shows that especially infrastructure (electricity, ICT, ways of transport) is sensitive to flood exposure. Liquid bulk (e.g. oil, gas, LPG) is also considerd to be sensitive. These sensitivities might have important consequences for maintaining the supply chain; it might create knock-on effects extending over a regional and national scale. Social disruption might therefore be the consequence. Nevertheless, the probability of flooding of the area might be decreasing (more frequent floods) although the return periods might be decreasing because of climate change (see part A & B). Also the measures companies take themselves should be taken into account, which possibly further minimize the risks.

Apart from the indirect damages, flooding of the port area also causes direct effects. The number of casualties for a given flood scenario with a depth of 1m, is expected to be small. Dozens of casualties are expected at most. This is mainly due to a low population density. Compared to the densely populated residential areas the amount of residing employees in the port area is relatively low. Furthermore, consequential effects (e.g. explosions or the release of hazardous goods) are expected to be limited since effective measures are taken to minimize such events.

One of the main concerns in the area is the sensitivity of the power grid to flooding. The provision of electricity is easily compromised which will have severe consequences for keeping up ICT-facilities in the area. These are vital for operation but also during crisis management.

Many of these insights have been investigated further by assessing the consequences of flooding for an (hypothetical) chemical plant in the area. The initial qualitative assessment of casualty rates where reinforced. Furthermore, the number of estimate casualties in offsite areas is expected to be nil. Nevertheless, flooding of chemical installation could increase the hazard of potential health effects for the population in the vicinity. Water acts like a transport medium in which toxic materials could be distributed outside the port area resulting in increased exposure. This could also lead to increased environmental damage. In general though, the flood probability for the area is low compared to the probability of autonomous failure of installations in the area. Additional risk provided by flooding is therefore limited and are expected to be acceptable within the limits of the external safety policy in the Netherlands. The conclusions of the case study are summarized in table 3.

Table 3. Comparison of autonomous risks and additional flood risk for the Rotterdam port area (based on a case study with one chemical plant)

	Worst Case Scenario: No Flooding	**Including Flooding**
Casualties	None/Limited	None/Limited
Affected persons (health effects)	1000(~10 health effects)	1000-2000(~100 health effects)
Economic damage	10-100 m² (plant, down time, claims)	Idem
Environmental damage	Minor	Significant
Cultural damage	None	None

Note that the insights gained from this study do not necessarily apply to all the industrial and port areas within the region. Many, especially older brownfields, are located on lower areas which might be prone to a higher flood risk. Further study needs to be performed to identify these areas and to asses the potential risks.

General conclusions and recommendations

Currently the vulnerability towards frequent floods for the Rijnmond-Drechtsteden area is limited. Because the unembanked areas are located on a relatively high level of elevation, they area is hardly exposed to frequent flooding. This confirms historical data since no major flood events have been recorded in the area. Yet, the area is susceptible for 'extreme events'. Flood impacts are expected to be considerable, which urges for a flood management strategy that does not rely solely on flood prevention. This becomes more prudent when the expected consequences of climate change are taken into account. Floods that are currently considered extreme events might occur much more frequently. Nevertheless does the differentiation found in the unembanked area (e.g. in elevation, asset concentration) provide a multitude of opportunities for adaptation. The high level of detail used in this study identified local hotspots as well as sparsely distributed flood risk. This might further broaden the response portfolio. Special attention is needed for the cultural heritage in the area; many historic buildings are prone to future flooding if no action is taken. Although the studied closable but open option does not contribute significantly to the reduction of flood risk, the outcomes are largely dependent on the failure rate of the storm surge barriers. Decreasing the failure rate might provide a more significant effect and could decrease flood vulnerability for the entire region. Because of the relatively low flood velocities, structural damages as well as casualty rates are not expected. Nevertheless, local exceptions might need further study to minimize these risks.

The Rotterdam port area provides a special case in the flood risk assessment, especially since the possible indirect damages (societal disruption) might be substantial. While on individual level the flood risk seems limited, research has to be performed on the scale effects of flooding; when multiple installations and plants are affected by flooding the consequences might be more substantial than currently estimated. Research is also needed to better asses flood vulnerability of the lower areas. The port area might provide many feasible responses that could increase flood resiliency without major efforts. An example of this is flood proofing the electricity supply to the area.

Ultimately, flood modelling and the subsequent vulnerability and damage assessment is prone to error. While sensitivity and uncertainty analyses have been performed, one of the major factors creating a bias in any research project that includes climate change is the choice of scenarios. While the choice of the scenario might seem arbitrary (especially since climate change scenarios are updated regularly), this doesn't necessarily compromise the legitimacy of the outcomes; since the expected probabilities are associated to specific water stages within the adjacent rivers, the outcomes can be interpreted as a study on the sensitivity of the area towards increasing water stages. Although the probabilities might shift as knowledge on climate change advances, the outcomes of this study might still be relevant in the future.

6. SIGNIFICANCE OF OUTCOME

This research is the first study in the Netherlands that provides insight in the effects of climate change on the flood risk of unembanked urban en port areas, both in general as in detail. Even without the climate change effect this study is of great importance for the present view on flood risk and the associated effects in unembanked areas. The results are useful for the implementation of the Flood Directive of the European Union, and development of evacuations plans and building policies for unembanked areas. In addition, the outcomes provide important input for the Dutch Deltaprogram due to the detailed analysis of the problems this region might face in the future.

The breadth and with of this study could provide a solid base for further study as well as material to actually adapt current flood management strategies. Especially because of the high level of detail, flood risk is no longer a vague external factor that should be taken as a facultative consideration during further development of the urban extent. The considerable level of differentiation in flood risk found in this study, could lead up to tailored solutions that might fit to the often sensitive and decentralized process of urban redevelopment. Also, the breadth of this study shows that flood risk is not an issue concerning one or two individual municipalities. It could serve to cross boundaries between municipalities and fill up a knowledge gap normally unattainable for smaller municipalities. Therefore considerable effort should be put in disseminating the outcomes to all municipalities involved.

Additionally, the outcomes could feed the discussion on current safety standards for the embanked areas. While (future) flood risk for the unembanked areas is considerable, the risk progresses gradually. For the embanked areas on the other hand, residual risk due to climate change might lead to a considerable shift in risk distribution. One reason is that the potential for damage and loss of life in the embanked areas is larger due to the low elevation and the concentration of population and assets. Secondly, considerable damage in unembanked areas is expected to occur during extreme water levels that will also likely lead to flooding of the embanked areas (either because of dike breach or overtopping). Furthermore, the elevation of the unembanked terrain and the tidal effect of the water cause automatic drainage of the flooded areas directly after an extreme event. After a dike breach, the polder area will remain flooded (like a bathtub) untill the breach has been repaired and the floodwater has been pumped out. In extreme situations like this, the unembanked areas will recover much faster than the embanked areas, in some cases even within hours. This might lead to a paradigm shift in which unembanked areas are no longer seen as hazardous. On the contrary, they might serve as 'safe havens' and play in important role in catastrophe management. This is currently further studied in the INTERREG IVb project 'Managing Adaptive Responses to Changing Flood Risk' (MARE) as well as in the Framework 7 project 'Floodprobe'.

The application of the results within policy trajectories or into actual urban (re)development plans is not always straightforward. In the end, experts as well decision makers have to agree on the severity of the indentified risk and on a possible response. The first step in which the usability as well as the identification of potential obstacles will be determined, is the upcoming project in the Knowledge for Climate Programme (HSRR09). In this project these results will be used as a reference for the development of two flood prone case-study areas.

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Further information (including download reports):
http://kennisvoorklimaat.klimaatonderzoeknederland.nl/nl/25222746-Regio_Rotterdam.html
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