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Comparing Extreme Rainfall and Large-Scale Flooding Induced Inundation Risk – Evidence from a Dutch Case-Study

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1. Introduction

Flood risk is an important force in shaping land use patterns. Attention for flood risk is even more important in view of climatic changes that will impact sea-level rise, river discharge and precipitation patterns. Flooding typically results from two types of events: extreme rainfall events and large-scale floods. The former can be defined as inundation due to more rainfall than the water system in a specific area can handle and the latter as a temporary covering of land by water outside its normal confines due to flooding or breaching of the primary or regional defense structures such as dikes.

In recent history, the Netherlands has seen a number of events with both extreme rainfall and large-scale flooding. For example, an extreme rainfall event occurred in 1998 that caused substantial damage in the southwestern part of the Netherlands (Smits et al., 2004) and a large-scale flood almost occurred in 1993 and 1995 (Wind et al., 1999). Extreme rainfall events generally have a high probability of occurrence but a low impact, while large-scale floods have a low probability but a high impact (Merz et al., 2009). It is, therefore, interesting to compare the flood risk for both types of events. Flood risk is interpreted here as the product of the probability of a certain flood event and the (economic) impact that the event would cause if it occurred (Sayer et al., 2002).

Recent studies have already made initial progress with comparing flood risk from large-scale floods and extreme rainfall events (van Veen, 2005; Merz et al., 2009). Other studies examined several aspects differing between extreme rainfall events and large-scale floods, including the regional differentiation in precipitation, communication, types of measures, possibilities to reduce flood risk and the possibility of insurance (Kok and Klopstra, 2009). It is still not known, however, how the flood risk (in terms of expected annual damage) of extreme rainfall exactly compares to the risk of large-scale floods. Since both inundation due to extreme rainfall and large floods from the sea or river can cause economic damage, it is interesting and valuable to calculate them in a consistent way in order to compare them.

At the moment, more policy measures are taken to mitigate and prevent large-scale floods in the Netherlands, than to mitigate extreme rainfall events (Kok and Klopstra, 2009). Due to climate change, there is the expectation that not only the occurrence of extreme weather events will increase in the future (IPCC, 2007), but also a possible increase in large-scale floods (Milly et al., 2002; Te Linde et al., 2010). This can result, in combination with various socio-economic changes, in an increase in economic damage from floods (Bouwer et al., 2010; De Moel et al., 2011). Therefore, the risk of both extreme rainfall events and large-scale floods are both likely to increase. In order to prioritize it is interesting to have both types of flood risk calculated in the same way.

The objective of this research is to assess the flood risk, in terms of 'annual expected damage' (AED) of inundation due to extreme rainfall and large floods in a consistent way in order to compare the respective types of risk. Therefore, it is interesting to know to what extent flood risk from extreme rainfall events and large-scale flooding can be compared and how they relate to each other. To do this, the main objective of this research is to make an integrated model to compare the different types of flood risk in a plausible and consistent way.

In section 2, the study area, 'Noord-Beveland', which will be used to test the model, will be briefly discussed and described. In section 3, we then discuss the different conditions that must be taken into account to be able to put the comparison of the different forms of flood risk in a proper perspective. In section 4, the methodology will be described that was used to make to integrated flood risk model. In section 5, the results will be described after using the data from the study area as input for the integrated flood risk model. In section 6, the results will be discussed to see whether or not the model matches our expectations. Finally, in section 7, conclusions will be drawn.

2. Study area

The area of focus of this chapter is the Netherlands, which is located in the western part of Europe. The country borders to the North Sea in the west. The general low altitude in the Netherlands and therefore potentially high risk of flooding has stimulated the development of an extensive network of dunes and dike-rings. Currently, the Netherlands consists of 57 dike-rings, varying from safety norms between 1/1250 in the river areas, up to 1/10000 along the coast (see section 3.2 for a further explanation about these safety norms).

The study area that is used to test the integrated flood risk model is 'Noord-Beveland', which is a municipality in the Dutch province of Zeeland. 'Noord-Beveland' is within dike ring '28' and has a safety norm of 1/4000 (TAW, 2000). Noord-Beveland is the smallest island of Zeeland and is connected with three dams and a bridge to the mainland. It is relatively safe for large-scale floods since most of its shore is located behind the Oosterschelde barrier, part of the 'Delta Works'. This barrier borders 'Noord-Beveland' in the northwestern part, whereby the northern and eastern shore of Noord-Beveland is secluded from the North Sea. The municipality has 7,408 inhabitants (CBS, 2011) and has a total area of 120 km^2 of which 34 km^2 is water. Noord-Beveland is mostly flat and is about one meter above sea level. A closer look to the land use in this area (Figure 1) reveals mainly agriculture uses, with some small villages, a few recreational areas and other rural activities. The most common agricultural land uses include: potato fields, wheat fields, pastures, corn fields, beet fields, orchards and other agriculture.

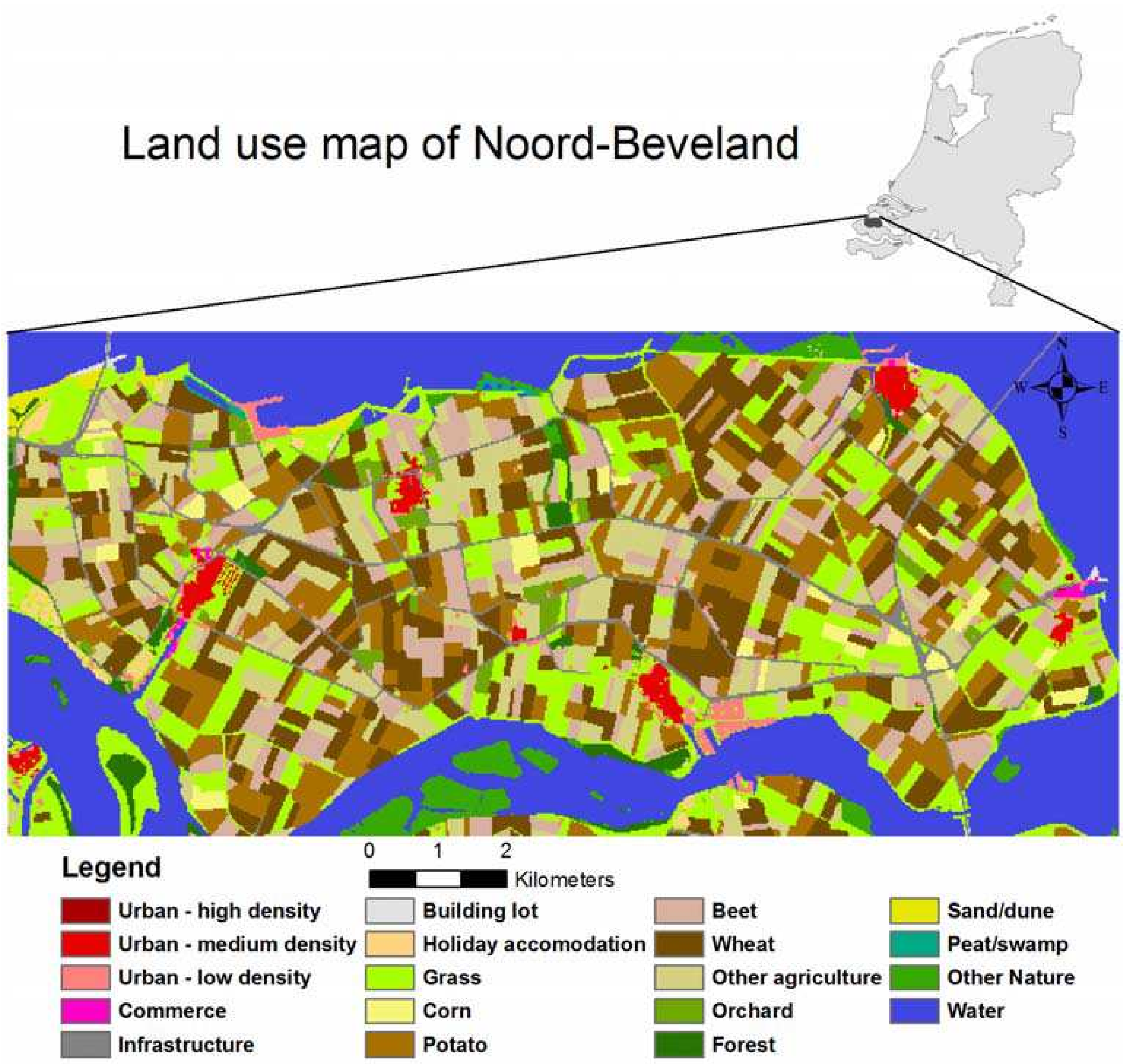

Fig. 1. Land use map of 'Noord-Beveland'. Based on the LGN4 and Land Use Scanner maps (see www.lgn.nl and Riedijk et al., 2007)

3. Differences between flood risk resulting from extreme rainfall events and large-scale floods

In this section, a number of conditions will be described that need to be taken into account to make a consistent comparison between the flood risk induced by extreme events and that resulting from large-scale floods since it is important to assess both types of risk in a comparable way. This should be done to avoid methodological biases as much as possible. Besides the issue of probability (large differences in probability for both forms of risk), there are many more fundamental differences between inundation due to heavy rainfall and large scale flooding with respect to their processes, consequences, exposure and the way they are dealt with. These differences should first be identified properly in order to allow for proper comparisons from which appropriate conclusions can be drawn.

3.1 Flood risk of extreme rainfall events

Flooding from extreme rainfall events vary from upwelling groundwater levels, which occurs frequently but with little damage to very large inundations of land which occur less frequent but with lots of damage. Inundation due to extreme rainfall events occur when there is more rainfall than the water system in a specific area can handle (Hoes, 2007). There can be several reasons for this inundation: the rainfall is not able to infiltrate into the ground or not able to properly flow away, there is insufficient pumping capacity or there is a too little storage capacity in the area to store all the water.

Besides the issue of storage capacity of a specific area, the duration of a rainfall event determines the amount of inundation. First, slow and fast reacting water systems can be distinguished in a specific area. Green houses and urban areas are for example fast reacting water systems, while pastures are an example of slow reacting systems and arable land responds usually between the two systems. For quick responsive water systems, a short period of several hours to several days with heavy rainfall is often necessary to have the land inundated, while the slow-reacting systems often need an event spread over several days (Smits et al., 2004).

Other important factors that determine the amount of inundation are the soil type, the water levels before a rainfall event and the time of occurrence in the year. The soil type determines how fast the rainfall can infiltrate in the ground. For example, if the soil is rich in sand, water can much more easily infiltrate then when the soil is rich in clay. The water levels before a rainfall event determine how much more water can be stored during the extreme rainfall event. High water levels before an extreme rainfall event means that less water can be stored, which results in faster inundation of the area. Furthermore, most of the extreme rainfall events, both short and large, occur at the end of the summer and in the autumn (Smits et al., 2004).

The consequences of extreme rainfall can sometimes be relatively large. For example, the extreme rainfall event that occurred in the autumn of 1998 caused around half a billion euro in damage. Looking at the exposure, this can be relative large but also very local. In 1998, the south-western parts of the Netherlands had problems with this extreme rainfall event (Smits et al., 2004), while in 2006, the problems occurred at a much more local scale (i.e. minor flooding in Egmond aan Zee, which is a small town located in the northwestern part of the Netherlands). One of the models that is used to predict and determine the damage of

Land-use type	**Probability criteria [1/yr]**
Pastures	1/10
Agriculture	1/25
High quality agriculture and horticulture	1/50
Greenhouses	1/50
Urban area	1/100

Table 1. The probability that a certain land use type may become inundated. (Nationaal Bestuursakkoord Water, 2003)

extreme rainfall events, is the model made by Hoes (2007), which determines the expected annual damage per pixel.

For extreme rainfall events, a number of probabilities have been authorized in the 'Nationaal Bestuursakkoord Water' (2003), which are necessary to take into account in the comparison between the two different types of risk. Important to note that in the Netherlands the probabilities of extreme rainfall events define the safety norms that describe how often different land uses are allowed to inundate. In Table 1 an overview of the different probabilities is given. Finally, policy on water management in the Netherlands is mostly the responsibility of Regional Water Boards.

3.2 Flood risk of large-scale flooding

Large-scale flooding can be defined as a temporary covering of land by water outside its normal confines due to flooding or breaching of primary flood defenses, which can result in large inundation depths, high damages and even human casualties (Kok and Klopstra, 2009). Important to notice for floods in the Netherlands, is that the Dutch area is divided into so-called dike rings. Dike rings are areas that are surrounded by levees, dunes or other higher areas that protect the inner area of the dike ring from flooding. Large-scale flooding happens when a dike or dune cannot stop the water from flowing into the inner part of a dike-ring. This happens when water levels exceed the height of the defense or when the water barriers breach. The results of large-scale floods can vary from only a few decimeters of inundation up to several meters of inundation.

Different safety norms apply to different dike-ring areas, which are described in the 'Water Protection Act'. These safety norms can be defined as the probability of occurrence of a certain water level and wave conditions that are higher than the dike or dune, as described in Table 2. Important to note is that these water level exceedence probabilities are different than the flood probabilities. It can happen that a dike or dune already breaches before the water level is higher than the dike or dune due to various failure mechanism (Vrijling, 2001; RWS-DWW, 2005). This means that the probabilities which are described in the 'Water Protection Act' are not always the exact flood probabilities. Also other factors, such as the probability of breaching and thus the strength of the dike at a certain place play a role (de Bruijn, 2007).

Area	Probability criteria [1/yr]
Coastal areas	Between 1/2000 to 1/10000
Areas along large lakes	Between 1/2000 to 1/4000
Areas along tidal rivers	1/2000
Other areas among main rivers	1/1250

Table 2. Flood probabilities for different areas in the Netherlands

Furthermore, as discussed in section 3.1, a number of other factors should be taken into account when describing flood risk. The consequences of large-scale floods are in general quite large. For example, the economic damage of the flood of 1953 was, in present value, around one billion euro (van Veen, 2005). With large-scale flooding, there is not only damage to crops and sewers, but also human casualties and damage to buildings and infrastructure.

Looking at exposure in the case of large-scale flooding, it is usually limited to one or maybe two dike rings or part of a dike ring, due to safety measurements before a flood will occur or during a flood. These safety measurements are for example strengthening of closely located weak parts of the dike, closing the breach or the closing of possible weirs that are in the area.

In the Netherlands, the HIS-SSM ('Hoogwater Informatie Systeem - Schade- en Slachtoffermodule') is commonly used for the determination of the flood risk of rivers and sea. With the HIS-SSM model, expected damage and the expected amount of casualties because of large-scale floods can be calculated (Kok et al., 2005). Another model, the Damage Scanner, is a simplified model of the HIS-SSM that calculates the expected damage of a large-scale flood (de Bruijn, 2006; Klijn et al., 2007). Whilst the HIS-SSM model calculates the damage per object, the Damage Scanner calculates the damage per land-use class (van der Hoeven et al., 2009). Finally, in the case of large-scale floods, policy is mostly made by 'Rijkswaterstaat', which is a governmental institution that is responsible for national water management and the roads of national importance in the Netherlands.

3.3 Comparison of the different conditions

When looking at the two sorts of flood risk described in the previous sections, a number of important differences can be determined, wherefore in Table 3 an overview is given. In this section, these dissimilarities will be further explained.

Factor	Extreme rainfall event	Large-scale flood
Occurence	Relatively frequent	Relatively unfrequent
Impact	Low	High
Exposure	Relatively unlimited	Relatively limited
Amount of inundation	Few decimeters	Few meters
Flow speed	Low	High
Human casualties	None to few	Few to many
Type of water	Fresh water	Fresh, salt or brackish water
Costs of prevention	Relatively low	Relatively high
Safety norms	Actual inundation	Possibility of overflow
Models	Hoes (2007)	HIS-SSM and Damage Scanner
Policy	Regional Water Boards	Rijkswaterstaat

Table 3. Overview of the differences between extreme rainfall events and large-scale floods

A number of observations can be made based on the table. First, there is a large difference in probability of occurrence. While the flood risk related to extreme rainfall events has a relatively high probability of occurrence, flood risk resulting from large-scale flooding has a relatively low probability of occurrence. When looking at the differences in impact (damage), we see that extreme rainfall events have a relatively low impact in comparison with large-scale floods, which have a much higher impact. With these two conditions in mind, there is now one clear difference: high probability/low damage (extreme rainfall events) versus low probability/high damage (large-scale floods) (Merz et al., 2009).

Second, while exposure for extreme rainfall events concerns almost the whole of the Netherlands (extreme precipitation can happen anywhere), exposure to large-scale flooding is relatively limited since it is confined to those areas contained within the dike rings. Also important is the amount of inundation of both forms of flood risk. Whilst the inundation of extreme rainfall events is most of the time much lower than that of large-scale floods, usually a few decimeters, the inundation for large-scale floods is much higher (up to a few meters). Not only the amount of inundation determines the damage though, but also the speed of the water flow. A high speed will usually cause much more damage, especially in terms of human casualties. With extreme rainfall events, there is usually very little or almost no flow speed, while large-scale floods can have very high flow velocities, especially near the breach. The occurrence of human casualties is an important difference between the two forms of risk. For large-scale floods the chances of human casualties are much higher than for extreme rainfall events. There can also be a difference in the 'type' of water that inundates the area. While extreme rainfall events mainly involve fresh water, large scale floods are usually salt or brackish water. The latter is especially for agriculture much more harming than fresh water inundation (Nieuwenhuizen et al., 2003). Finally, flooding from extreme rainfall events mainly occurs due to minor bottlenecks in the regional water system, while flooding from large-scale floods mainly occur due to failure of primary water defenses. Due to this difference, for extreme rainfall events minor (relative cheap) measurements are expected to prevent flooding, while for large-scale floods much larger (and more expensive) measurements are expected to be implemented. Nevertheless, Kok and Klopstra (2009) found in a simple cost-benefit analysis that the cost-effectiveness of reducing the risk of large-scale floods is in general much higher than that of reducing the risk related to extreme rainfall events.

There are also clear differences in the probability criteria. As described before, the safety norms of extreme rainfall events are not only higher than those of large-scale floods, there is also a clear difference in the interpretation. The safety norms for extreme rainfall events mean the minimum probability that there will be an actual inundation, while the safety norms for large-scale floods are defined as the levels at which the dikes could possibly overflow.

Another important difference is the determination of flood risk, since both types of flood risk are determined in different models that use different input parameters to determine the risk. For extreme rainfall events, the damage model of Hoes (2007) has been developed, while for large-scale floods, the HIS-SSM of Kok et al. (2005) is most commonly used. While looking at these two models, there are already a few differences. Not only different inundation maps are used to determine the expected inundation (e.g. starting at different depths), but also different land-use maps with different land-use classes are used. While in the model of Hoes many more agriculture classes are used, the HIS-SSM provides more variety in urban classes. Other differences are observed in the definitions of maximum damages and damage curves.

Of final importance are the differences in policy. Whilst for extreme events the Regional Water Boards are responsible for policy making, is 'Rijkswaterstaat' responsible for the policy making with large-scale floods. Due to this difference, other criteria or other processes are seen as important for flood policies.

4. Methodology of the integrated flood risk model

Since it is now clear what the conditions are that need to be taken into account and what the dissimilarities are between the flood risk of extreme events and large-scale flooding, it is possible to continue with the actual integrated flood risk model. Even though both types of risk are normally estimated using different models that differ in several aspects, both models are based on the same underlying concepts, namely: depth-damage curves and maximum damages. It should therefore be possible to integrate both approaches into a single integrated flood risk model. This is possible since the integrated flood risk model – like the models it is based on – is mainly focused on direct damage and most of the differences described in the previous section (e.g. human casualties, costs of preventing floods) do not have a direct influence on that. Several studies note that the most important factor that determines direct damage in both extreme rainfall events and large-scale floods is the flood depth (Merz et al., 2007; Penning-Rowsell et al., 1995; Wild et al., 1999). Therefore, the integrated flood risk model will be built around this parameter. In this section, a general description of the methodology will first be explained, then the input will be described and finally the damage factors and maximum damages.

4.1 General outline of the flood risk model

The integrated flood risk model uses the same approach as the Damage Scanner and the HIS-SSM model. In this approach, a land use map and inundation map are used, which are combined using damage curves and maximum damages per land use. Every land-use class has a different maximum amount of possible damage and uses a different damage function, whereby the possible amount of damage is in millions of euro per hectare. Every damage function shows a curve where the possible inundation is on the x-axis and the damage factor on the y-axis (Figure 2). To determine the amount of damage in the area, a number of steps have to be taken:

1. Inundation depth: Inundation maps determine the maximum inundation depth for each cell, which varies depending on the scenario.
2. Land-use class: Land-use maps determine the land-use for individual cells.
3. Damage factor: a damage factor is derived from the damage functions and represents the percentage of the maximum total damage. The damage function used is defined by the land-use class. Then, the inundation depth defines the damage factor, which is measured in percentage terms. These damage curves and maximum damages per land use will further be described in section 4.3.
4. Damage calculation: the final step is to determine the amount of damage for a specific cell by multiplying the damage factor with the maximum amount of damage. This quantifies the damage that occurs in each cell.

Once the calculations are done, the outcome will be a map and a table for every inundation map with the different amount of damage respectively per pixel and per land use in euro. In the table, not only the different amount of damage is described, but also the average damage, the standard deviation and the total area per land use. Once these damages are calculated, the final outcome can be determined. As described in the introduction, the flood risk is determined by multiplying the flood probability with the consequences, which can be described as the maximum amount of possible damage in a specific area that is calculated in the integrated flood risk model. The final outcome is the flood risk in terms of Expected Annual Damage (EAD).

4.2 Land-use and inundation data

The key inputs to this model come from two different maps. One is the land use map and the other is the inundation map. For the land use map, a new land use map is made which is a combination of the land use map from Land Use Scanner (described in Riedijk et al., 2007 and used in the Damage Scanner) and the 'Landgebruikskaart Nederland' (LGN4, used in the model of Hoes, 2007). The former are derived from a land use model that is applied to simulate land use changes and that is mainly focused on urban areas (see, for example, Koomen et al., 2008 and Koomen and Borsboom-van Beurden, 2011). The latter dataset is more focused on agriculture and distinguishes more classes in these categories (de Wit and Clevers 2004; de Wit 2003; van Oort et al. 2004). Since extreme rainfall events mainly damage agriculture but large-scale floods also damage urban areas and infrastructure, we combine those two to cover enough land-uses for both types of flood risk. The other map we use is the inundation map, which shows us the maximum inundation in a specific area for the different flood probabilities.

The combined land use map contains 25 different land-use classes which can be aggregated into four major land-uses: urban land-uses, agriculture, nature and infrastructure. The urban land-uses consist of five classes: Urban - high density, Urban - low-density, Urban - rural, Commerce and Building lot. Where 'Urban - high-density' are the main cities and towns (like Amsterdam or The Hague), 'Urban - low density' are suburbs and villages (like Egmond aan Zee) and 'Urban – rural' are farms and large houses between pastures and along rural roads. Commerce is all the commercial areas within the Netherlands. The agricultural land-uses consist of nine classes: Greenhouses, pastures, corn, potato, beet, wheat, orchard, bulbs and other agriculture. The nature land-uses consist of seven classes: fen meadow, forest, sand/dune, heath, peat/swamp, water and other nature. Finally, the infrastructure land-uses consist of three classes: Airport, seaport and infrastructure, where the 'infrastructure' class are all the roads, railways and other infrastructure that is not included in airport and seaport.

The inundation maps depict the inundation of extreme rainfall events or large-scale floods. These maps show the inundation in a specific area for different return periods, varying from a probability of 1/10 to a probability of 1/40000. The inundation maps used in this study for large-scale floods, which are calculated for different scenarios, are obtained from the province of Zeeland. The inundation maps can be subdivided into four scenarios: 1/4000 with RTC, 1/4000 without RTC, 1/400 with RTC and 1/40000 with RTC. "RTC (Real Time Control) is a module in the SOBEK model which allows the system to react optimally to actual water levels and weirs, sluices and pumps'' (Deltares, 2010). Important to note is that for the 'North Sea-side' of Noord-Beveland all four scenarios are used, while for the 'Oosterschelde-side' only the first two scenarios are used. This is due to the fact that with high water levels the 'Delta Works' will close.

The inundation maps used in this study for extreme rainfall events are obtained from the water board. These maps, which have been calculated with the use of SOBEK RR and Channel Flow, are made for the water boards in response to the 2003 'Nationaal Bestuursakkoord Water'. For the study, the inundation maps with return periods of 1/10, 1/25, 1/50 and 1/100 are used, whereas the higher return periods have the lowest inundation depths and the lowest return periods the highest inundation depths.

Finally, two additional maps were used for a closer examination of the damage that can occur with respect to the safety norms. For large-scale floods, the Risk Map for the Netherlands (www.risicokaart.nl) has been used and for extreme rainfall, an inundation map has been made with an overall inundation of 0.165 meter, which is the average inundation level above zero of the four different inundation maps for extreme rainfall events.

To be able to use all the maps properly in the model, the land use map and the different inundation maps are modified with ArcGIS to match the same study area. Several adjustments must be made to be able to fit the different inundation maps in the same model. Since the maps for inundation from large-scale floods start at inundation above 0, all the zero values in the map mean no water. But with extreme rainfall events, a value of zero means that there is water up to the ground level. Therefore, the inundation maps of large-scale floods need to be adjusted to have no damage in areas where there is no inundation.

4.3 Maximum damage values and damage curves

Maximum damages and damage curves were created using various sources. The maximum damage for most of the land-use classes is derived from their mean damage per hectare in the damage maps of the HIS-SSM for ten meters of inundation, above which hardly any extra damage occurs. A few land use classes were new and thus not able to have their correct maximum damage derived via the HIS-SSM damage maps. These maximum damages were therefore derived by comparing the specific land use class to damages given in various other studies (Brienne et al., 2002; de Bruijn, 2006; Hoes, 2007; Klijn et al., 2007; Vanneuville et al., 2006). Urban – high density is calculated by first determining the amount of dwellings in high density residential areas (Jacobs et al., 2011) and then multiplied with the amount of damage per dwelling as described in studies of Briene et al. (2002). The maximum damage for rural area is not only derived from the maximum damage per farm, as described in studies of Briene et al. (2002), but also derived after determining the average amount of rural area in the land-use map. Once the maximum damage has been calculated, a simple calculation allows us to estimate the damage per hectare for rural areas. Finally, the maximum damages for the different types of natural land use (e.g. forest, heathland) are set to zero, since no economic valuea can be attached to these areas. This is consistent with studies of Briene et al. (2002), Hoes (2007) and Vanneuville et al. (2006). In Table 4 is an overview of the different maximum damages per hectare.

Furthermore, damage curves are developed that specify the different amount of damage for different inundations. These curves allow us to calculate the different damage factors for different possible inundations. These inundations vary from elevated groundwater levels (-0.3 meters) up to high water levels (5 meters). These curves are mainly based on results of the HIS-SSM, but also other studies (Hoes, 2007; Vanneuville et al., 2006) were used to adapt the curves to our specific land-use classes. The damage maps of the HIS-SSM were used to calculate the amount of damage for different inundation depths. By dividing the damage of a certain water depth by the total possible damage (at ten meters of inundation), the damage factor for that inundation depth can be determined. In Figure 2, the different damage curves are shown.

Land use	**Million euro per hectare**
1 - Urban - high density	9.9
2 - Urban - low density	5.3
3 - Rural area	1.2
4 – Commerce	7.9
5 – Seaport	5.5
6 – Airport	11
7 – Infrastructure	1.4
8 - Building lot	0.8
9 - Holiday accomodation	0.4
10 - Green houses	0.65
11 – Pastures	0.015
12 – Corn	0.025
13 – Potato	0.025
14 – Beet	0.025
15 – Wheat	0.025
16 - Other agriculture	0.025
17 – Orchard	0.140
18 – Bulbs	0.050
19 - Fen meadow	0.015
20 – Forest	0
21 - Sand/dune	0
22 – Heath	0
23 - Peat/swamp	0
24 - Other Nature	0
25 – Water	0

Table 4. Maximum damage per land use in millions of euro

A close look at Figure 2 reveals that damage curves for the agriculture classes reach the maximum amount of possible damage relatively quickly. This is consistent with the Damage

Scanner and the HIS-SSM (Klijn et al., 2007) and studies of Hoes (2007) and Vanneuville et al. (2006). This occurs because only a small amount of inundation is sufficient to harm the crops. The damage curve for airports also shows a very steep curve at the beginning, which is due to a lot of indirect damage (e.g. cancelling of flights) that will happen if there is water on the runways. Damage to the urban and other build up areas are relatively similar. A final comment is warranted on the damage curve for 'Commerce', which starts relatively flat and then rises relatively steeply above 3 meters of inundation. Limited information and large heterogeneity makes it difficult to determine the exact damage curve for commerce (Vanneuville et al., 2006).

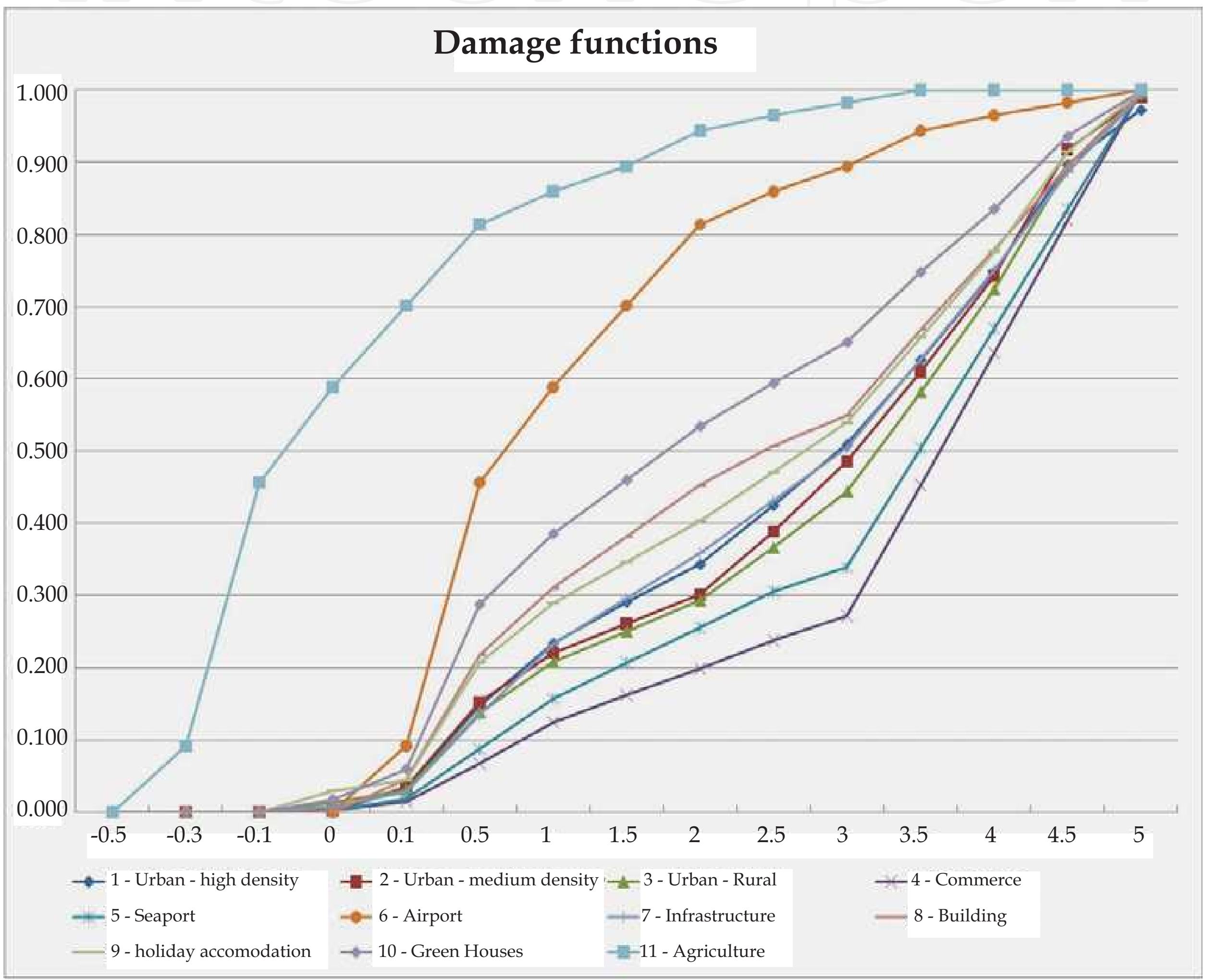

Fig. 2. Damage curves per land use type

5. Results

In this section, the outcome of the model will be described using the land use map and different inundation maps for 'Noord-Beveland'. To compare the different types of flood risk in a consistent way, we will compare them in two different ways. One of the comparisons is the 'existing situation', which describes the most plausible inundation scenarios given the characteristics of the regional water system and primary defenses. For extreme rainfall events, the return periods of 1/10, 1/25, 1/50 and 1/100 are used, while for large-scale floods the probability maps of 1/400, 1/4000 and 1/40000 are used. The other is the comparison with respect to the safety norms, which describes the amount of damage for all the land uses looking at the different safety norms (i.e. what is socially and politically acceptable). In other words, when looking to extreme rainfall events, an urban area is for example allowed to inundate once every 100 years and with a large-scale flood, the whole area is in the case of Noord-Beveland allowed to inundate once every 4000 years. This means that in the second comparison, the whole area will be inundated to see what the amount of damage will be with respect to the safety norms.

5.1 The current situation

5.1.1 Extreme rainfall events

For extreme rainfall events, four different inundation maps are used. For these different inundation maps, potential damages were calculated with the use of the model. Data showed that most of the damage occurs in agricultural area and infrastructure, and the most damage occurs in areas with wheat, potato and pastures. This is due to the fact that these simply have the largest area. The reason why mostly agricultural areas have large amount of damages reflects the fact that crops are severely damaged with only small amount of inundations.

If we take a closer look at the flood risk for the different probabilities, we will look at the annual expected damage. The annual expected damage is calculated by multiplying the probability times the total damage. In Table 5 we see an overview of total damage and the different flood risk per probability for extreme rainfall events.

Return period	**Total damage (x €100,000)**	**Flood risk (x €100,000)**
1/10	9.5	0.95
1/25	33	1.3
1/50	62	1.2
1/100	99	0.99

Table 5. Overview of the estimated total damage and flood risk (in terms of Expected Annual Damage) per probability for extreme rainfall events

In the table above, we see that higher return periods are associated with higher total damage but not higher flood risk (measured in annual expected damage). This is mainly due to the fact that when the probability of specific events becomes lower, the annual expected damage is also lower because you will multiply the total damage with a much lower factor. Interestingly, the highest total damage occurs for the return period of 1/25 and that all the return periods have almost the same flood risk in terms of EAD (about 100,000 euro per year), even though the total damage varies considerably.

It is also interesting to see where the damage exactly occurs. Figure 3 shows that even with a very low inundation probability (1/10), there is already a relative large amount of damage in the northwestern part of the area. This is mainly due to the fact that there are higher inundation levels in these areas and agricultural land uses that undergo damage at even low inundation levels. If we compare this with the land use map of the region (Figure 1), we see that these are all agricultural crops (wheat, beet, and grass).

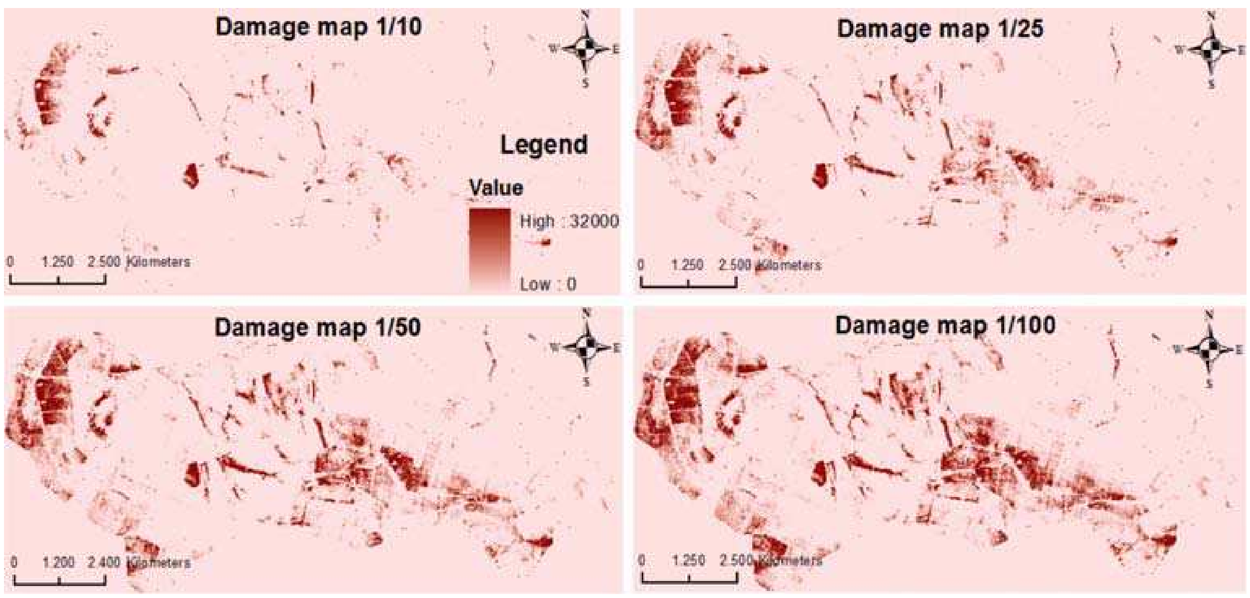

Fig. 3. Damage maps for the four return periods for extreme rainfall events

5.1.2 Large-scale floods

For large-scale floods, two scenarios are used to determine to the total damage in the area. One scenario is a flood that results from a dune breach at the 'North sea-side' of 'Noord-Beveland', the other scenario is a flood that results from a dike breach at the 'Oosterschelde-side' of 'Noord-Beveland'. For the 'North sea-side' the flood scenario is sub-divided into four more sub scenarios, which are 1/4000 with RTC, 1/4000 without RTC, 1/400 with RTC and 1/40000 with RTC. For the 'Oosterschelde-side', the flood scenario is sub-divided into two more sub scenarios, which are 1/4000 with RTC and 1/4000 without RTC (see section 4.2). The breach at the 'North Sea-side' is chosen because there is simply only one place where the dune could breach. The breach at the 'Oosterschelde-side' is chosen since this section in the dike has not been reinforced yet and has therefore at the moment a higher possibility to breach compared to other dike sections at the 'Oosterschelde-side'.

After determining the damages for the dune breach at the North Sea, results for this scenario show that the highest damages occur in the agricultural areas. In Figure 4, which shows the damage in the area with respect to the four sub scenarios, it can be seen that the flood from the North Sea mainly inundates the western part of Noord-Beveland. This area mainly consists of agricultural areas (see Figure 1). Only the inundation with the probability of 1/40000 inundates a much larger area, including a village. This can be seen in the damage map as a much darker spot in the middle of the area that inundates.

For the other breach location at the 'Oosterschelde-side', it is interesting that the results show major differences between the two sub scenarios. In the sub scenario with the RTC-module, there is much more damage. Especially the damage in the infrastructure changes from 22.3 million euro to 1.7 million euro in the sub scenario without the RTC-module. When looking at Figure 5, we see that the main reason for the higher damages is that there is a much larger area that inundates in the sub scenario with the RTC-module even though the inundation depth is lower.

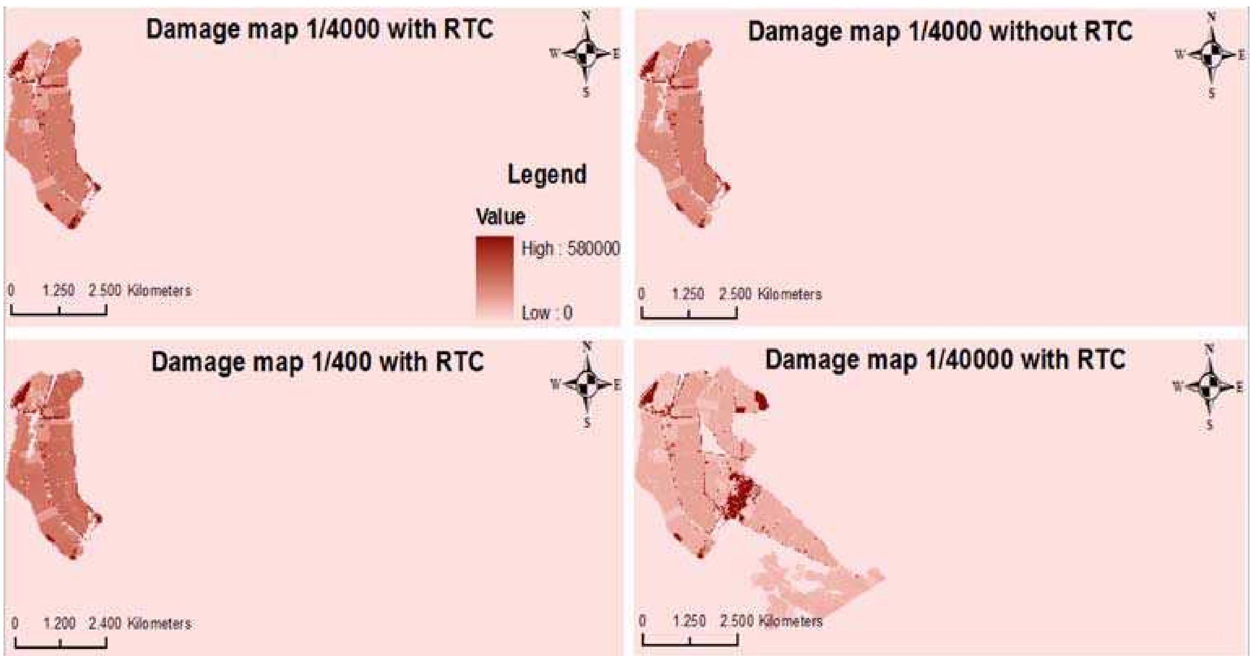

Fig. 4. Damage maps for the four different sub scenarios with the 'North Sea breach'

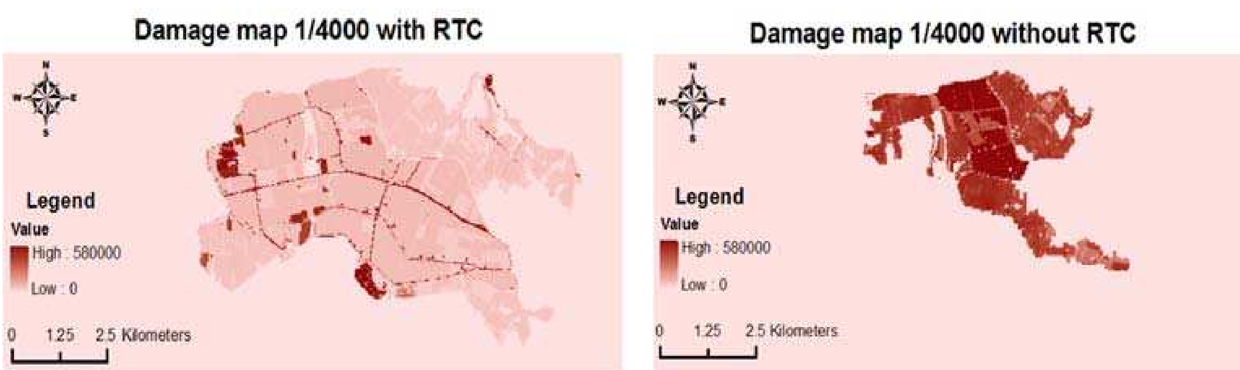

Fig. 5. Damage maps for the two different sub scenarios with the 'Oosterschelde breach'

Finally, the flood risk per sub scenario was calculated (Table 6). At first, we see the highest total damages in the 'Oosterschelde sub scenario 1/4000 with RTC' and the 'North Sea sub scenario 1/40000 with RTC'. This is mainly due to the fact that, as described above, a much larger area inundates with a lot more urban area in both these sub scenarios and a lot more infrastructural areas in the first sub scenario. If we closer examine the flood risk values, we see the highest flood risk in the 'North Sea' sub scenario 1/400 with RTC and the 'Oosterschelde' sub scenario 1/4000 with RTC. The reason why the first sub scenario has a much higher flood risk is because it has a much higher probability of occurrence. The reason why the latter has a high flood risk is simply because there are very high total damages.

	Return period	Total damage (x €100,000)	Flood risk in terms of EAD (x €100,000)
North Sea	1/4000 with RTC	162	0.04
	1/4000 without RTC	162	0.04
	1/400 with RTC	137	0.3
	1/40000 with RTC	575	0.014
Oosterschelde	1/4000 with RTC	943	0.2
	1/4000 without RTC	224	0.06

Table 6. Flood risk for all the sub scenarios with large-scale floods

5.2 Safety norms

5.2.1 Extreme rainfall events

After looking at the current situation, it is also interesting to see what the maximum damage could be if we assume that the probability of flooding equals exactly the safety standards for every cell, regardless of breach scenarios or the local water system. The safety norms for extreme rainfall events, described in Table 7, imply that different areas are allowed to inundate with different probabilities. In Table 7, we see the maximum damages and flood risk per land use if all the land is inundated with 0.165 meters of water. This inundation level is chosen because this is the average inundation above ground level for all four inundation maps.

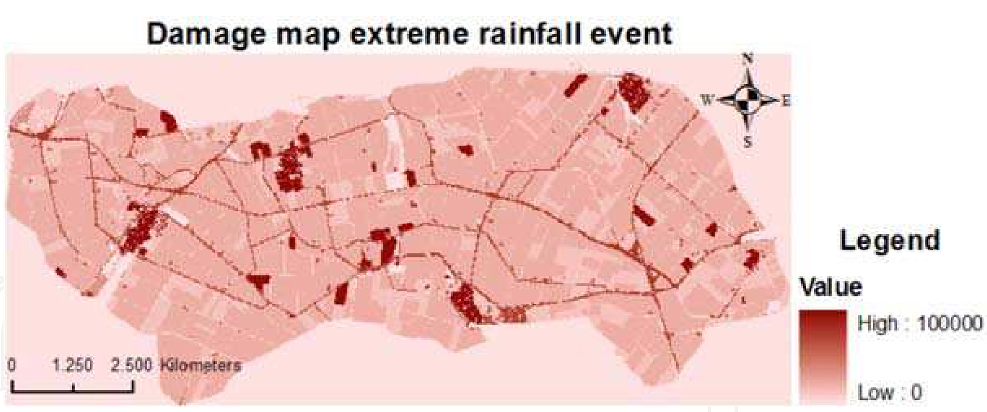

Fig. 6. Damage maps for an extreme event in Noord-Beveland (inundation of 0.165 meters)

In Table 7, the annual expected damage is calculated per land use, according to the different safety norms described in Table 1. If we look at the maximum damages, we now see that highest amount of damages are in the urban areas and infrastructure, which is in contrast with the highest damages in the 'current situation' where we saw that the highest damages were found in the agricultural land uses. Important to note is that the damage in agricultural land-uses are still much higher than in the 'current situation'. When examining the flood risk more closely, we see that the highest flood risk occurs in agricultural areas. This is mainly due to the fact that these areas have low safety norms.

Figure 6 shows the spatial distribution of the damage. In this figure, there can be seen that in urban areas the highest damages occur, which is consistent with the data for this scenario. The figure also highlights the difference in agricultural land uses. Much of lighter areas in the damage map are associated with pastures.

Land use	**Maximum damage (x €100,000)**	**Flood risk in terms of EAD (x €100,000)**	**Area (ha)**
1 - Urban - high density	2.9	0.03	0.56
2 - Urban - low density	340	3.4	118
3 - Rural area	62	0.6	105
4 – Commerce	6.7	0.07	3.7
7 – Infrastructure	210	2.1	330
8 - Building lot	1.3	0.01	2.1
9 - Holiday accomodation	7.4	0.07	25.6
11 – Pastures	140	14	1305
12 – Corn	28	1.1	157.4
13 – Potato	250	10	1363.4
14 – Beet	170	6.8	938
15 – Wheat	280	11.2	1538
16 - Other agriculture	220	8.8	1203
17 – Orchard	140	5.6	138.7
20 – Forest	0	0	59.7
21 - Sand/dune	0	0	1.7
23 - Peat/swamp	0	0	1.8
24 - Other Nature	0	0	57
25 – Water	0	0	4
Total	*1860*	*64*	*5598*

Table 7. Total damages and flood risk for an extreme rainfall event with an inundation of 0.165 meters

5.2.2 Large-scale floods

To determine what the maximum damage will be in 'Noord-Beveland' when looking at the safety norms for large-scale floods, the Risk Map for the Netherlands. For the creation of this map it was assumed that the complete dike ring inundates in case of flooding up to a level where flood water would spill out of the dike ring (RWS-DWW, 2005).

Calculating the damages showed that the highest damages occurred in the urban – low density areas and to infrastructure. The total damages in the agricultural land uses are almost the same as the total damages seen in Table 7 with extreme rainfall events. In Figure 7, we see that even though the dike or dunes breach at all the possible locations, not all areas are inundated. For example, a few areas in the middle are not inundated. Furthermore, the damage map clearly shows the location of villages and infrastructure, because these are the areas that incur the highest damages.

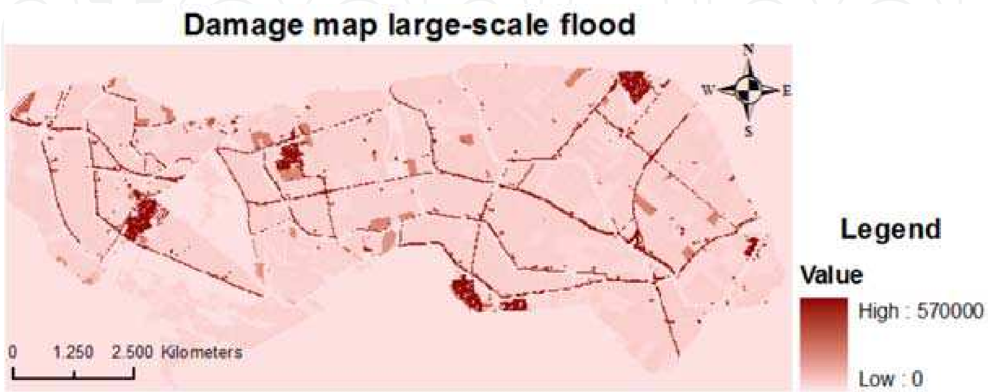

Fig. 7. Damage map for a large flood in Noord-Beveland (dike ring fills up completely)

For large-scale floods in this scenario, the total damage and flood risk are described in Table 8, where a total damage can be seen of approximately 388 million euro and an expected annual damage of approximately 97,000 euro per year.

Return Period	Total damage (x €100,000)	Flood risk in terms of EAD (x €100,000)	Total area (ha)
1/4000	3880	0.97	5598

Table 8. Total damage and flood risk for a large flood in Noord-Beveland

6. Discussion

In this section we provide some critical discussion on the structure of our model and our results. First, we consider the results from the study area according to the 'existing situation' and the safety norms. Second, we identify possible methodological issues with the integrated flood risk model and our analysis.

6.1 Total damage and flood risk estimates

In this section, a few results will be examined more closely. First, the differences between the total damage and flood risk for extreme rainfall events and large-scale floods will be examined, for respectively the 'current situation' and the safety norms. Second, the differences between the 'current situation' and the safety norms will be discussed.

If we examine the results of the 'current situation' carefully, we see two important differences. One is the difference in exposure. While for extreme rainfall events, the area of exposure is almost the whole dike-ring area, for large-scale floods the inundation area is limited to a much smaller area. Reasons for this are that there are higher areas (roads or inner dikes) within Noord-Beveland that act as secondary defenses and that simply not much water flows into the dike ring after a breach near the dunes (where the difference in elevation between the water level and the land surface is limited). The other difference is in the damage distribution. While for extreme rainfall events the highest damages are found in agricultural land uses, the highest damages for large-scale floods mainly are found in urban areas and infrastructure.

	Return period	Total damage (x €100,000)	Flood risk (in terms of EAD)
Extreme rainfall events			
	1/10	9.5	95000
	1/25	30	133000
	1/50	60	125000
	1/100	100	99000
Large-scale floods			
North Sea	1/4000 with RTC	162	4000
	1/4000 without RTC	162	4000
	1/400 with RTC	137	34000
	1/40000 without RTC	575	1400
Oosterschelde	1/4000 with RTC	943	24000
	1/4000 without RTC	22.4	6000

Table 9. Total damage and flood risk for all the different scenarios

In Table 9, all the total flood risk values are listed for the 'current situation'. In the table can be seen that flood risk for extreme rainfall events is much higher than the flood risk of large-scale floods, which is remarkable since the total damages of extreme rainfall events are in general much lower than that of large-scale floods. The main reason for this is that even though the total damages are much lower for extreme rainfall events, the probability of occurrence is much higher. This is an interesting result, since much more policy has been made to prevent or mitigate the chance of large-scale floods (Kok and Klopstra, 2009).

If we examine the results with respect to the safety norms closer, we see the same differences as in the 'current situation'. In Table 10, we see that even though the damages of large-scale floods are higher, the flood risk in terms of annual expected damage is much lower. This comparison is more interesting because of the dissimilarities between the two types of flood risk, described in section 3.3. The probabilities and safety norms for extreme rainfall events can be interpreted as 'accepted risk'. In other words, the area is allowed to inundate with these probability levels. Also important is to take into account what the effect is for both events on for example the insurances, indirect damage, human casualties and the social disturbance. These effects are not taken into account in the calculated annual expected damage but have, especially for large-scale floods, a very high effect on the total impact. Taking these unquantified effects into account would probably bring both types of risk closer together. It is, however, questionable whether the difference would completely be bridged by these additional effects given the large (64 times) difference.

	Total damage (x €100,000)	Flood risk (in terms of EAD) (x €100,000)
Extreme rainfall event	1860	64
Large-scale flood	3880	1

Table 10. Total damage and flood risk for the safety norm maps

It is important to note that the inundation maps with respect to the safety norms for both types of events are hypothetical. For extreme rainfall events, it is not plausible that the whole area inundates with the same height, since the norm is a lower limit and many areas will probably be much safer than the norm. Similarly, for large-scale floods the compartmentalization within the dike-ring area will probably prevent the whole area from inundating unless there are many dike failures at all sides. Nevertheless, by contrasting these situations we could compare the types of risk as they are 'allowed' by current policy.

It is interesting that the total damage calculated with the integrated flood risk model is much lower than the total damage calculated with the Damage Scanner and the HIS-SSM for dike-ring 28. The total damage calculated with these latter models is respectively 583 and 653 million euro (Klijn et al., 2007), while the total damage calculated in the integrated flood risk model is only 388 million euro. That figure is more in line with total damage estimates of around 400 million euro determined by Klijn et al. (2004) and van der Klis et al. (2005). One explanation for the higher damages in the Damage Scanner and the HIS-SSM could be the difference in cell size. In the Damage Scanner, the grid cell size is 100x100 meter, instead of 25x25 meter in the integrated flood risk model, which can result in higher damages because of aggregation of multiple land uses in one grid cell, resulting from overestimation of residential land in the aggregation process. This can also be seen when one compares the land use map used in this study with the land use map used in the Damage Scanner; the amount of residential and commercial land-use is 7.5 per cent higher in the Damage Scanner than in the land use map used in this study. This overestimation results from the fact that residential land tends to dominate, but not completely fill cells at a coarser resolution, as has also been observed by Bouwer et al. (2009). Another reason could be that in the integrated flood risk model a greater variety of agricultural land uses are used with much lower maximum damages. For these classes, much lower maximum damages are chosen because it is not likely that inundations of more than 0.5 meter will cause any more damage to agricultural crops. Finally, the HIS-SSM model calculates the damages by using objects. In the integrated flood risk model, objects such as tractors and other agricultural machines are not taken into account, which results in lower damages.

Even though high flood risk values are found for extreme rainfall events in Noord-Beveland, this does not mean that this will also be the case for the rest of the Netherlands. Since Noord-Beveland has much agriculture, not many urban areas and many secondary defenses, it is not very representative for the rest of the Netherlands. For instance the 'Randstad' area (middle west of the Netherlands) is much more urban and will therefore probably have a different comparison of the examined types of flood risk.

6.2 Methodological issues

The model used in this study seemed very useful when determining flood risk for both extreme rainfall events and large-scale flooding. But several methodological issues remain that should be taken into account. First, the aggregation of the built up areas in the land use maps could have been better. There are only three different urban land use classes, while more differentiation would be desirable. Second, there could have been more detailed investigation about the maximum damages for a number of land use classes. For a number of classes, determining the maximum damages was sometimes difficult, even though it was calculated with HIS-SSM damage maps and literature studies. Therefore, more research and investigation is required to provide consistent estimates of the maximum damages. Third, it was difficult to develop the model with different inundation maps as inputs. Several adjustments must been made to fit the different inundation maps in the same model.

Also important to take into account is that the model only has been used for determining the flood risk of a small, specific area. It is interesting to see whether results for larger areas or areas with different land uses are similar to those reported in this study.

Finally, it is always hard to validate the model in a consistent way when observation data is lacking. Since there have not been many large-scale floods or extreme rainfall events, it is hard to test if the model calculates realistic absolute damage estimates. As both types of risk are estimated using the same model, the influence of any bias in, for instance, maximum damages will affect both estimates.

7. Conclusion

The main objective of this study was to create a common methodology to assess flood risk of extreme rainfall and large-scale flooding in the Netherlands. Based on the literature we were able to incorporate both types of flood risk within an integrated model that allowed us to compare the different types of flood risk in a plausible and consistent way.

We then applied the model to analyze flood risk in the 'Noord-Beveland' area. Results show that even though the highest total damages are found to result from inundations of large-scale floods, the flood risk of extreme rainfall events are in general much higher when both are expressed in terms of annual expected damage. The reasons are that extreme rainfall events cause larger areas to inundate and occur with a higher probability, which combines to drive up flood risk. Further investigation should be done in other parts of the Netherlands to test if this is the case for more dike rings.

Our model does not quantify some types of indirect damage, such as human casualties and social disturbances. These should be taken into account to provide an even more consistent comparison. We expect that they would have increase the damage associated with large-scale floods. Nonetheless, we question whether the difference large difference (64 times) would be completely bridged by these additional effects. Aside from these unquantified factors, there are a number of data comparability issues, such as the differences in exposure and the distribution of the damage, which should also be kept in mind when comparing different types of flood risk.

Even though the model requires further refinements our initial results suggest it is possible to compare different forms of flood risk within an integrated model. Our finding that higher flood risk can be associated with extreme rainfall events suggests there is a need for the focus of public policy to shift away from large-scale flooding onto extreme rainfall events.

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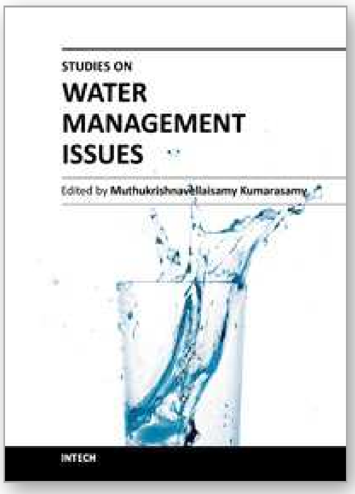

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This book shares knowledge gained through water management related research. It describes a broad range of approaches and technologies, of which have been developed and used by researchers for managing water resource problems. This multidisciplinary book covers water management issues under surface water management, groundwater management, water quality management, and water resource planning management subtopics. The main objective of this book is to enable a better understanding of these perspectives relating to water management practices. This book is expected to be useful to researchers, policy-makers, and non-governmental organizations working on water related projects in countries worldwide.