Knowledge
for Climate

Flood risk in unembanked areas
Part C Vulnerability assessment based on direct flood damages

KfC report number **KfC 022C/2010**

ROTTERDAM.**CLIMATE**.INITIATIVE
Climate Proof

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Flood risk in unembanked areas

Part C Vulnerability assessment based on direct flood damages

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Samenvatting

Binnen het HSRR02 project, onderdeel van het Kennis voor Klimaat programma, is een kwetsbaarheidstudie gedaan naar huidige en toekomstige overstromingsrisico's binnen de Rijnmond-Drechtsteden regio. Hierbij lag de focus op het bepalen van de directe schade als gevolg van overstromingen voor het buitendijkse gebied. Aangezien dit gebied in hoge mate verstedelijkt is, wat gepaard gaat met een hoge mate van differentiatie, is gewerkt met een hoog detailniveau waarbij overstromingsschade is gemodelleerd op individueel gebouw- en wegniveau. De modellering is gebaseerd op de huidige kansverdeling voor overstromingen alsmede op die voor twee klimaatscenario's: het G+ scenario voor 2050 en het Veerman scenario voor 2100. Analyse van de uitkomsten richtte zich op de ruimtelijke spreiding van de schades, schadecomponenten, de distributie van de schade over de leeftijd van de gebouwvoorraad en de vergelijking van de uitkomsten voor de klimaatscenario's met de huidige situatie.

Met name voor hogere herhalingstijden is de te potentiële schade binnen de huidige kansverdeling substantieel. Deze stijgt van ongeveer €4 miljoen voor een overstroming met een herhalingstijd van 10 jaar naar €37 miljoen voor 10,000 jaar. De potentiële schade wordt drastisch hoger onder invloed van de toegepaste klimaatscenario's. De potentiële jaarlijkse schade bedraagt momenteel €157.000, maar stijgt onder invloed van het G+ 2050 en Veerman 2100 scenario naar respectievelijk €277.000 en €683.000. Een deel van deze toename wordt veroorzaakt door het grote aantal historische panden dat door hogere waterstanden overstroomt. Analyse van de schadecomponenten toont dat de schade aan infrastructuur aanmerkelijk lager ligt dan die voor woningen. Verder blijkt dat bij woningen, de schade voor de helft te wijten is aan schade aan het interieur (meubels e.d.). Bewustwording en adequate waarschuwingsmethodes zouden een aanmerkelijke reductie kunnen bewerkstelligen. Veel van de schade vindt plaats binnen beperkte gebieden: zgn. 'hotspots'. Deze zouden wellicht d.m.v. locale adaptatiemaatregelen overstromingsbestendig kunnen worden gemaakt. Op gemeentelijk niveau valt op dat de potentiële schade vooral plaats vindt binnen de gemeentes Bergambacht, Dordrecht, Nederlek en Rotterdam. Met name in Rotterdam is de potentiële schade als gevolg van de gebruikte klimaatscenario's omvangrijk. Dit wordt voor een groot deel veroorzaakt door de grote aantallen woningen en wegen in het buitendijkse gebied. De gemiddelde schade per woning in het buitendijkse gebied is dan ook laag. Naast technische adaptatiemaatregelen, lijkt het gebied zich te lenen voor zgn. 'non-structural' maatregelen als verzekering. De combinatie van gemiddeld relatief lage potentiële schades en de relatief grote gebouwvoorraad bieden hiervoor mogelijkheden. De haalbaarheid hiervan zal in een verdere studie moeten worden onderzocht.

Summary

Focusing on the unembanked areas, this water safety project in the Knowledge for Climate program addresses the flood damage assessment within the Rijnmond-Drechtsteden region. Because of the high level of urbanization and the resulting differentiation within the area, the assessment was made using a very high level of detail with an emphasis on housing and infrastructure. The assessment was made for the current probability distribution and for two climate change scenarios. The resulting outcomes have been further analyzed, focussing on spatial distribution, damage composition and comparing the current flood impacts with those expected for the climate change scenarios.

The results showed a substantial rise in expected damage levels for the two climate change scenarios. A significant part of the damage to housing is due to the vulnerability of the interior (furnishing). Furthermore, significant future flood damages are to be expected to historic buildings. The Rotterdam municipality is because of its sheer size prone to future flood impacts. Other vulnerable areas include Bergambacht, Nederlek and Dordrecht. The damages are mainly located at specific 'hotspots', which might provide opportunities for local adaptation options. In absolute terms, the damages are significant for flood events with higher return periods. These range between €10 million and €38 million for flood events with return periods between 100 and 10,000 years. After application of the climate change scenarios, these levels have increased to €42 million and €157 million for the Veerman 2100 scenario respectively. Averaged out over the complete building stock in the study area tough, the expected mean annual damages are limited. This especially holds for Rotterdam and Dordrecht where the damages are distributed over a large number of housing units. Within the current conditions, the average mean annual damage is limited to €3.7 and €5.4 respectively per housing unit. Apart from structural responses, the observed 'risk landscape' might provide opportunities for the introduction of non-structural measures like a flood insurance programme.

1. Introduction

Flood impact assessment focusing on urban areas is a vital step in the development of an integrated urban flood management strategy. Especially since current standards are challenged because of the possible consequences of climate change, a detailed study is needed to obtain further insights in the current and future impacts of flooding. Furthermore, an increasing uncertainty about return periods of climatic events causes a paradigm shift in risk assessment: the current emphasis on probability management increasingly moves towards impact assessment. While the increasingly dynamic climatic system [Milly et al., 2008] poses severe questions about its predictability, potential impacts can be controlled by a range of measures.
Within The Netherlands, this is especially prudent for unembanked areas since no actual protection standards exist for these areas [Bergh et al., 2008].

Within this project a detailed flood damage assessment is made for the Rijnmond-Drechtsteden area, Netherlands. Because of the large concentration and differentiation of assets, the level of detail on which the assessment is made is much higher than currently practiced [Kok et al., 2002] within The Netherlands. This could not only enhance the precision of the outcomes, but might also provide a basis for tailored solutions instead of large scale flood protection schemes. Especially since many of the unembanked areas are located on relatively high elevations, the flood risk varies per location. Furthermore, asset concentration (e.g. housing densities) differs substantially.

The project is part of the HSRR02 research project, which consists of the following research topics:

- Flood depths in the unembanked areas: climate scenarios are translated into flood maps. Maps are made based on possible climate adaptation strategies (e.g. ‘Closable but open’ Rijnmond);
- Flow velocities in unembanked areas in the downstream reaches of the rivers Rhine and Meuse. The expected flow velocities are determined and evaluated for their significance within the vulnerability analysis;
- Vulnerability analysis of direct damage: based on the flood maps induced damage occurring in the outer dike area is determined (e.g. urban areas);
- Vulnerability of port infrastructure in unembanked areas: analysis of the port infrastructure and the vulnerabilities, in particular those of the chemical industry.

This report covers the results of research topic 3 describing and analyzing the expected direct flood damages for the current probability distribution, two climate change scenarios as well as the ‘Closable but open’ adaptation proposal [Huizinga, 2010]. The topics within this report cover a description of the i) methodology and objectives, ii) a case description, iii) the exposure to flooding, iv) the estimated aggregate flood damages, v) the deconstruction of the expected flood damages, vi) the spatial distribution of the expected damages and vii) the expected damages over the administrative boundaries within the study area. Furthermore a sensitivity analysis has been performed as well as a discussion on the consequences and opportunities resulting from the outcomes.

2. Methodology and objectives

2.1 General methodology

Ex-ante urban flood damage estimation is a research field which is highly volatile and still in development [e.g. Wind et al., 1999; Merz et al., 2004]. While the hydrological and hydraulic principles of urban flooding are largely known, the high level of differentiation and detail needed for precise flood damage estimations in urban areas still provides obstacles. Furthermore, the exact relation between flood depth, flood velocity, flood duration and the resulting damages are only partly understood. Flood damages, or for this matter damages stemming from natural hazard impact, can be subdivided into direct and indirect damages [Rose, 2004]. While direct damages are classified as damages on property level (e.g. cleaning costs, costs for reconstruction), the estimation of indirect damages focuses on losses resulting from business interruption utility lifeline interruption (e.g. interruption of power or gas lines) as well as knock-on effects within regional or national supply chains (disruption of supply lines causing production losses in related industries). While estimating indirect damages often results in outcomes that vary in orders of magnitude [Veerbeek, 2007], the range in outcomes while assessing direct flood damage estimations is substantially more limited. Yet, empirically acquired data covering direct flood damages is sparse and often limited to single events. Often these events have particular features that make generalization of the obtained damage characteristics problematic (e.g. in case of a dike breach resulting in high flood velocities). Furthermore, local characteristics between cities differ dramatically, which complicate estimations based on a broad urban scale. Therefore it seems vital to assess direct urban flood damages at a high level of detail in which low scale urban typologies are expressed [Veerbeek et al., 2009].

Direct flood damage assessment is generally performed using a set of stage-damage curves. These curves relate expected damage levels to a given flood stage [e.g Büchele et al., 2006] for some urban feature (e.g. a neighbourhood, a housing type, a road). The damage levels can either exist as aggregates or as a composition of different damage components (e.g. cleaning costs, repair costs, replacement costs, etc.). While direct flood damages are often calculated by using the flood stage, other factors can significantly influence the expected damage levels. Generally these consist of the flood velocity and the flood duration. High flood velocities could lead to structural collapse resulting in massive renovation or even replacement of an object [e.g. Roos, 2003], while long flood duration can lead to severe degradation of material properties within the object (e.g. rotting wood). Stage-damage curves as well as velocity and duration-damage curves differ from object to object. Obviously, the curves for infrastructure differ from those for buildings, but also within a given object class, large differences can be perceived; the associated damage levels for an apartment block with a parking garage located on ground floor level differ from those for a bungalow where all living quarters are located on ground floor level. Additionally, the material properties influence the relation between flood characteristics and damage levels: a brick road founded on a sand bed behaves differently from a highway using a composite foundation. Furthermore, anthropogenic factors differ. The furnishing between households differs resulting in different flood damage levels. This doesn't necessarily mean that ex-ante direct damage estimation is impossible. Stage-damage curves as well as velocity and duration-damage curves are slowly becoming available for different object classes including versions for different material characteristics. Demographic and real estate value information is available on almost individual housing level, which in combination with data from the insurance industry is specific enough to estimate household characteristics on an individual housing scale.

Within the scope of the project, the aim is to apply a flood damage assessment model that:

- Is capable of discriminating individual features (buildings, roads, etc.);
- Calculates the direct damages associated with given flood characteristics;
- Uses and provides damage components: e.g. cleaning costs, etc.;
- Is capable of computing large amounts of individual features in combination with high resolution 2d inundation maps;

To achieve this, a new damage assessment model has been developed which is derived from the model used in the Urban Flood Management (UFM) project for the city of Dordrecht [Veerbeek et al., 2009]. One of the challenges in the adaptation of the model results from the extent of the project area, which is significantly larger than for the UFM project. Furthermore, the 5m resolution inundation maps used as input data to indicate local flood stages result in a massive dataset which without adaptation of the model, would result in unfeasible computational loads and calculation times.

Apart from the flood damage calculations, the resulting output needs to be analyzed and described thematically. This addresses the spatial distribution of the flood damages, the damage levels for a range of return periods as well as other modes of representation. These steps are vital since the applied level of detail is too large for manual interpretation. Also, individual characteristics of the damage distribution in relation to urban characteristics (e.g. the age of the building stock) might provide clues for effective response strategies. Finally, different climate change scenarios with associated river discharge levels, sea level rise and resulting flood stages and damages need to be compared to assess future exposure and vulnerability of the region in question.

2.2 Datasets, constrains and assumptions

The targeted level of detail used for the assessment is of course dependent on the available data. The main dataset used for representing the urban extent stems from the TOP10 Vector dataset [TDK, 2009] which provides the highest available level of detail for the complete project area. Unfortunately, descriptive attributes about industry sectors are not available within this dataset which makes flood damage assessment for non-residential objects virtually impossible. The information about individual households is partially obtained from the regional dataset available from the Statistics Netherlands [CBS, 2009], the Rotterdam municipality as well as proprietary information from the insurance sector. The stage-damage curves are based on those used in the UFM Dordrecht project [Veerbeek et al., 2009]. These contain proprietary information provided by the infrastructure and building sector. Since apart from housing, descriptive stage-damage curves for high levels of detail application were only available for infrastructural objects, other surface areas within public space (e.g. parks) have been omitted from this study. Finally, the flood data for a range of return periods is provided by HKV consultants at resolutions of 25 and 5 meters.

Note that extensive statistical information on the industrial and business sectors within the area was unavailable. Apart from identifying potentially flooded buildings or installations, it is therefore virtually impossible to make sound predictions about expected damages for these sectors. Therefore these have been omitted from the damage assessment.

The stage-damage function set used within the project consists of 60 individual curves covering aspects like (i) cleaning costs, (ii) repair/replacement of doors, windows and fittings, (iii) damages to kitchen, (iv) installations and (v) interior (for housing units) as well as (i) material costs, (ii) labour costs and (iii) additional costs for infrastructural objects. Although the amount of stage-damage curves used in this study is substantial, they do not cover the differentiation in housing and infrastructural types found within the area.

Since the expected flood velocities for the unembanked areas are expected to be relatively low [Asselman, 2010], structural collapse of objects is unlikely. Furthermore, the expected duration of the floods is relatively short [Huizinga, 2010] which excludes extensive coverage of damages resulting from degradation of materials. Flood durations beyond 12 hours could lead up to a 20% increase of the expected damages [Flood Hazard Research Centre, 2003]. Consequently, only stage-damage curves have been applied in the calculation process. Also, damages to vehicles or other property is left outside this study although these might add substantial additional damages [Wind et al., 1999].

The hydrological boundary conditions, water-stage levels, return periods and applied climate change scenarios as well as the adaptation scenarios have been provided by HKV consultants.

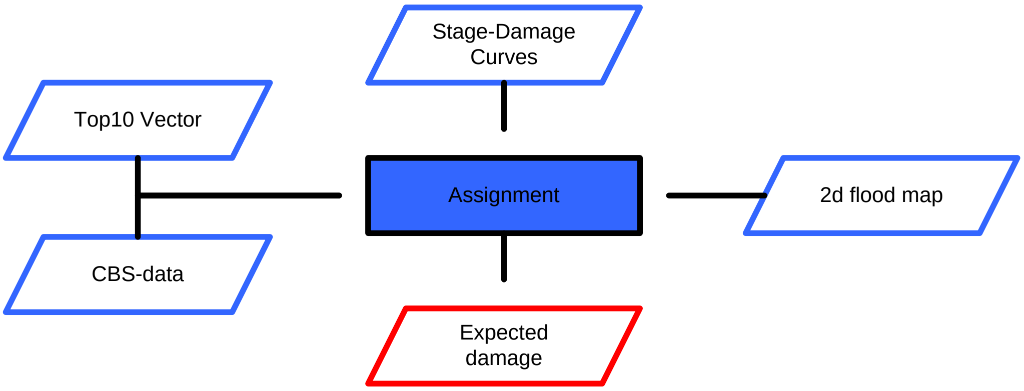
2.3 Procedure

The actual flood damage estimation for individual objects within the project area proceeds as follows:

1. *Flood assignment*. If a feature intersects with a ‘flooded’ grid cell within the 2D flood map corresponding to a flood event with a given return period, the object is assigned as ‘flooded’;
2. *Flood stage determination*. From all intersecting ‘flooded’ grid cells, the maximum flood stage is acquired and assigned to the object;
3. *Stage-damage curve assignment*. The corresponding stage-damage curve is assigned, based on the characteristics of the object in question;
4. *Damage assignment*. Using the assigned stage-damage curve, the damage level corresponding with the assigned flood stage is assigned to the object.

Note that in case of housing, the choice of stage-damage curves requires an additional step. Through a probabilistic assignment based on demographic data (household size), age, real estate value (WOZ value) the value of the interior is estimated. This value is used in the assessment of damages to the furnishing of the household.
The stage-damage curves used are based on discrete flood-stage values with 0.3 meter intervals. Since the majority of flood stages will fall between these values, the associated damages are interpolated using the lower and upper values within an interval. The flood damage estimation method is depicted in Figure 1.

Fig. 1 Flood damage estimation method



Before covering the final outcomes, it is important to describe some of the further steps in model refinement. One of the aspects that has been addressed are possible characteristics of individual buildings that make them less susceptible to flood damages. This holds especially for some of the historic buildings in which ground floor levels are raised significantly above ground level. Also, in some apartment blocks the ground floors are used for parking instead of living quarters which reduce or even eliminate their susceptibility to flood damages. Note that these characteristics are not described in the available datasets. Since the assumption is that such features potentially reduce flood damages significantly, a survey has been performed using Google Street View. The outcome of this survey was that 261 housing units divided over 71 buildings were either adjusted in ground floor elevation height or designated as ‘flood proof’. Since the flood exposed housing stock is largest for the ‘most extreme’ scenario for climate change (Veerman 2100 scenario), the subsequent impact of integration of individual housing characteristics is assumed largest for this scenario. The expected flood damage reduction for different return periods is presented in table 1.

An additional refinement step consisted of application of smaller grid cells in the inundation maps, shifting from a resolution of 25 meters towards 5 meters. Here the assumption is that the coarse grid for the 25 meter maps will result in significant amounts of incorrectly classified objects.

Table 1. Aggregate flood damage reduction in the study area resulting from increasing grid cell resolution for the range of return periods.

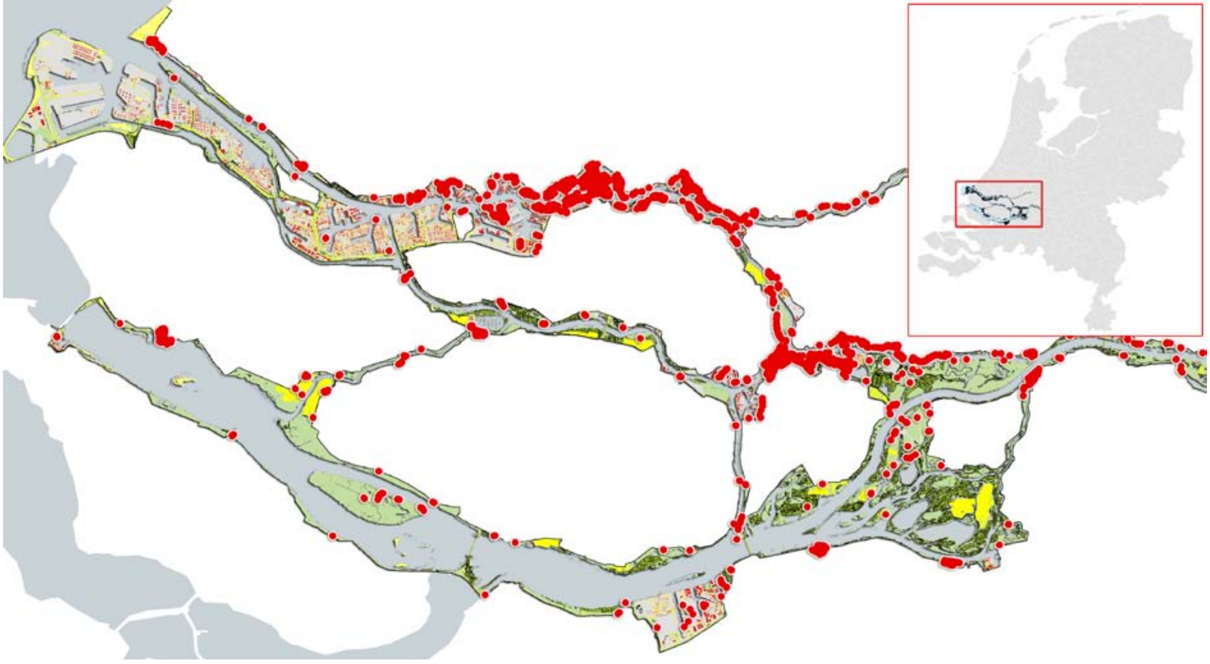
return period	**10**	**50**	**100**	**1000**	**2000**	**4000**	**10,000**
damage reduction adjusted houses	44%	41%	39%	33%	33%	32%	32%
damage reduction increasing resolution	25%	27%	27%	29%	29%	30%	31%

As can be observed, the expected damage reductions are substantial and accounts for both a baseline shift towards lower damage levels as well as a significantly lower damage progression for higher return periods. Furthermore, the reduction because of adjusting the housing characteristics is higher for low return periods (e.g. 44% for a 10-year return period compared to 32% for a 10,000-year return period) but is almost equal to the reduction obtained by application of a higher resolution for higher return periods. This can be explained by the amount of flooded houses; since for shorter return periods the number of flooded houses is assumed to be relatively low, reducing the number of flooded units result in higher reduction levels than for long return periods.

3. Case Description and base figures

The Rijnmond-Drechtsteden area, located in the province of Zuid-Holland (see figure 2), is a highly urbanized area, which includes one of the main ports of The Netherlands: The Port of Rotterdam. It crosses a large amount of administrative areas, including 46 different municipalities. The area contains the cities of Rotterdam and Dordrecht as well as a number of towns and villages. A substantial part of this area is located on a relatively high level of elevation either as a result of sedimentation or man-made structures. This area is located outside the main dike rings alongside the river Meuse. Note that a more thorough description of the hydrological conditions is provided in research topic 1 of this project [Huizinga, 2010].

Fig. 2 Overview of the study area including population centres (marked in red)



The base figures on the area are presented in table 2. Note that the figures are covering only the unembanked areas. Extensive coverage of the economic activities (e.g. harbour facilities) was not available from the datasets and has therefore been omitted.

Table 2 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

4. Exposure to Flooding

Before the actual flood damage assessment it is important to obtain some general insights into the amount of flooded housing units for different return periods. The results are depicted in table 3 in which both the absolute number of flooded housing units is shown as well as the percentage of the total housing stock.

Table 3 Number of flooded houses for different scenarios and return periods.

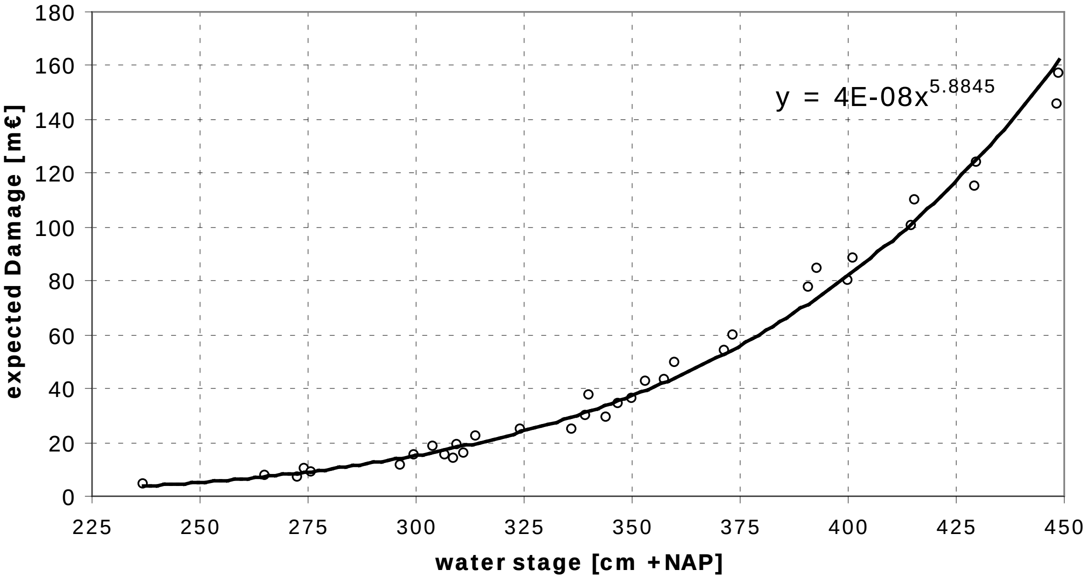
Return Period	**10**	**50**	**100**	**1000**	**2000**	**4000**	**10,000**
Current	385 (1%)	660 (2%)	**101**7 (3%)	2132 (7%)	**2836** (9%)	3297 (10%)	4534 (14%)
2050 G+	**1050** (3%)	1941 (6%)	2541 (8%)	5216 (16%)	7121 (22%)	8361 (26%)	10804 (33%)
2100 Veerman	**2674** (8%)	4965 (15%)	6691 (21%)	11147 (34%)	12516 (38%)	13268 (41%)	14591 (45%)
2050 Closable but Open	779 (2%)	1592(5%)	2246 (21%)	3920 (12%)	5030 (15%)	6711 (21%)	9764 (30%)
2100 Closable but open	2456 (8%)	3788 (12%)	5227 (16%)	10114 (31%)	11757 (36%)	12025 (37%)	13627 (42%)

What can be clearly perceived is first of all the significant increase in flooded houses for the applied climate change scenarios (including the ‘Closable but open’ variants). In the most extreme case (2100 Veerman, RP = 1000) this accumulates till about 45% of the total housing stock in the area. Furthermore, the climate change scenarios result in a shift towards lower return periods; the number of flooded houses during a 10-year flood in the 2050 G+ scenario equals a flood with a 100-year return period in the current probability distribution. For the Veerman scenario in 2100, this shift moves towards a 2000 year flood. Furthermore, the reduction in flooding expected from the ‘Closable but open’ options seems relatively modest when compared to the 2050 G+ and the 2100 Veerman scenarios respectively.

5. Estimated Aggregate Flood Damages

The return periods for the different scenarios relate to predicted water stage levels within the Meuse and Rhine rivers along the project area. Since the flooding and the resulting damages are obviously a result of the water stage within the river, the calculated aggregate damage levels for the different scenarios can easily be integrated into one figure. This provides a clear relationship between water stage and expected damage levels and increases the accuracy of the prediction since more values are evaluated. The results are depicted in figure 3.

Fig. 3 Expected aggregate damage levels (housing and infrastructure) for varying water stage levels. Note that the water stages have been determined by averaging the individual water stages for the complete study area.



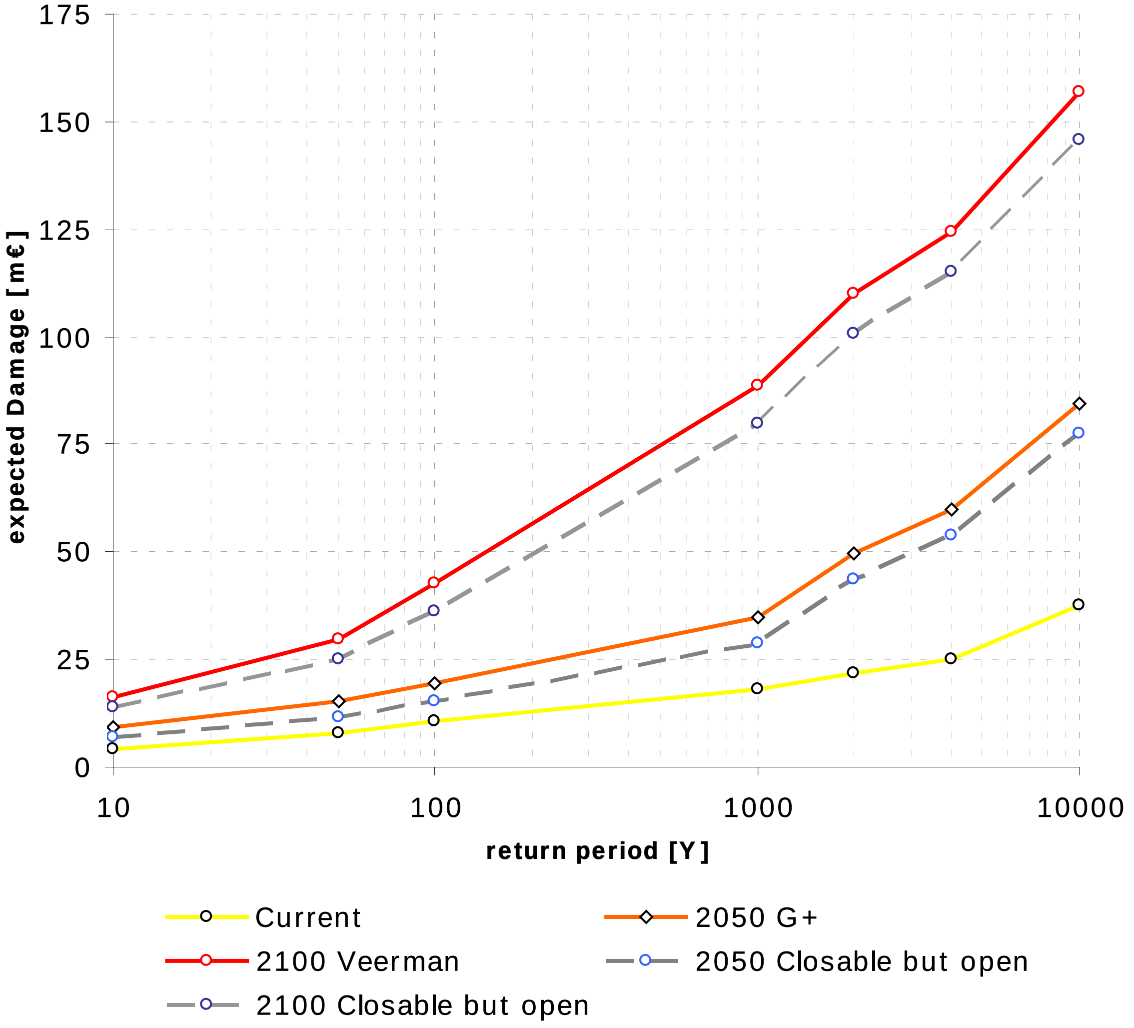
One of the main observations from figure 3 is the absence of significant discontinuities. This means that no disproportional damage levels occur within the region after some increase of the Meuse river level. The relative smoothness of the curve does make it fit for regression into a function. The trendline obtained after regression, which describes the expected damage for housing and infrastructure d as a function of the water stage y is composed as:

$$d = \frac{4}{10^8}\left(y^{5.8845}\right), y \geq 236.8 \quad (1),$$

where y is the water stage in cm + NAP.

As explained before, the water stage levels are associated with return periods, which in turn relate to the different scenarios that have been taken into account in this study [Huizinga, 2010]. To gain insight into the damage levels and to make inter-scenario comparison possible it is important to depict the expected aggregate damage levels. For every scenario the results have been calculated for the 10, 50, 100, 1000, 2000, 4000 and 10,000-year floods. The outcomes are depicted in figure 4. Note that the x-axis in the graph is set in logarithmic scale. This makes the results easier to interpret but might lead to false conclusions about damage progression over the different return periods.

Fig. 4 Expected aggregate damage levels (housing and infrastructure) for the range of periods and scenarios.



One of the first observations from figure 4 is the substantial increase in expected damages for the G+ 2050 and the Veerman 2100 scenario. The range of expected damage increases compared to the current probability distribution varies between 84% (RP = 100) and 139% (RP = 4000) for the G+ 2050 scenario and 277% (RP = 10) and 400% (RP = 2000) for the Veerman 2100 scenario. In other words, for the given scenarios, the expected flood damages more than double in 2050 and more than triple in 2100. Another observation that can be made is that the Veerman 2100 scenario causes a disproportional trend shift when compared to the shift caused by the G+ 2050 scenario. If these scenarios were to become reality, the already increasing flood damages for 2050 increases even more rapidly towards 2100.

Furthermore, the proposed ‘Closable but open’ options limit the expected damage levels to some extent (although not drastically). Note that this doesn’t necessarily mean that the options are therefore unfeasible. Depending on the costs, these still might be justifiable alternatives to limit future consequences of river flooding. Although a comprehensive appraisal of the cost/benefits of these options is outside the scope of this study, the calculation of the expected mean annual damages (MAD)[e.g. CGER, 2000] might provide some initial insights into avoided damages. These are displayed in table 4.

Table 4 Expected mean annual damages (housing and infrastructure) for the different scenarios

MAD	Scenario	Mean Annual Damage [k€]	% increase
157683.9	Current	157.7	
276545.1	2050 G+	276.5	75%
683298.9	2100 Veerman	683.3	147%
225814	2050 ‘Closable but open’	225.8	-18%
574769	2100 ‘Closable but open’	574.8	-16%

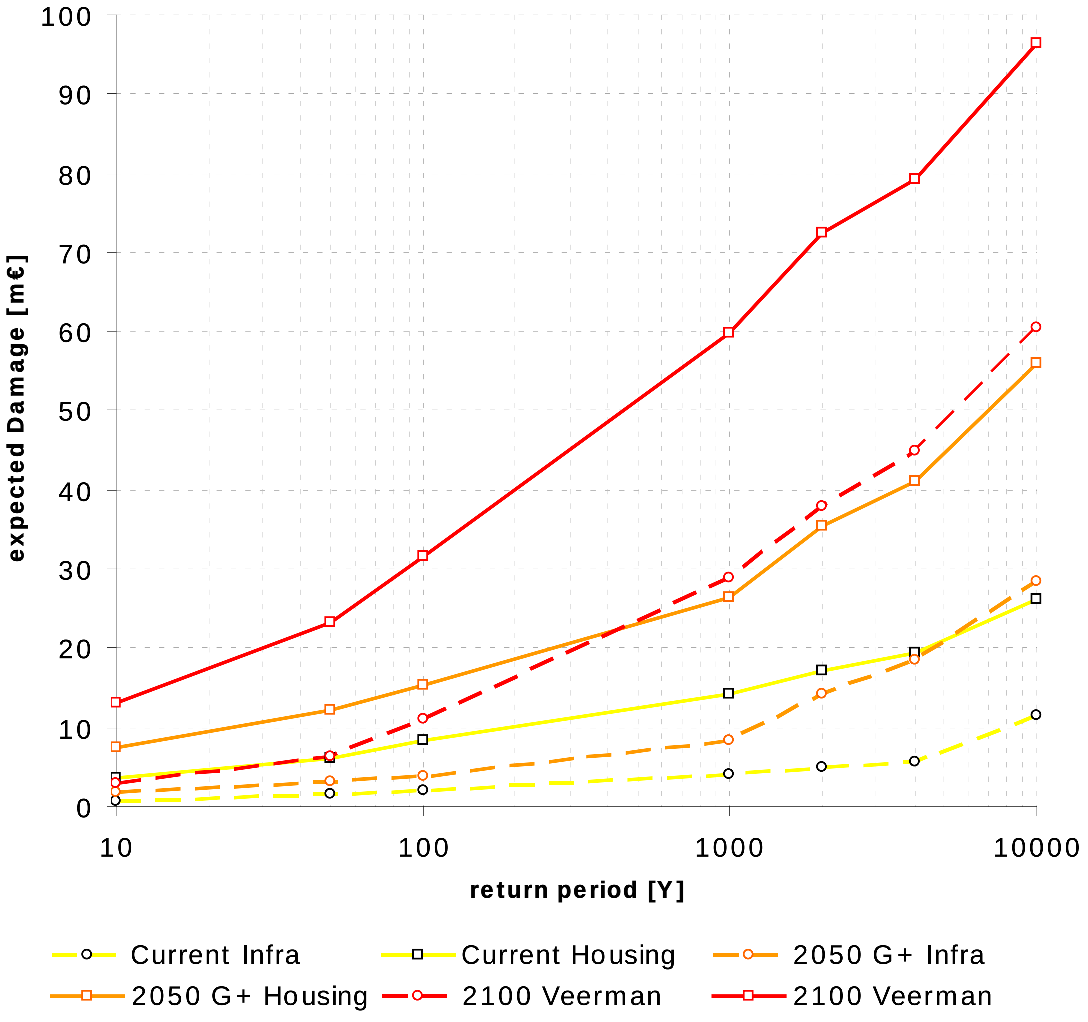
Note that because of the relatively short intervals between the return periods, the damage for the floods with low return periods (e.g. 10, 50 or 100 years) contribute significantly higher to the MAD levels than those at the higher end of the range of return periods.

6. Deconstructing Expected Flood Damages

6.1 Damage differentiation for housing and infrastructure

As mentioned before, flood damages have been calculated for housing and infrastructural objects in the study area. While further decomposition of flood damages to housing objects will be described further in this paragraph, it is important to mention some of the factors that influence flood damages to infrastructural objects. Although parking lots and other paved areas come in all kinds of varieties, damages often occur because the base layer on which the pavement is placed is washed away. The base layer consists of a base course and a subbase, which in case of major roads (e.g. highways) often consist of concrete, rocks and sand or other sturdy materials which are, especially for moderate inundation, relatively ‘flood proof’. Brick roads, on the other hand, for which the foundation often consists only of densified sand, are highly susceptible to the effects of flooding. Generally though, the damages to infrastructure are assumed to be lower than those for actual buildings. Note that indirect damages (traffic interruption) is not taken into account here; damaged roads can cause severe obstacles in case of evacuation (public safety) as well as economic damage because of interruption of transport routes. The expected damage levels for housing and infrastructure are presented in figure 5.

Fig. 5 Expected damage levels for housing and infrastructure for the range of return periods and scenarios.

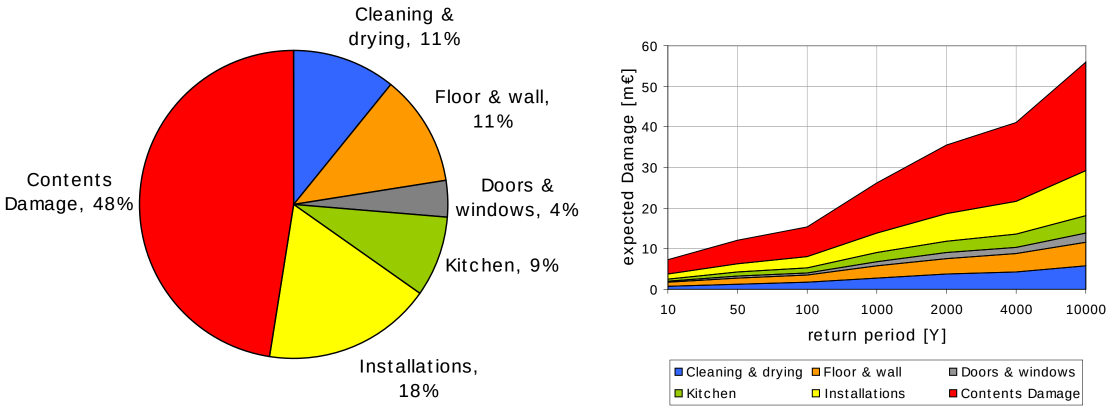


As expected, the damage levels for infrastructure are well below those for housing. Depending on the scenario, the levels are between 82% (current, RP = 10) and 61% (Veerman 2100, RP = 10,000) lower. Note that this doesn’t necessarily mean that the extent of flooded infrastructure is limited. A substantial number of roads is constructed along quays or other location along the riverside. Furthermore, it seems that for the two climate change scenarios the expected damage levels exceed those for housing. In case of the G+ 2050 scenario this occurs around a return period of 5000 years. In turn the infrastructure damages for the Veerman 2100 scenario exceed those of the G+ 2050 scenario at a return period of approximately 300 years.

As observed for the aggregate damage levels, the influence of the climate change scenarios is substantial; the curves are almost identical in shape as in figure 4.

Since the stage-damage curves for housing are composed of different components, it is possible to investigate their distribution over the different return periods and scenarios. One of the outcomes is that the ratio between the different components only marginally differs. Within the complete range of return periods and scenarios, only the ratio between flood damages to kitchen and those to installations change by 1%. This is partly due to the relatively static fractions for the components within the stage-damage curves. The results both in relative and absolute form are presented in figure 6.

Fig. 6 (left) Average ratio between damage components for housing. (right) Damage levels for individual components for the Veerman 2100 scenario for different return periods.



One of the most striking observations from figure 6 is the extensive contribution of interior damages (furnishings). These add up to almost half of the total damages. Somewhat similar observations have been made by Thieken et al. (2005) and Büchele et al. (2006), in which the assessment was made empirically. The damages to installation are primarily caused by replacement of the electricity (transformers substation). Note that most of the damage components consist of replacement costs; such a calculation method is generally applied by the insurance industry. If homeowners decide to clean their house only, the calculated damages would be considerably lower since most components within a house are relatively robust towards the effects of flooding; the only real danger consists of the wood rot because of insufficient ventilation and drying.

Finally, it is important to gain insight into the distribution of flood damages over the age of the building stock. Since the urban fabric is part of continuous renewal cycles, increased future flood risk might be imposed on buildings already at the end of their technical or economic lifespan. In contrast, historic buildings of great importance to the cultural identity of a city might require urgent responses against potential future flood damage. The results for the current probability distribution, the G+ 2050 scenario and the Veerman 2100 scenario are depicted in figure 6. Note that the figures only depict the consequences of frequent floods up to 100 years since these are more likely to occur during the lifespan of the building stock. On average, in The Netherlands it takes about 100 years to renew the building stock [Hoogers et al., 2004].

Fig. 7 Number of flooded houses over the age of the building stock for (from top to bottom) i) the current probability distribution, ii) the G+ 2050 scenario and iii) the Veerman 2100 scenario.

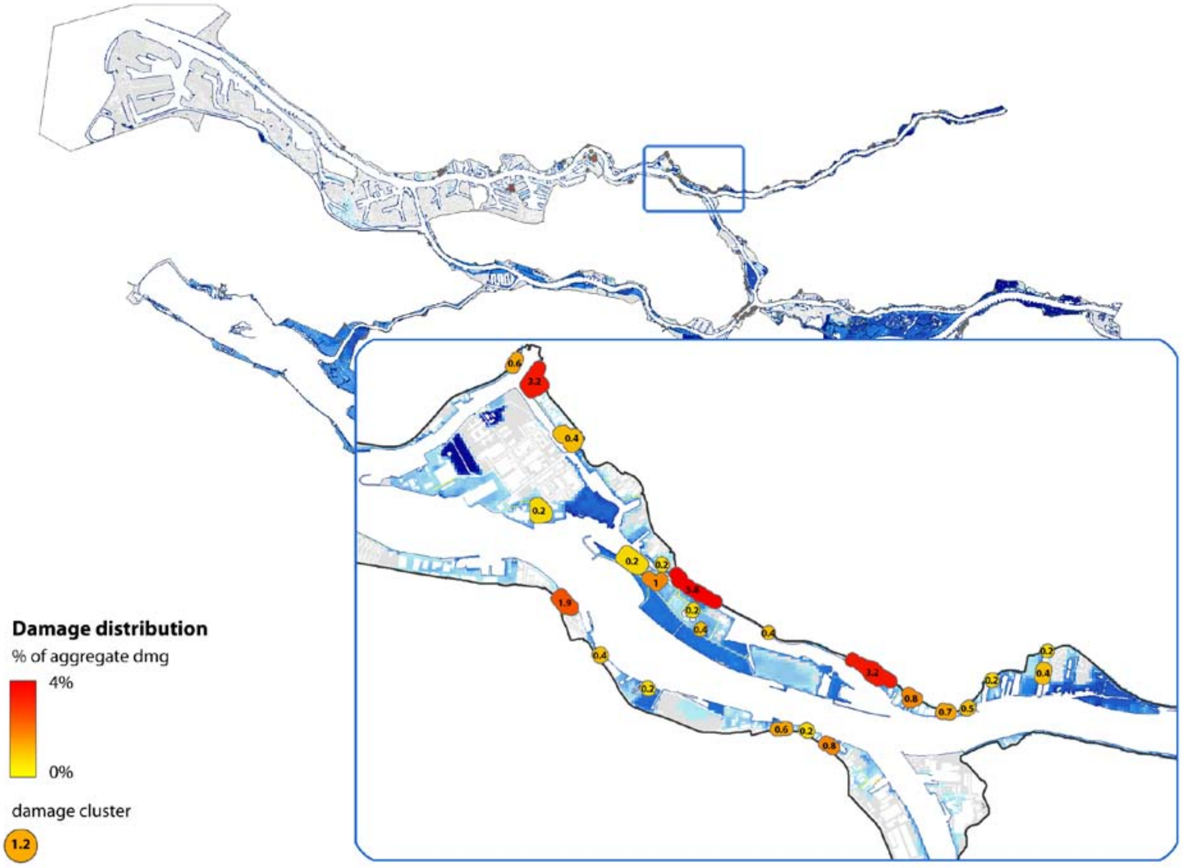
Several observations within figure 7 are a cause for concern. First of all, the majority of expected flooded buildings in the current probability distribution stems from the period between 1980 and 2000 (see top bar graph on figure 7). This would indicate that only recently the flood risk within the area has been increased. Secondly, the amount of historic buildings susceptible to flooding increases dramatically within the 2 climate change scenarios. Many of these buildings will most certainly be preserved for the next decades or even centuries, so it is likely that the predicted shifts in flood probabilities pose a future threat. Depending on the rate of climate change, a significant number of buildings might already be replaced within the next 50 or 100 years. Note that this doesn't imply that floods with longer return periods cannot occur during these intervals.

6.2 Spatial distribution of flood damages

One of the main aims of this study is of course to identify where expected flood damages will occur. Are the expected damages concentrated in a few locations or are they spread across the region? What is the extent of the damage prone regions and do they expand in case of severe floods?

The high level of detail used in this study makes it difficult to interpret the spatial distribution of the expected flood damages. The large amount of information spread out over different maps for return periods and scenarios makes human interpretation virtually impossible. Therefore, a clustering algorithm has been applied similar to Veerbeek et al. [2009]. In this way damage clusters identifying 'hotspots' can be analyzed in size, distribution, etc. A spatial representation is provided in figure 8 in which the location and extent of the clusters is displayed as well as their relative contribution to the total amount of expected damage for a given return period and scenario.

Fig. 8 Spatial representation of damage clusters for a 1000 year flood for the current probability distribution. The annotations in the figure express the percentage of damage within the cluster of the expected aggregate damage level.



Analysis of the distribution of the damage clusters shows first of all that the maximum individual contribution of damage clusters reaches 12.6% (RP = 10), 14.3% (RP = 4000), 13.3% (RP = 1000) for the current probability distribution, the G+ 2050 scenario and the 2100 Veerman scenario respectively. What also can be perceived is that a limited amount of clusters is responsible for most of the expected damages. This phenomenon is depicted in table 5 in which the amount of clusters responsible for different ratios is shown. What can be perceived is that in all scenarios for all return periods, the number of clusters responsible for respectively 25%, 50% and 75% is just a fraction of the total number of damage clusters. The most extreme example is found in the Veerman 2100 scenario, where for a flood with a 4000-year return period, 50% of the damages are only caused by 4.7% (9 out of 233) of the total number of damage clusters. Note that the total number of clusters does increase substantially. Within the current probability distribution, the area is for a 10-year flood populated by 46 clusters. This amount approximately triples during a 10,000-year flood to about 147, indicating a large number of small clusters suffering minimal damages (e.g. individual houses with minimal inundation). In summary, it seems that there is a limited set of damage 'hotspots' combined with an increasing amount of dispersed damages for increasing return periods and climate scenarios. The latter contribute only minimally to the expected overall damage suffered within the region.

Table 5 Number of clusters needed to reach a given ratio (25%, 50%, 75% and 100%) of the aggregate damages for different return periods and scenarios.

	return period	10	50	100	1000	2000	4000	10,000
25% dlevel	Current	3	5	4	5	5	5	4
	G+ 2050	4	6	5	4	3	3	3
	Veerman 2100	4	3	3	3	3	3	3
50% dlevel	Current	7	11	13	16	17	15	14
	G+ 2050	12	15	15	14	12	13	12
	Veerman 2100	11	11	11	10	10	9	11
75% dlevel	Current	20	32	40	47	47	42	44
	G+ 2050	36	41	44	43	40	43	41
	Veerman 2100	37	36	38	37	37	36	38
100% dlevel	Current	46	71	88	122	127	132	147
	G+ 2050	79	103	125	150	169	189	201
	Veerman 2100	106	139	163	208	221	233	234

Note that the relative stability of the number of significant damage clusters observed in table 5 does not indicate if the observation is made about the same clusters; a cluster containing 10% of the total damages during a 10-year flood can be a different cluster than one reaching a similar percentage during a 100-year flood. Inspection of the behaviour of individual clusters learns that this is indeed the case. Table 6 shows the progression for the 2 clusters that contribute maximally to the aggregate damage level. The cluster located in the municipality of Nederlek does this for a 10-year flood in the current probability distribution, while the cluster in the municipality of Dordrecht does this for a 10,000-year flood.

Table 6 Damage contribution of 2 individual clusters of a range of return periods for the current probability distribution.

return period	10	50	100	1000	2000	4000	10,000
Cluster Dordrecht	0.0%	0.0%	0.3%	2.4%	2.6%	3.8%	7.5%
Cluster Nederlek	12.6%	10.6%	8.6%	5.8%	5.2%	4.7%	3.8%

Table 6 clearly indicates the shifting of main damage contributors to other locations. The cluster located in Dordrecht initially (RP = 10 and 50) suffers no flood damages at all. Nevertheless, for a 1000-year flood the cluster becomes the maximum contributor. The cluster located in Nederlek shows the opposite behaviour: while initially being the maximum contributor, its relative importance decreases significantly with increasing return periods.

6.3 Distribution of flood damages across administrative boundaries

Since urban flood management policy is to some extent a local affair, it is important to provide the aggregate damage levels per municipality or even neighbourhood. Furthermore, insight into the expected flood damages for increasing return periods and climate change scenarios on a municipal level could provide further awareness since risk profiles might alter dramatically.

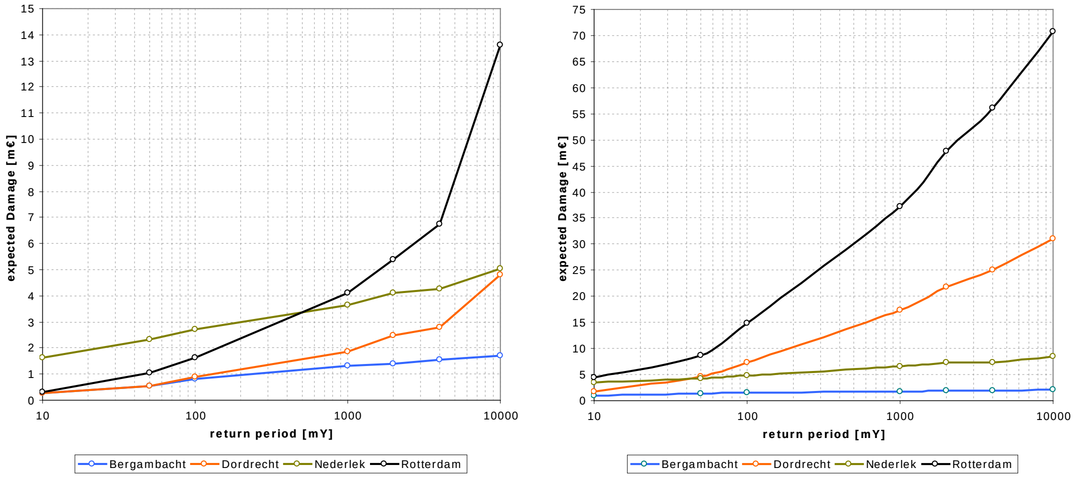
Although an extensive analysis for all municipalities has been made, this report will only cover the results for the most vulnerable municipalities: Bergambacht, Dordrecht, Nederlek and Rotterdam. This ranking has been based on the expected mean annual damages for the current probability distribution as presented in table 7.

Table 7 Mean annual damage per municipality for 3 different scenarios

Municipality	Scenario	Mean Annual Damage [k€]	% increase
Bergambacht	Current	31.3	
	G+ 2050	32.8	5%
	Veerman 2100	33.7	3%
Dordrecht	Current	33.1	
	G+ 2050	122.6	270%
	Veerman 2100	348.9	185%
Nederlek	Current	66.5	
	G+ 2050	77.1	16%
	Veerman 2100	94.1	22%
Rotterdam	Current	79.6	
	G+ 2050	196.4	147%
	Veerman 2100	618.4	215%

When examining the different MAD levels for the different scenarios, a few important observations can be made. The influence of the climate change scenarios is not significant for all municipalities. In fact, for Bergambacht and Nederlek, both the G+ 2050 scenario and the Veerman 2100 scenario hardly lead to dramatic changes. This is to a large extent due to the limited housing and infrastructure stock prone to flood damages. For Dordrecht and Rotterdam the two climate change scenarios cause continually increasing damages. Rotterdam, being by far the largest municipality within the area, is much more susceptible to the impact of increasingly high water levels. When looking at the absolute levels for the expected mean annual damage, it is striking that the range in damage levels is limited. Although the MAD for Rotterdam is about twice as much as the MAD for Bergambacht, the difference in size would suggest a much larger range. Note that the housing stock in Bergambacht (in the unembanked areas) only consists of 51 units that are apparently all located in flood prone areas. Another explanation is the bias in the calculation of the mean annual damages. Since this consists of the weighted average of the expected flood damages for the range of return periods, flood damages associated to high return periods add much more substantially to the MAD than those for low return periods (extreme events). Some of these explanations can be further verified when looking at the actual damage levels for individual return periods. These are for the current probability distribution and the extreme Veerman 2100 scenario shown in figure 9. To increase the readability, the damage levels (y-axis) between the two graphs differ in scale.

Fig. 9 Aggregate damage levels for Bergambacht, Dordrecht, Nederlek and Rotterdam for different return periods using (left) the current probability distribution and (right) the Veerman 2100 scenario.



One of the most important observations from left portion of figure 9 is the dramatic increase in expected damages for Rotterdam during higher return periods. Instead of levelling somewhat out, the graph for the current probability distribution shows a strong increase in expected damages even after a return period of 2000 years. The mean annual damage level therefore seems substantially affected by damages caused by infrequent events. In fact, Rotterdam seems to adopt a risk profile for a typical area within a dike ring: the expected damages for frequent floods are relatively low but increase dramatically for extreme events. This is to a lesser extent also the case for the Dordrecht municipality. Furthermore, it is clear for both scenarios that after an initial rise, the damage levels for Bergambacht and Nederlek remain almost the same for longer return periods; the damage levels are reached already during frequent floods. For the Veerman 2100 scenario the figure shows a much more regular progression. Note here that the damage curve for Rotterdam exceeds the one for Nederlek for all return periods, while for the current distribution this only happens for return periods of about 500 years or more.

As mentioned, the absolute damage levels are strongly related to the size of the building stock and infrastructural extent within the municipalities; if more houses and roads are located within the flood plains, the expected damages will increase more rapidly. To put the results in perspective it is important to calculate the damages as a ratio of the building stock. Table 8 shows the expected mean annual damages for housing, divided by the building stock.

Table 8 Mean annual damage for housing per municipality for 3 different scenarios divided by the total size of the municipal building stock.

Municipality	Scenario	Mean Annual Damage / house [€]	% increase
Bergambacht	Current	613.9	
	G+ 2050	642.3	5%
	Veerman 2100	660.3	3%
Dordrecht	Current	5.4	
	G+ 2050	19.8	270%
	Veerman 2100	56.4	185%
Nederlek	Current	224.7	
	G+ 2050	260.5	16%
	Veerman 2100	317.9	22%
Rotterdam	Current	3.7	
	G+ 2050	9.2	147%
	Veerman 2100	29.0	215%

The results of table 8 clearly change the perspective on the previous results. Because of the small housing stock in Bergambacht (51) and Nederlek (296), the expected mean annual damages per housing unit are extremely high compared to those for Dordrecht and Rotterdam. This might have consequences for the portfolio of possible response measures. The introduction of flood insurance or other financial compensation might be an adequate alternative for the Dordrecht and Rotterdam area since the risk seems distributed across a sufficiently large housing stock.

7. Sensitivity and Uncertainty

In order to verify if the produced outcomes are robust, a number of sensitivity tests have been performed. These tests concern 3 basic parameters. The first one controls the probabilistic assignment of the value of individual households. Since data about individual households are unavailable key indices determining this value are based on statistical information on zip code neighbourhood or municipal level. To determine the variance within this probabilistic assignment, a statistically significant number of test runs have been computed. The resulting standard deviation proved to be insignificant: 0.55%. This is to some extent due to the large number of housing units within the area. Two other variables that might influence possible outcomes are the applied threshold values for housing and infrastructure. These determine the baseline level for damages to be calculated (i.e. the minimum flood depth resulting in actual damage). These have been set at an elevation level of 25cm, which represents the average height of doorsteps (including the base). Since this value might be arbitrary, the effect of changing the threshold value for flooding has to be examined. For housing, a sensitivity test has been performed with threshold values ranging between 0 and 40cm. The range of standard deviation for different return periods is presented in table 9.

Table 9 Sensitivity analysis of the threshold parameter (housing) for different return periods.

return period	10	50	100	1000	2000	4000	10,000
standard deviation	11.26%	8.85%	6.82%	2.72%	2.58%	2.20%	1.41%

In case of damage estimation to housing the threshold value seems especially significant for frequent floods. The significance is reduced gradually for higher return periods. For infrastructure (table 10) the results are similar. Here the tested threshold values ranged between 0 and 50cm.

Table 10 Sensitivity analysis of the threshold parameter (infrastructure) for different return periods.

return period	10	50	100	1000	2000	4000	10,000
standard deviation	14.61%	10.09%	8.22%	3.63%	3.29%	2.49%	1.28%

Apart from the sensitivity tests on the described variables, there are a great number of factors that increase the uncertainty levels of the outcomes. All claims made related to return periods should be interpreted with caution. Over the last years, a substantial body of scientific evidence has been presented supporting the claim that climate change increases uncertainty levels in the statistical distribution of flood probabilities [e.g. Kabat et al., 2005; EEA, 2006]. This means that the confidence intervals on the statistical probabilities decrease and hence the residual risk (e.g. for extreme weather events) increases. Furthermore, there is a range of assumptions which might create bias towards over- or underestimation of the expected flood damages. Some of the factors leading to overestimation are:

- *Retrofitting measures already applied to individual buildings*. Although this is to some extent covered in the model refinement steps, many measures to minimize flood impact were not taken into account (e.g. application of flood proof shutters);
- *Response due to flood warnings*. When lead times are sufficient, significant reduction of flood losses can be achieved [e.g. Parker, 1991]. E.g., vulnerable household goods, cars and equipment can be relocated depending on lead times and maximum inundation level.

Underestimation on the other hand might be a result of:

- *Omitting various industrial sectors from damage assessment*. Large variability within and between industrial sectors prevents composition of accurate stage-damage-functions without applying a one-to-one mapping [Booyens et al., 1999]. Although general stage-damage curves for industrial sectors exist [e.g. Smith, 1994], the resulting accuracy of the outcomes would be substantially compromised. Therefore these have been omitted from the damage assessments, possibly resulting in underestimating actual flood damages. Especially the industrial area in The Port of Rotterdam could boost expected damage levels significantly. Note that within the framework of this study, a qualitative assessment of flood vulnerabilities has been made for the harbour area of Rotterdam [Lansen et al., 2010]

- *Inaccurate stage-damage-curves for historic buildings*. Relatively little is known about actual flood damages to the historic building stock. Reconstruction of various unique details within building stock might be more costly than assumed.

Additionally, underestimation of expected flood damages is resulting from exclusively focusing on the estimation of direct damages. Since Rijnmond-Drechtsteden area hosts the Port of Rotterdam, business interruption could have cross-national consequences due to interruption of supply-chains (e.g. petrol). Estimation of the resulting economic impact requires a sophisticated economic model in which the economic flows between regional, national and international scale levels are combined. This is outside the scope of this study but is qualitatively touched upon in the chapter titled: ‘Vulnerability of port infrastructure in areas undefended by primary flood defenses’.

8. Interpretation of the results

The produced outcomes clearly show a substantial increase in expected flood damages for the Rijnmond-Drechtsteden area. When increasing the water stage in the adjacent rivers the consequent flooding results in a rather gradual increase in expected damages; no sudden increase in expected damage levels can be perceived. When the water stages are associated with the applied climate change scenarios, a shift in baseline levels can be perceived for a flood with a 10-year return period. Furthermore, a trend change occurs towards increasingly higher damage levels for longer return periods. The observations lead to the following set of conclusions:

- *Increase of expected mean annual damage*. These levels increase by 75% for the G+ 2050 scenario and additionally by 147% for the Veerman 2100 scenario;
- *Proportional damage increase*. The applied climate scenarios result in a proportional increase of expected damages for the range of return period;
- *Shifting return periods*. When compared to the current probability distribution, the G+ 2050 scenario increases flood damages by about a factor 100, while the Veerman 2100 further amplifies this increase to a factor 1000;
- *'Closable but open' options.* The damage reduction for the 'Closable but open' options is limited to 18% when compared to the G+ 2050 scenario and 16% to the Veerman 2100 scenario.

Decomposition of the expected damages shows that the expected damages to infrastructure are substantial, but significantly lower than those for housing. Both the expected damage progression for housing and infrastructure show a relatively gradual progression towards higher return periods. The damage composition for housing is dominated by damages to the interior (furnishing). This contribution remains stable over the range of return periods. The housing stock prone to flood impacts is currently dominated by recently built units. As a result of the applied climate change scenarios this trend shifts towards historic buildings. In summary:

- *Damages to infrastructure.* The expected damages for infrastructure range between 18% and 40% compared to those for housing;
- *Equal trends.* The damage progression over higher return periods for infrastructure and housing shows similar behaviour;
- *Damages to housing.* The expected damages for housing comprise for 48% of damages to the interior (furnishings). Expected damages for cleaning and drying (11%), floors and interior walls (11%), doors and windows (4%), kitchen (9%) and installations (18%) account for the remaining 52%;
- *Robustness.* The ratio of damages to housing remains stable for the range of return periods.
- *Temporal distribution.* Within the current probability distribution, 60% of the frequently flooded houses (RP = 10) are built within the period 1980-2000. This percentage drops to 35% for a 100 year flood event. For the Veerman 2100 scenario, the majority of flooded buildings is almost uniformly distributed in age classes for a 10 year flood event, but consists during a 100 year flood event for 30% of historic buildings.

The spatial distribution of the expected damages shows a significant variance in location. Several 'hotspots' can be identified that account for the most of the expected flood damages. Increasing return periods results in a large amount of minor damage clusters that are limited to single buildings. While most hotspots increase in extent and level for increasing return periods and the applied climate change scenarios, the relative importance of individual damage clusters shifts between different locations. In general:

- *Damage clusters*. For lower return periods, 50% of the flood damages are located in about 15% of the identified damage clusters. For longer return periods and the applied climate scenarios this ratio decreases further to about 7%.
- *Shifting clusters*. For increasing return periods, the relative importance of individual high level clusters shifts.
- *Individual hotspots*. The maximum contribution of an individual cluster to the total damages is 12.6% for the current probability distribution. Levels of 14.3% and 13.3% are reached for the

G+ 2050 and the Veerman 2100 scenarios. The associated return periods are different because of shifting clusters.

Individual differences between the expected damage levels for individual municipalities are to a large extent caused by the differences in size. As a general rule, larger municipalities show a higher susceptibility to flood damages. This holds especially for higher return periods. During the current probability distribution 4 municipalities show a significantly higher vulnerability to flooding: Bergambacht, Dordrecht, Nederlek and Rotterdam. Nederlek is the most susceptible municipality to damages associated with frequent floods. For infrequent floods this is the municipality Rotterdam. Application of climate change scenarios cause a massive increase in expected damages to Rotterdam and to a lesser extent to Dordrecht. Because of the large housing stock and infrastructural extent, the average expected flood damages for Rotterdam and Dordrecht almost diminish. In summary:

- *Current vulnerability.* For flood events with a return period of 500 years or lower, Nederlek is the most vulnerable municipality. The housing stock in Nederlek is limited to 296 units. For higher return periods, these levels are exceeded by those for Rotterdam, where the housing stock consists of 21,352 units.
- *Trend change*. Rotterdam shows a significant trend change for extreme events. Flood events exceeding a return period of 4000 years result in a disproportional amount of damage. A similar trend change is found for Dordrecht.
- *Different impact of climate change*. The applied climate change scenarios hardly influence the expected damage levels for Nederlek and Bergambacht. For Rotterdam and Dordrecht though, the expected damage levels increase dramatically. The mean annual damage for these municipalities increases by 147% (G+ 2050) and an additional 215% (Veerman 2100) for Rotterdam, and 270% (G+ 2050) and 185% (Veerman 2100) for Dordrecht.
- *Relative damage*. The relative mean damage levels spread over the complete housing stock show substantial differences. For the current probability distribution, these drop to less than € 6 per housing unit for Rotterdam and Dordrecht. Because of the small housing stock, in Bergambacht this accounts for more than € 600 per housing unit. Application of the climate change scenarios result in about a 10-fold increase for Rotterdam and Dordrecht, while being almost stable for Bergambacht and Nederlek.

9. Consequences and possible responses

The appearance of damage 'hotspots' might provide options for local adaptation towards future flood impact. Instead of the application of regional flood defence regimes, structural measures on neighbourhood, building block or individual housing level deserve further investigation. For some municipalities or areas, there seems to be a window of opportunity for non-structural responses. Because of the relatively large housing stock and the limited flood extent, risk differentiation in the Rotterdam and Dordrecht areas seems to be possible; flood insurance might be an option since the expected damages per individual housing unit are limited. Furthermore, because of the high contribution of damages to the interior, a substantial damage reduction can be achieved by increasing lead times in combination with an adequate education program for dwellers (increasing awareness and response options). Special attention is needed for the preservation of historic buildings. The application of climate change scenarios shows a substantial increase in vulnerability of these buildings.

Finally, it might be appropriate to investigate an easy response measure: elevating the area to comply with the current standards within the adjacent dike rings. Unfortunately, the standards differ in exceedance probability. The Rotterdam urban area is protected by a 1:10,000 year standard, while other areas (e.g. Dordrecht) are protected by a 1:2000 year standard. For this exercise, the 1:10,000 year standard has been applied. Furthermore, the area consists not only of urbanized zones but also includes marshlands and other areas where flooding is acceptable. Therefore the calculations have been made using the urban extent as currently defined by the Dutch Environment Agency [Ritsema et al., 2009]. The results for the different applied scenarios are shown in table 11.

Table 11 Volume and area required to elevate the flooded area up to standard

scenario	volume [m.m3]	% increase	area [ha]	%increase
Current	1.11		2085	
2050 G+	1.34	20.72%	3831	83.74%
2100 Veerman	1.41	5.22%	5025	31.17%

What can be clearly perceived is that bringing the area up to current standards (so prior to application of climate change scenarios) is a major effort. The subsequent additional volume needed to keep up the standard during the climate change scenarios is relatively nominal. The costs connected to elevating the area can be compared to those required for other response measures (e.g. flood proofing buildings).

10. Conclusions

This report covered the outcomes of the flood damage assessment for the Rijnmond-Drechtsteden region in The Netherlands. The outcomes are based on application of a flood damage assessment model using a high level of detail to express the level of differentiation within this highly urbanized area. This also created a limitation: the assessment focused exclusively on housing objects and infrastructure. Calculations included the application of two climate change scenarios: the G+ 2050 scenario and the Veerman 2100 scenario. Furthermore, the damage reduction as a consequence of an adaptation measure has been calculated: the ‘Closable but open’ variant. On aggregate level, the damage level progression as a result of higher water stages is relatively gradual; no sudden shifts in expected damages appear because of step-wise inundation. When the water stages are associated with probability distributions, including those for the applied climate change scenarios, the impact of climate change is substantial. The return periods associated with the damage levels shift a factor 100 for the G+ 2050 scenario and a factor 1000 for the Veerman 2100 scenario. The damage reduction resulting from the ‘Closable but open’ option is about 17%. Expected damage levels for infrastructure are substantially lower than those for housing objects. Within the housing objects, half of the damages are resulting from flooded interiors (furnishings). Historic buildings are especially vulnerable for climate change; a substantial part of the flooded building stock consists of historic buildings. Most of the damage is concentrated in a small number of ‘hotspots’. These vary in severity and extent for flood events with different return periods as well as climate change scenarios. From a municipal perspective, the municipalities prone to flood damages are Bergambacht, Dordrecht, Nederlek and Rotterdam. The applied climate change scenarios cause the expected damages in Rotterdam to rise considerable. This is to a large extent due to the size of the flood prone building stock and infrastructure. On average the expected damages in Rotterdam are relatively low. This makes Rotterdam an ideal region for the application of flood insurances. In the study, underestimation of expected damages might be caused by conservative stage-damage functions for historic buildings. Furthermore, damages to industrial objects are not taken into account. Overestimation might on the other hand be caused by applied retrofitting measures in the current building stock as well as response actions by current inhabitants after a flood warning has been issued.

This study provides plenty of room for future improvement and knowledge development. A vast knowledge gap exists in the assessment of flood damages to industrial objects, which cover a substantial part of the Rijnmond-Drechtsteden area. Appropriate stage-damage curves or other calculation methods hardly exist. This is especially due to sectoral differentiation and because of the individual differences between businesses. These latter could be covered by the availability of comprehensive datasets that are know spread throughout various agencies (e.g. chamber of commerce, cadastre). Similarly, more attention needs to be paid to damage assessment of historic buildings for which the damage levels are assumed to be higher. Because of the absence of appropriate flood records, better verification models need to be developed that accommodate individual differences model setups (e.g. scale level).

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To develop the scientific and applied knowledge required for Climate-proofing the Netherlands and to create a sustainable Knowledge infrastructure for managing climate change

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