Flood Risk Evaluation

Validation and Smart Flood Risk City Management

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Challenge the future

Flood Risk Evaluation

Validation and Smart Flood Risk City Management

by

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The cover page shows a flooded part of Bangkok during the 2011 flood event (http://www.abc.net.au/news/linkableblob/3299482/data/people-in-flooded-street-data.jpg)

Abstract

River floods are considered one of the most important natural disasters and causes huge damages every year, both in economic consequences and fatalities. Out of historical perspectives, human settlements are located in fertile and economic attractive delta regions. Deltas tend to be constantly changing nodes of economic and urban growth leading to increasing exposure to flooding. Climate change may lead to a higher intensity and magnitude of flood events in the future. This development puts huge pressures on government and other decision-making authorities to cope with these threat by developing adequate flood mitigation plans. It is recognized that prevention is not possible and a shift towards integrating flood management into urban planning making it both robust and adaptive to future uncertainties is required to reduce the risk. Finding the set of measures appropriate for the risk situation of a city is difficult, because for a lot of non-structural measures the benefit is not yet defined in a quantitative way.

Flood risk assessments are useful tools for indications of economic damage and identifying the most vulnerable cities worldwide. However, only considering economic damage as flood indicator will lead to an one-sided quantification of flood risk. Therefore, other risk indicators need to be considered to give a more comprehensive indication of flood risk. In this research, a framework is suggested to get a quick overview of the flood risk management of a city containing preventive, spatial, emergency, recovery and adaptive status. The economic risk is extended with the risk indicators; individual risk, household risk and a damage distribution. Based on this, an evaluation of the flood risk situation of a city can be derived, resulting in a preliminary advice for the appropriate measures and measures where the highest cost benefit ratio can be achieved. Focusing on the most beneficial measures could save a lot of time and resources. Next to that, this framework could eventually lead to a more proper flood risk assessments for identifying vulnerable cities and a way to communicate flood management status leading to some sort of competition between cities to come up with sustainable solution to be as safe as possible.

Two historical flood events are being used as case study, namely the 2011 Thailand Flood and the 2013 Central Europe flood focusing on Germany. Both events are being assessed using the Flood Risk Assessment Tool (FIAT), where the calculated damages of the events are compared with the official reported damages. This gives an indication of the validity of this tool for damage calculations. After that, a closer look into the flood management of Bangkok by looking at the risk reduction plans after the flood event is conducted related to our suggested framework. For Germany, the cities of Hamburg and Dresden are being assessed by combining the flood risk indicator and smart city flood risk framework to come up with a qualitative assessment if the cities recognized their shortcomings and turned the tables. This is also done for Rotterdam and Vienna eventually leading to a comparison between these two cities and Hamburg and Dresden to assess the multi-layer flood management status.

In the end, the calculated damages compared to the reported damages were in the same order of magnitude for both events within a 10% boundary. However, looking more closely at the German state, results are less accurate. A closer look at the city of Bangkok showed that the weak spots of the urban flood management are still not recognized and focus on preventive measures still dominates. Including individual risk, household risk and damage distribution led to evaluation of the top 25 German cities, where differences between cities led to different advises. For instance, the city of Bonn has really high individual risk and high share of residential damage making insurance, precautionary measures and flood prove building appropriate measures. The city of Dresden managed to reduce its vulnerability from 25% to only 4.5% by finding appropriate measures. Hamburg is the frontrunner for flood risk management integrated into urban planning by shifting to an adaptive flood risk approach. By comparing the four cities with approximately the same economical and individual risk showed that each city has managed to incorporate measures from different flood mitigation layers into the urban footprint. Rotterdam and Vienna largely rely on the high protection standards, where the German cities shift the responsibility more to household level. Rotterdam and Hamburg are inspirational cities how flood mitigation measures could be implemented in urban planning to cope with increasing urbanization rates and climate change threat. However, shortcoming are also recognized for all cities which makes room for improvements possible in the future.

Preface

This bachelor thesis is the end of my bachelor phase and my first acknowledgment with doing academic research. Leonardo Da Vinci said ages ago: *'Learning never exhausts the mind'*. I completely agree with this statement and this bachelor thesis was the first step in applying the learned knowledge in an actual research. Doing this research was very interesting and an eye opener for me confirming the right choice of my follow up master at TU Delft. The successful execution of this thesis project could not have been reached without the help of a few people.

First of all, I would like to thank my supervisors Saskia van Vuren and Bas Kolen for their thorough interest, guidance, freedom and most importantly they gave me the opportunity to do this research. Next to them, I would like to thank a few other people. Simon Schilder for providing me with the FIAT data and helping me with installation and the first steps of using it. I would thank Jan Huizinga from HKV as well. He provided me with information about the Thailand flooding and could always be reached for questions about QGIS. Also fellow bachelor student Daan Bader was essential for the execution of my research. Together we helped each other with QGIS and FIAT and off course discussions about the content of our researches. I owe my sister Yvette lunch for a final check on my English spelling and grammar.

I really enjoyed the last ten weeks and I am satisfied with the result of my bachelor thesis.

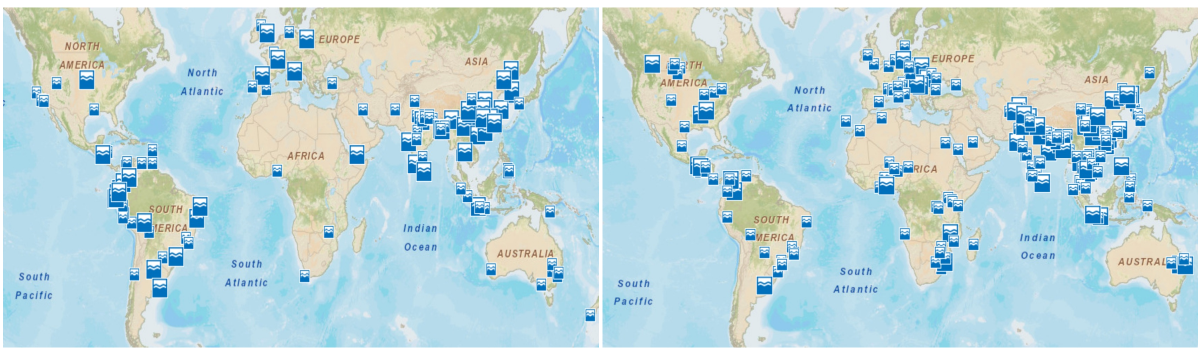
Contents

1
INTRODUCTION

1.1. INTRODUCTION

River floods are considered one of the most important natural disasters in the world and causes huge damages every year, both in economic consequences and fatalities. In 2015, floods accounted for 27% of the natural disasters worldwide in US$ meaning US$28.0 Billion . Next to that, floods caused 66% of the fatalities in that same year, almost 5500 in total (MunichRe, 2014). An observation is made that economic losses due to extreme floods have drastically increased during the last decades even though flood protection investments have also been increased (de Moel *et al.*, 2009; Field *et al.*, 2014; UNISDR, 2011). As can be seen in figure 1.1, where flood events are shown from 1980-1985 and 2010-2015, floods happen on every continent. However, out of historical perspectives, urban settlements are located along fertile river grounds and in economical active delta regions, resulting in the fact that most river flood damage occurs in densely populated regions. In the developed countries, extreme floods are characterized by huge losses in damage to economic activity, for instance the flooding in parts of Germany in 2013 (overall losses US$12,500m, 25 fatalities). Moreover, in the developing countries, where the flood protection standards are the lowest, coping with floods is even harder and result besides economic damages in many fatalities. Examples of this are the flooding of parts of Nigeria in 2012 (overall losses US$500m, 363 fatalities) and Pakistan in 2011 (overall losses US$2,500m, 520 fatalities)(MunichRe, 2014).

The occurrence of extreme floods is expected to increase even more in the future due to a constantly changing world. Socio-economic factors and climate change are considered the main drivers of the increase in flood risk (IPCC, 2007; UNISDR, 2013). Socio-economic factors like urbanization, increase in wealth, increased population and economic development have caused that more people and more valuable assets are prone to flooding. Human population has increased rapidly in the past century from 1.6 billion in 1900 to 6.9 billion in 2010. Moreover, the global population living in urban regions has increased from 16% in 1900 to more as 50% in 2010 and this trend is expected to go on in the future (Kummu *et al.*, 2011). Also climate change is an inevitable phenomenon and affects zones prone to flooding as a result of increase in sea-level and magnitude of extreme events. (Jongman *et al.*, 2012). These changes put increasing pressure on governments and other decision-making instances for dealing with these extreme events and because extensive flooding is likely to occur in multiple countries at the same time, it puts increasing pressure on trans-national risk reduction (Jongman *et al.*, 2014). To assess and carefully handle these risks , studies are needed to measure the risk and map them in order to give an overview of the most vulnerable regions. However assessing



(a) 1980-1985 (b) 2010-2015

Figure 1.1: Flood events obtained from the MunichRe, 2014 database for time periods 1980-1985 and 2010-2015. The scale of the rectangular indicates the impact of the flood event

floods is a complex task, because of the complex nature of flood generation (Bouwer *et al.*, 2010) and the uncertainty of failure mechanisms of dikes and embankments. In order to give an overview of the risks involved and the associated damages of flood events, flood hazard maps need to be derived and most favorable on the highest possible spatial resolution to make it meaningful for end users.

1.2. PROBLEM STATEMENT

Because of the increasing concerns, there is an increasing scientific and political interest for the global assessment of natural disasters (Winsemius *et al.*, 2013). An effective insight in the underlying trends and causes of extreme events and the resulting damages of these events are extreme useful for policymakers and financial institutes to assess and decide which and where investments have to be made to reduce the risk of natural disasters(Winsemius *et al.*, 2013). However, for a long period of time, assessment of flood risk was only available on a local, regional or national spatial scale (Jongman *et al.*, 2012). Expending this to a global scale is really difficult and expensive, because of the large differences between countries and specific regions in countries and to assess all places, local characteristics have to be taken into account. However, a global flood risk assessment can give an indication which regions or cities are most vulnerable to flooding. More detailed studies can be done further on based on this.

HKV consultant and Deltares are working together to develop their own method to assess global flood risk on city scale by making use of widely available data in order to derive flood risk profiles. Using this quick tool by assuming uniformity between cities , the most vulnerable areas can be identified. Until now, two river flood assessment methods are developed, namely the "GLObal Flood Risk with IMAGE Scenarios" (GLOFRIS) and the "Bottom-up Climate Adaptation Strategies for Sustainable Europe" (BASE) The BASE method is a more comprehensive method using more refined data, but is only applicable for Europe. The GLOFRIS method can be used for a global assessment (Winsemius *et al.*, 2013 ; Ward *et al.*, 2013), but more simplifications are implemented in this method. The BASE method is more refined, because it uses five land-use classes and five damage functions but requires more detailed land-use information. These damage functions are derived from Huizinga (2007), who made depth damage functions for most European countries. The GLOFRIS method in contrast uses only two land-use classes and two damage functions. A research project of Nootenboom (2015), who used both methods extensively, showed that both methods are presenting approximately the same results for urban cities most vulnerable to flooding, although the GLOFRIS method gives a higher predicted damage in Europe. The BASE method is extended to all continents by making use of newly developed depth damage function of Huizinga and de Moel (2015) for all other continents. To apply the damage functions for multiple land-use classes, land-use maps are required. These have been derived by some bachelor students (Van der Veer, 2015; Kosters, 2015; Suijkens, 2015). They subsequently applied the same approach as the BASE method, but now for their specific continent. In the end, comparisons of both methods showed great similarities in flood risk results expressed in annual damages, although specific land-use information was sometimes scarce for other continents. Flood protection standards are not taking into account for these methods, because less information is available for flood protection standards in especially the developing countries. IVM-VU (together with partners) further improved the model by collecting information from several different sources to create a database and give an indication of the flood protection standards in different parts of the world, which could be used and combined with both the GLOFRIS and BASE model. Schilder (2016) did a global flood risk assessments for both methods for including and excluding protection standards. Again, the correlation between the results of both methods was indicated. Furthermore, the most important conclusion was that including flood protection standards significantly reduce the risk. To quantify the accuracy and reliability of the approach, validation studies are needed to give an indication how accurate the model represents the reality besides the theoretical correctness. Kosters (2015) validated the model by regenerating the data of the Jakarta flood event of February 2007 and compared the expected damage indicated by the both methods with the reported damage. This comparison resulted in an estimation of approximately € 415 million for the BASE method where the reported damage was € 433 million, which is really close. This research can be considered as a follow up study of previous work by validating the model for two new events, but also to give a close look in flood risk reduction measures on city scale. Identifying the most important components could help extent the model to better assess flood risk worldwide.

1.3. OBJECTIVE

The main objective of this thesis project is to further validate and extent the Flood Impact Assessment Model by means of remodeling the data of historical flood events and compare them to reported data. This gives more insight in the accuracy of calculated damage and reliability of the model. The flood risk assessment now is purely focused on the exposed damage and technical protection standards. By looking more closely on city scale to the flood event, the crucial focus points regarding flood risk management and other delta developments can be determined and set out in a framework. If the components of this framework could be included in the flood risk assessment, a more proper and improved global flood risk assessment could be made based on this. For this thesis, two flood events are considered. The first one is the 2013 flood in Central Europe, focusing on Germany and the second one is the 2011 flood event in Thailand.

1.4. RESEARCH QUESTIONS

The research of this bachelor thesis project concerns the following research questions:

- Which flood mitigation measures determine flood risk on city scale?
- In which way could the FIAT model be extended to come to an advice for appropriate measures?
- How closely does the BASE method approximate the reported damage of the 2011 Thai flood event?
- How did Bangkok scored in the derived framework before and after the flood?
- How well does the BASE model perform by means of an extensive validation study of the 2013 Central Europe floods?
- How did some German cities implemented flood management before and after the flood event taking into account FIAT extensions to determine current flood risk status?
- How do we improve the flood risk assessments to come up with a more proper one?

1.5. NOTE TO THE READER

In chapter 2, the definition and methodology of the flood risk assessment used is being described. Chapter 3 contains a suggested smart flood risk city framework for assessing flood mitigation measures taken by cities. The individual components are described separately. After that, risk indicators are described for the extension of the flood risk assessment.Chapter 4 is a case study for the 2011 flood event in Thailand and how our framework could be applied for the city of Bangkok. In chapter 5, the individual risk indicator is applied to Europe given a quick overview how this assessment looks like and which cities score high. Chapter 6 goes further into the risk indicators and how these can be translated into an advice for appropriate and most beneficial measures for five German cities. Chapter 7 contains a case for the 2013 flood event with focus on Germany. In chapter 8 an comparison is made between the cities of Hamburg, Dresden, Rotterdam and Vienna to identify current flood management status and how this could lead to a better risk assessment. Chapter 9,10 and 11 includes respectively the discussion, conclusion and further recommendation.

2
Risk Assessment

2.1. Flood characteristics

In order to assess the best measures to manage the risk of an area, insight is needed in the predominant types of floods that occur in this area and the local characteristics of the area. Each flood type has its own characteristics and therefore has it own most effective measures to protect against this flood type. Although every flood is an unique phenomenon, several types of river floods can be distinguished, including fluvial, pluvial, groundwater and flash floods (Green *et al.*, 2013). Fluvial flooding is most widely occurring river flood as result of large precipitation or snow melt with resulting high discharges and overflow of the river banks (Messner *et al.*, 2007). Pluvial flooding is another flood type that is induced by extreme rainfall. This flood type occurs in urban areas where the ground cannot absorb the run-off of rainwater and therefore flows freely throughout the urban area. This type of flood is very likely to increase in the future, due to increasingly dense urban developments (DHI, 2014). Flash floods are considered most difficult to forecast and can occur for different reasons. One cause can be due to extreme precipitation in mountain areas or areas with steep slope, which causes high velocities and water level in a short period of time. Another cause for a flash flood can be a dam or dike failure or a release of ice jams. Because the development of flash flood is very quickly, warning times are very short what makes them difficult to cope with (Messner *et al.*, 2007). Groundwater flooding is less dominating in terms of damage and shows similarities with pluvial floods, where groundwater flooding is the result of the inability of riverbanks, polders and drainage channels to cope with the amount of water. The overload of water result in a groundwater level above the ground level and will therefore result in an overflow of the surroundings. The occurrence of the different flood types are formed and influenced by the interaction of local factors like catchment area, meteorology, topography, geology, vegetation and so one (Merz *et al.*, 2014). Meteorology determines the intensity, duration and frequency of extreme rainfall. This is a good starting point for analysis of flood events, because different meteorological events can trigger different flood processes in the same catchment area. For example, in the United States summer thunderstorm cells can generate flash flood, where in winter periods storm deliver snow and rain characterized by sustained and cumulative flow (Merz *et al.*, 2014). Flood types generated from mixed mechanisms make it more difficult for catchment areas to find appropriate measures to cope with the floods. After the occurrence of a flood triggering event, catchment characteristics determine how it reacts further on this. The land form determines what proportion will infiltrate, drain off and more importantly, what proportion will remain runoff. Soil moisture is an important characteristic for the infiltration capacity of water, especially in case of flash floods (Cassardo *et al.*, 2002). Moreover, floods are also affected by basin conditions, such as pre-existing water levels in river, snow and ice cover, the soil permeability, rate of urbanization and the presence of dikes, dams and reservoirs (Kundzewicz *et al.*, 2013). Next to meteorological and basin characteristics, geographical characteristics should be taken into account for the response of a catchment area. Runoff is driven by gravity, both in terms of direction and speed, and by the frictional resistance which also influences the travel speed (Green *et al.*, 2013). This means that areas with steep slopes and low resistance factors will result in short time to runoff and high runoff velocities, characteristics of flash floods. This result in the fact that flash floods frequently occur in France rivers, because they originate from the Alpen mountains, however hardly occur in an European country like The Netherlands or England.

2.2. DEFINITION

To give an unambiguous interpretation of the term *risk*, a consistent definition had to be made. Amongst scientists in the field it is commonly agreed that *risk*, and in our case *flood risk*, is defined as the product of 1) *Hazard* , 2) *Exposure* and 3) *Vulnerability* (Kron, 2002). This definition is also being used by the Intergovernmental Panel on Climate Change (IPCC) but they slightly adjusted it over the last couple of years to the following more extended definition (Field *et al.*, 2012):

- *Hazard*: Hazard is defined as the potential occurrence of a natural disaster that could cause direct or indirect damage and losses. Hazard is used to define the threat or probability of an extreme event and not the event itself.
- *Exposure*: Exposure is referring to the presence of people, environmental services, infrastructure, economic and social assets which could be affected by a natural disaster and therefore can cause potential harm, losses and damage.
- *Vulnerability*: The characteristics of a person, group or place and their situation that influences their ability to anticipate, resist and recover from the effects of a disaster.

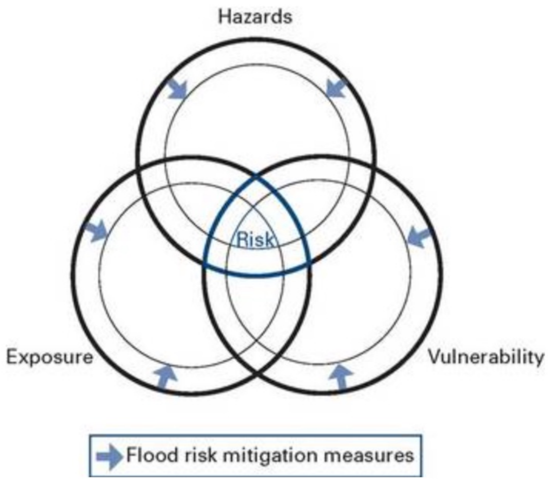


Figure 2.1: Flood risk definition with components vulnerability, exposure, hazard and risk mitigation measures (APFM, 2006)

Next to the framework of the three aspects of risk, a change in one or two of the aspects are shown and the resulting change in disaster risk. As mentioned before, it is expected that the number of hazards will increase in the future, which will result in an increasing overlap of disaster risk as shown in the figure 2.1. However to reduce the risk, the exposure, hazard or vulnerability of a region can be reduced. Exposure reduction can be obtained, for instance, by expending the city boundaries away from the vulnerable area, although this is difficult in practice. Reducing the vulnerability in contrast is more easily obtained, for instance by creating awareness, implementing better communication mechanisms or by improving flood protection standards. The ability to modify the flood risk in many ways changes the assessment of flood risk in a more dynamic assessment, because it varies in space and time.

2.3. HAZARD

The hazard components includes the flood characteristics. The flood hazard is characterized in terms of flood probability, flood depth, flow velocity, water level rise etc (De Bruijn and Klijn, 2009). These characteristics are therefore dependent on the flood types and geographical location of a country. An accurate estimation of this is a difficult task due to the complexity of the dynamics of a flood pulse and its translation onto the 2-dimensional flood plane (Feyen *et al.*, 2012) and because of this modeling of flooding is rather difficult. Most well-known modeling tool to do this is by means of an inundation model, based on statistical analysis, that combines the probability of an event to the inundation depth in a specific river basin, as shown in figure 2.2. In this figure, the inundation depths for a river are shown at normal level and in case of a flood event with a return period of respectively 5, 50 and 100 years. The most important parameter is flood depth, because this determines for a large extend if the bank full height will be reached, resulting in overflow of the flood prone area. Other important parameters are the flow velocity and water rise velocity. In steep upstream areas, insight in these parameters is of utmost importance for emergency planning, and according to Kok *et al.* (2005), more fatalities are expected when water levels rise fast. This in contrast with low-lying flat areas downstream, where these parameters can be almost neglected.

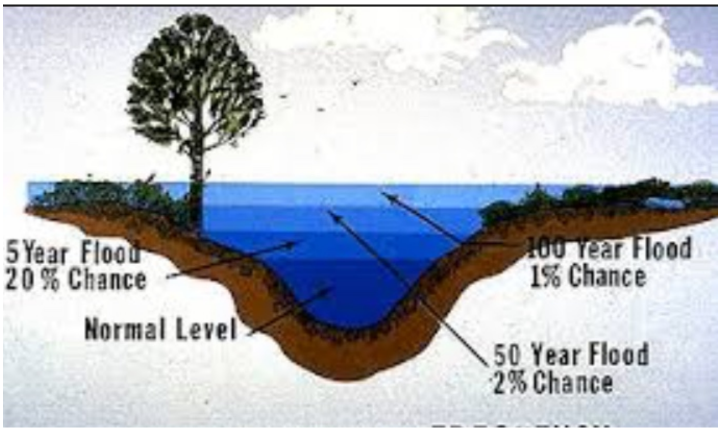


Figure 2.2: Overview of the floodplain with corresponding inundation depth by normal water level and by a 5, 50, and 100 year flood (DSWR)

GLOBAL HYDROLOGICAL MODEL

To simulate the river discharges in the different areas, the global hydrological model PCR-GLOBWB, developed at the Department of Physical Geography of Utrecht University (Van Beek and Bierkens, 2009), will be used. For the use of this model the computer software PC-Raster is needed, which is a Python-based software tool in which several environmental processes are simulated. One of these environmental simulations is the "PCRaster GLOBal Water Balance model" (PCR-GLOBWB). PCR-GLOBWB is a grid-based model of global terrestrial hydrology and calculates the water storage in the different layers of the soil on a daily basis for each grid cell on a spatial resolution of 0.5°x 0.5°. An overview of the model is shown in figure 2.3, where the different layers and water flows are shown. The soil layers are divided into two vertical soil layers and an underlying groundwater layer together with their resulting drainage components; direct run-off (QDR), interflow(QDR) and base flow (QBf). The red and blue arrows on the top are representing the interaction between soil and atmosphere (Van Beek and Bierkens, 2009). Also canopy interception and snow storage are included in this model. The right arrow indicates the total incoming and outgoing discharge of the system. This model is similar to existing general circulating models (GCM), but some new features are added. The dynamic routing of the model makes use of the kinematic wave equations, or the Saint-Venant equation instead of the diffusion wave approximation (Winsemius *et al.*, 2013). This takes into account the elongation and flattening of the wave as it travels downstream the river. Besides the river discharges, the flow outside the river banks can be modeled and is therefore suitable for the assessment of overflow of flood prone areas during extreme discharges. To do this, different return periods and the corresponding water discharges could be modeled and also the discharge differences due to climate change are possible input data for this model. Most widely used return periods for extreme events are T of 2,5,10,25,50,100, 250, 500 or 1000 years.

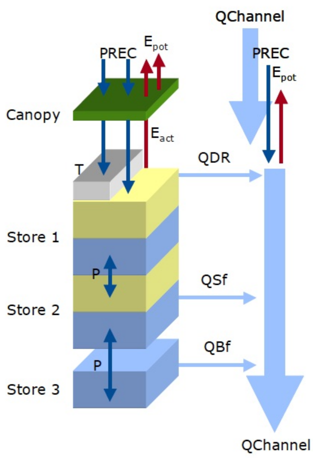


Figure 2.3: Schematized concept of the PCR-GLOBWB global hydrological model (Van Beek and Bierkens, 2009).

2.4. EXPOSURE

In general, the exposure component encompasses all flood impacts, both direct and indirect, on exposed assets in the inundated area. This is briefly summarized in figure 2.4, where various flood impacts are shown. Impact of a flood event is in most cases expressed in a monetary value or number of fatalities. This due to the fact that especially indirect and intangible impacts are very difficult to quantify (de Moel *et al.*, 2009). Therefore, flood impact or resulting damage is often expressed in an economic value, because a value can be added to tangible assets.

Category		Tangible	Intangible
Primary	Direct	Capital loss (houses, crops, cars, factory buildings)	Victims, ecosystems, pollution, monuments, culture loss
	Indirect	Production losses, income loss	Social disruption, emotional damage
Secondary		Production losses outside the flooded area, unemployment, migration, inflation	Emotional damage, damage to ecosystems outside the flooded area
Induced		Costs for relief aid	Evacuation stress

Figure 2.4: Negative flood impact categories according to de Bruijn (2005) divided into tangible and intangible primary, secondary and induced damages.

For several decades, human settlements are established near river basins and in delta areas, because of the fertile river grounds and economic activity in these areas. This has resulted in the long term that dynamics in the socio-economic system may alter consequences of floods in the future. In flood prone areas as well as the expansion of residential areas may significantly contribute to rise in damages from flooding events (Rojas *et al.*, 2013). Next to urbanization, increase in wealth and changes in land-use patterns may contribute to higher exposure to flooding. According to the study of Jongman *et al.* (2014), the potential impact of socio-economic changes on flood risk is significantly higher than the impact of climate change. This development requires measures to reduce the exposure of areas with high and increasing potential economic damage. This is however difficult, because urban settlements tend to be nodes of growth, attracting more enterprises and people. More importantly, the poorest residents of cities, which are least able to recover from a flood event, are often forced to settle in flood plains or other hazard-prone locations, as they cannot afford more suitable alternatives (McGranahan *et al.*, 2007). Therefore an important aspect of flood management is better insight in the socio-economic developments and how to mitigate the increasing risk. Especially shifting the direction of urban development away from flood-prone areas, by discouraging settling in these areas could be an important measure.

DEPTH-DAMAGE FUNCTIONS

Assessing the impact of floods in flood prone areas is rather difficult in absence of data that can translate water levels into an economic value for the direct damage in the area. In literature, different methods are used to assess the damage a flooding can cause, but the most common method is the so-called land-use method. The main principle of this method is to analyze the different types of land-use in a flood prone area and assign a damage value per surface area (€/m2) to this land type as a function of the inundation depth (Jongman *et al.*, 2012). This results in a function of the damage a flood can cause at a given inundation depth for a specific land type. These so called depth-damage functions represent the vulnerability of a land use type and is expressed as a value from 0 to 1 with increasing inundation depth. These depth damage functions are made for Europe by Huizinga (2007) based on literature and expert judgment and after additional research also for all other continents in the world in Huizinga and de Moel (2015). For convenience and to keep in line with previous work, the same depth damage functions will be used for the flood risk assessment in this research. Land-use types can be subdivided in five main types, which account for approximately 80% of the total average damage in Europe and consist of the following five categories:

- 1. residential (residential buildings and inventory)
- 2. commercial (commercial buildings)
- 3. industrial (industrial buildings)
- 4. infrastructure(e.g. roads and railways)
- 5. agriculture(agricultural areas such as arable land)

To calculate the maximum damage of a flood event, the inundation map will be overlaid with the map of the flood prone area and the maximum damage is the total area of the specific land-use type multiplied by the monetary value of this type by the given inundation depth.

CREATING LAND-USE MAPS

In order to get to a prediction of the maximum damage, the area of the different land-use types has to be determined in the flood prone area. Assessing land types in an area can be a very time consuming task and therefore methods are established to do this. In Europe, a global land cover map is available in a high spatial resolution of 100 m making use of 44 different land use types. This land cover map is named CORINE (Coordination of Information on the Environment (CLC)) and this high spatial map is derived from satellites imaging of the Landsat 7 Enhanced Thematic Map. To link the 44 land-use classes of the CLC to the five main land-use maps, it is assumed that most of these 44 land-use classes were part of one of the five categories. Conclusion of this showed that 28 out of the 44 classes where part of one of our five classes. These land-use maps are already available provided by (Nootenboom, 2015). For continents other than Europe, land type cover maps like CORINE do not exist and therefore maps have to be made from other information sources. An effective and proven approach for processing land cover maps outside Europe is by making use of OSM data (Open Street Maps). OSM is a free to use detailed map of the world made for and made by people after restrictions for the use of other map information. Based on satellite information, big parts of the world are available in high resolution and divided in different land-use types. These maps can be processed easily in software programs like QGIS to create land-use maps for a specific area. The surface area of the different land-use types can be obtained by looking at the land-use categories of the OSM data and observe which categories corresponds to which of our five land-use classes. These maps are made for each continents and for our assessment, we use the map of Asia derived by Kosters (2015).

2.5. VULNERABILITY

Vulnerability is the last component in our flood risk framework. It describes the potential to be harmed or the susceptibility of the flood prone area by a flood hazard (Feyen *et al.*, 2012). It is therefore an indication of the measures taken to mitigate the risk. Because vulnerability is to some researcher a very unambiguous term, also the term 'coping capacity' is used for this component (de Moel *et al.*, 2009). Vulnerability is related to exposure, because it expresses to what extend the exposure is being damaged. Vulnerability is often the most difficult component to assess, because it involves various dimensions as social, economic and organizational/institutional. Therefore, challenge remain in the transformation of these concepts into operational tools for management purposes (Merz *et al.*, 2010). An expression for vulnerability according to (Merz *et al.*, 2010) includes the following aspects:

$$V(t) = f(E(AC(t)), S(AC(t)), RC(AC(t))) \tag{2.1}$$

This can also be expressed in a graphic form with a slightly different definition, but it comes down to the same components, which we shall use for convenience. In figure, 2.5 the components or domains are expressed in damage as a function of the return period, with increasing damage by higher return periods.

Three domains are indicated in this figure. First of all, the *threshold domain*, which is the ability to prevent damage by setting the flood protection standards. This is normally done based on historical data and flood management policies. The height is determined by a country its social, institutional, technical and economic abilities(De Graaf, 2008). It is easily understood that increasing the flood protection standards will increase the threshold domain. Increasing the threshold also results in a bigger magnitude of flooding in case of failure, so increasing pressure on ensuring the quality and preventing failure mechanisms of the protection measures. The second domain consist of the *coping* and *recovery* ability. *Coping* in case of flooding is the ability the reduce the damages by an event that exceeds the threshold domain. Possible indicators are the presence of evacuation plans, damage reducing measures like sand bags and communication plans to create awareness. Also the time period of this plays an important role. Next to coping, *recovery* plays an important role in this domain. This domain is determined by the ability to recover the state of the flood prone area to the state before the exceedance of the threshold and coping domain. This ability to recover is based on several factors and begins right after the disaster ended. Finance capacity and technical knowledge determine the time period of recovery, but is by all means dependent on the scale and magnitude of the flood event. Insurance is one of the main determining factors of the recovery. A high insurance cover rate means a greater ability to recover. The last domain and also the domain which is most difficult to influence is the *adaptive*

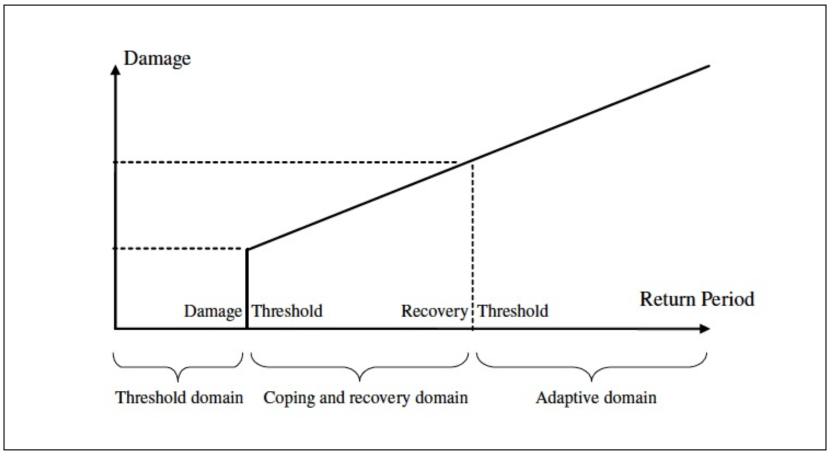


Figure 2.5: Three domains of vulnerability illustrated by a damage return period graph (De Graaf, 2008)

domain and includes the ability to cope with and adapt to future uncertainties in the occurrence of extreme events and modifications to previous domains . The future adaptive measures can differ in great extent from each other depending on the kind of uncertainty it will reduce. Examples of uncertainties are climate change, subsidence and socio-economic factors. In general, these measures encompass large investments with long time horizons and because of the high uncertainties and nature of extreme events, decision making is difficult for this domain. *Adaptive* capacity can also include adaptations by modifying the susceptibility, increasing recovery and coping capacity and reducing the exposure.

2.6. FLOOD PROTECTION STANDARDS

Even though every country has some sort of protection standards, information about these protection standards is rather scarce which makes it difficult to compare and include the information in flood risk assessments. The study of (Schilder, 2016) made it clear that ignoring flood protection standards in flood risk assessment can cause huge overestimation of the resulting flood damage and results of the most vulnerable cities shifts by including or excluding this information. This because the integration of damages takes place along the whole spectrum of return periods, including flood events that are often prevented by protection standards. Various methods are used in previous research to determine the degree of flood protection standards and include them in their risk assessments.

Uniform standard One of those variants is to assume a constant flood protection standards, for instance 1 in 5 year in the analysis of Ward *et al.* (2013). This means that all areas are protected against a flood event with a probability of 1/5. Careful consideration whether to include or exclude the standards into your model is necessary, because the sensitivity of this parameter is high for the final result. This is also concluded in the same study where including flood protection standards of 1/5 a 1/100 led to a reduction in the simulated annual expected damage of 41% and 95% compared to the situation without standards(Ward *et al.*, 2013).

Method GDP/capita Another commonly used method is to assume that the flood protection standards are related to the GDP/capita and that this ratio is a measure of the protective capacity as was showed in the Feyen *et al.* (2012) study. In this study, the average European GDP/capita is calculated and after that the flood protection standards are based on the ratio of average GDP/capita and country GDP/capita. Countries with a GDP/capita larger than 110% of the average GDP/capita were assigned a flood protection standard with a return period of 100 year. Countries with ratios ranging from 55 to 110 %, which is the biggest group of European countries, were assumed to have flood protection estimations with a return period of 75 year. The last group of countries with GDP/capita lower than 55% of the average value were assigned flood protection standards that could resist flood events with a return period of 50 year.

Risk-based method Jongman *et al.* (2014) was the first study that developed estimates of flood protection using a risk-based approach in a three step process. First step is determining the minimum and maximum flood protection standards in Europe based on literature research. This minimum and maximum were estimated on respectively 10 and 500 years. Secondly, the European average flood protection was determined by running the flood risk model for a range of flood protection standards and compare the resulting damage to historical events in order to get a indication which standard is most representative for Europe. Last step is assigning every basin its own flood protection standard between the minimum and maximum value based on the expected damage in basin under the assumption that areas with higher potential damage have higher protection standards. This is done for every basin and in this way a system of standards for each areas is constructed.

FLOPROS Where the aforementioned approaches showed the importance of including flood protection standards, validation and correctness of this information is far from perfect. Besides that, approaches beyond Europe are very limited, because of the lack of representative information. Institute for Environmental Studies (IVM) together with partners Deltares and the World Resources Institute have developed a flood protection database named FLOPROS (FLOod PROtection Standards) that could solve the bottleneck in accurate flood risk assessment. The database consist of information from different sources like specialized literature, policy documents and modeling techniques and it aims to incorporate input of experts in the field and let them contribute to expend the database (Scussolini *et al.*, 2015). The general principle is to find the best information available for each location. The database is structured in three information layers with the following names and definition according to Scussolini *et al.* (2015):

- the *Design layer*, containing information about protection defined by engineers in design and realisation of currently existing river and coastal flood protection infrastructure;
- the *Policy layer*, specifying the legislative and normative (or "required") standards of protection to river and coastal flood;
- the *Model layer* for river flood protection, which is based on a flood-modeling approach and on the observed relationship between per capita wealth and protection based (based on the aforementioned approaches of (Jongman *et al.*, 2014) and (Feyen *et al.*, 2012)

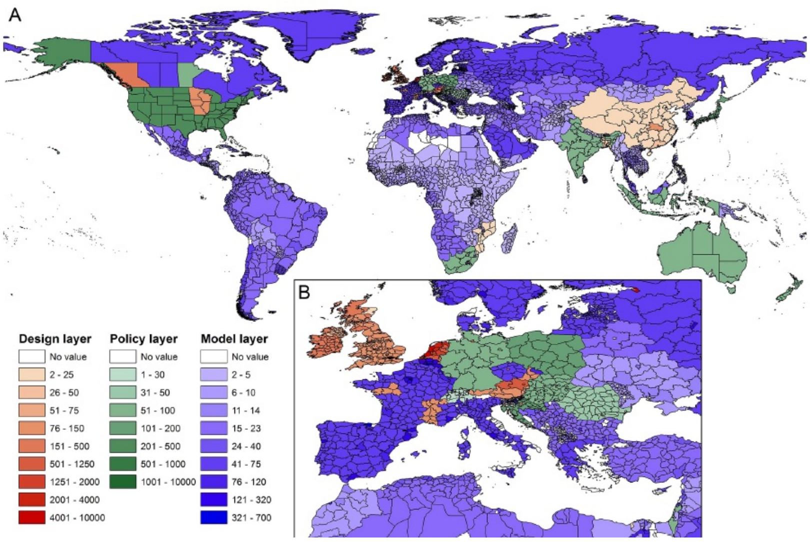


Figure 2.6: Merged maps of flood protection standards contained in the FLOPROS database on a World scale (A) and European (B) scale. The three different color scales indicate the Design, Policy and Model layers. White indicates no information available. (Scussolini *et al.*, 2015)

For further assessment of the information, the design layer is considered to be most reliable for representing the protection standards, because it is based on direct information from existing infrastructure. The policy layer is the second most reliable layer, because it represents information from policy document about planned standards, but it is unknown if the realisation is finished in reality or not. The model layer is considered the least reliable information layer, because it is an indirect modeling approach, based on some assumptions and uncertainties. All layers can be used separately, but for the best result and usefulness on a high spatial scale, the layers will be merged into one layer consisting of all the information.Merging is done by taking the available information of the most reliable layer. Only in the case when no information in the design and policy layer is available, the model layer will be employed. Merging the three information layers results in the world map with color indication of the different protection standards as can be seen in figure 2.6. The differences in spatial scale and the reliability of the information makes it very hard to compare and represent the data in a correct way, especially in developing countries with limited information. Therefore extended research and input from more information providing sources is needed for improved versions of the database in the future. In order to achieve this, the institutes who developed the database are planning to make it available on an online platform so it can be accessed by experts and potential end users of the database to find the best way to further improve it. In this research, findings could be compared with the data present in this database to look at the similarity of this and to get an idea of the reliability.

2.7. RISK

In the overall flood risk assessment, the risk quantification is calculated by overlaying the hazard, exposure and vulnerability components. It is the damage caused by flood hazard to the exposed assets. The magnitude of the damage is dependent on the return period of the event. In most assessments, a damage-probability curve is plotted by calculating the damage for the corresponding return period. Flood risk is the integral of these damages as a function of the probability of exceedance (Messner *et al.*, 2007), as shown in figure 2.7 on the left. As mentioned in the exposure section of this report, damages are in generally expressed in monetary value and therefore the risk is also quantified in monetary value expressed in expected annual damage (EAD). Flood risk can also be expressed in terms of affected people, loss of life, Gross Domestic Product and health impact (Winsemius *et al.*, 2013), but therefore different damages functions are needed. Flood risk can be expressed in a mathematical formula and to keep in line with the dynamic flood risk assessment as defined, we use the definition of Merz *et al.* (2010) :

$$RI(t) = \int_{h_D(t)}^{\infty} f_h(h,t)D(h,t)dh \tag{2.2}$$

In this mathematical expression, flood risk RI depends on the probability density function $f_h(h,t)$ of the inundation depth and the damage $D(h,t)$ at this inundation depth. The expression $f_h(h,t)$ in the integral is the threshold depth above which flood damage occurs, covering the combination of all flood protection standards. Because via flood risk management, all parts can be managed and adjusted, the expression is time

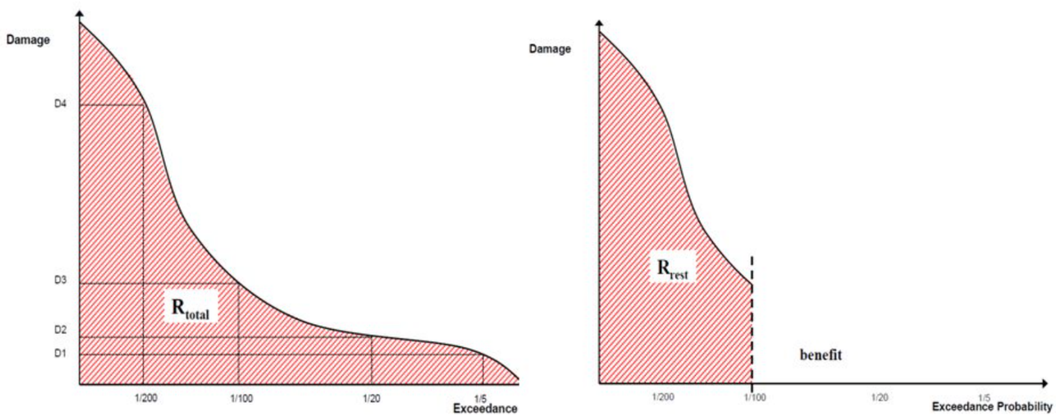


Figure 2.7: On the left the total damage-probability curve for a giving area and on the right the truncated damage-probability curve at protection threshold of 100 year for the same area (Messner *et al.*, 2007)

dependent. In figure 2.7 on the right, the truncated damage-probability curve for the corresponding flood protection threshold $f_h(h,t)$ is shown. In this example, the threshold is set on a return period of 100 year. The integral of the remaining part after truncation quantifies the expected annual damages caused by river flooding (Rojas *et al.*, 2013).

Flood Impact Assessment Tool (FIAT)

In the end, the risk must be assessed quantitatively and expressed in potential damage in €. After processing all previous data, this set of data can be merged in the Flood Impact Assessment Tool, or FIAT, to calculate the damage according to the definition of flood risk addressed above. In FIAT, it is also possible to include effects of climate change and socio-economical development by means of supplying data on climate change and socio-economic growth scenarios. This makes the FIAT model very useful for decision-making purposes, because it can show the changes in future flood risk as a result of these influencing factors. Input data of the FIAT model must be in a consistent file format, which are raster files with a spatial resolution of 30 arc-seconds. It is therefore required that all input files are scaled to this resolution, otherwise it will give a misrepresentation of the real situation.

Uncertainties in flood risk assessments

Flood risk assessments are being used for policy analysis, insurance estimates and for determining investment strategies. However, great difference between different models exist (Wagenaar *et al.*, 2016). Without understanding of the errors and uncertainties involved, using flood risk assessments in decision making is not considered effective and useful. Errors occur in all three components of the model. The hazard model includes information about discharges in river basins all over the world expressed in water depths for different return periods. However, water rise velocities are often very important in flood risk determining the extent of the damage and the response time of the evacuation. Also, river changes over time lead to different conditions in basins. Uncertainty is also included in the depth-damage functions. Knowledge about how damages occur and to what extent is limited. Using average data could lead to miscalculation of the damage. Also extending data from one country to another is often not representative. This is also shown in Huizinga (2007), where depth-damage functions and maximum damages differ widely between countries. Just taking average values of other countries result in significant under or over estimations, also shown by the research of Suijkens (2015), and should be carried out carefully. In the vulnerability assessment, flood protection standards do not take into account possible dike breaches. For instance in the 2013 flood event in Germany, which will be discussed later, overtopping of the dikes occurred at no place indicating that protection standards were sufficient in height. However, dike breaches let to flooding of large parts of Germany resulting in damages that are not taking into account by just including protection standards in the model. In the ideal case, flood risk assessments should take into account all relevant flood scenarios and dependencies. However, this is not possible because inserting local characteristics need in depth research of each area. Next to that, we lack the knowledge to assess some dependencies like dike breaches and maximum damage estimations. Therefore, the calculated risk should be interpreted between some uncertainty bounds. (Apel *et al.*, 2004).

3
SMART FLOOD RISK CITY MANAGEMENT

Cities and deltas as a whole are constantly changing and this makes flood risk management a dynamic process. The ability to change the vulnerability of a city is dependent on the corresponding urban flood risk management. Flood risk management has traditionally been focused on technical solutions to defend against water. However, it is recognized that flood protection only is not enough and a shift towards a more integrated flood risk management , containing both structural and non-structural measures, to prevent, defend, mitigate, prepare, respond and recover from flood events needs to be included in flood management plans (Raadgever *et al.*, 2014). In Europe, this shift is initiated by the Water Framework Directive (2007/60/EC), which requires EU member states to undertake a preliminary assessment of flood risks and to prepare flood hazard maps, flood risk maps and flood risk management plans for areas with a significant flood risk (Moster and Junier, 2009). The non-structural measures includes measures that reduce the damage of a flood event in case of exceeding of the flood prevention structures. This includes measures like warning systems, emergency, spatial planning, flood-proofing buildings and insurance solutions (Merz *et al.*, 2010). Underlying though of this is the thinking that all these measures, on different levels, do not stand alone and when integrated with each other, could reduce the overall damage of a flood event more than the sum of the individual measures together. Integrated flood management avoids isolated perspectives and the misinterpretation of assuming that some forms of interventions are always appropriate and others are always bad (APFM, 2009). A successful flood management plan compares the available options and selects the strategy or combination of interventions which is most appropriate for the region and the given situation. These strategies should be robust, but at the same time flexible and adaptive to future changes given different scenarios. To do this, flood protection needs to be integrated in urban development planning adapted to future conditions. Organizations, institutions and society in which the flood management is embedded play a key role in this transition. However, little is known about the effective implementation of these new strategies by governments, because identifying the appropriate set of measures and interventions is a complex decision.

3.1. FRAMEWORK

For finding appropriate measures and management focus of cities based on the threat of flooding, a framework for the implementation of multiple layer flood risk measures in a city is suggested. The different measures are divided into five layers; prevention, spatial planning, emergency management, recovery and proactive. Based on this framework, an indication can be made on which measures authorities focus particularly and which are not present at all. By combining this with risk indicators on city-scale could lead to an evaluation if the chosen measures or focus are appropriate and efficient for this city. This framework is not meant to present the 'best' or 'ideal' combination of measures, because implementation dependent also on cost-efficiency and risk attitude of city's authorities. Jongejan (2008) said this in a beautiful way: *'Risk appraisal is a value-laden activity. No scientist can rightfully claim to possess superior knowledge about the risks that ought to be acceptable to all'*. The following definitions and scale factors are used in the framework, presented in figure 3.1 and being discussed afterwards per component:

- *Protection Standards*: Degree of protection in return period. (5) High degree - (0) Low degree
- *Public preparedness*: Risk awareness and precautionary measures. (5) high degree - (0) low degree
- *Land-use management*: Room for the river concept (5) Active land use management – (0) No land use management
- *Early warning system*: Availability of early warning. (5)Extensive early warning in place - (0) No warning systems

- *Disaster planning*: Disaster planning available. (5) Disaster planning - (0) No disaster planning
- *Evacuation planning*: Evacuation planning in order. (5) Evacuation prepared - (0) No planning
- *Insurance*: Insurance cover ratio. (5) High coverage (100%) - (0) No insurance (0%)
- *Future Adaptation*: Future scenarios into management plans (5) Pro-active approach – (0) Passive approach

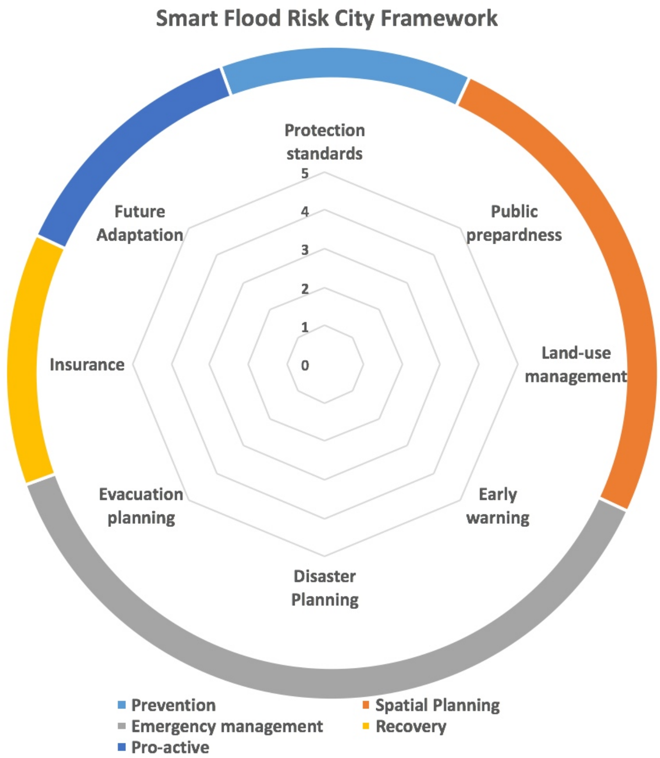


Figure 3.1: Smart Flood Risk City framework consisting of risk reduction layers prevention, spatial planning, emergency management, recovery and pro-active

3.2. PREVENTION

FLOOD PROTECTION STANDARDS

Generally spoken, flood protection standards are the degree of technical protection against a possible flood event. Flood protection standards are often recognized as the most important element of flood control and prevention in decision making policies. The most well known flood protections are dikes and embankments along the river. Other common measures are increasing river capacity, underground flood ways, increasing urban drainage and reduction of the stormwater runoff (De Graaf, 2008). Over the last couple of years, is was assumed that the easiest way to prevent floods was focusing on the flood protection standards. However, taking climate change and socio-economic factors into account for dike height calculations, dike improvements could be relatively expensive. These protection standards differ widely between countries and within countries. For instance in The Netherlands where more than half of the country is exposed to large scale flooding. The Dutch governance has decided to develop a flood protection system by subdividing the country in 'dike rings' with its own specific protection standards. The level of flood protection vary from 1/2500 years for the upper reaches of the Rhine river to 1/10000 years for the most densely populated areas along the Rhine and Meuse (Kind, 2014). The other extreme is flood protection standards in some African countries, where little money is available for enhancing the flood protection near cities. Natural levees along river provide some protection but due to major urban growth, cities have expended over some parts of the flood plain resulting in parts of the cities below flood level (Douglas *et al.*, 2008). Flood protection standards are already included in FIAT as was referred earlier in section 2.6. FLOPROS is the newest and most extensive database for flood protection standards, although not validated yet as the most representative one.

3.3. SPATIAL PLANNING

Spatial planning includes all spatial measures on city or state scale that can possibly reduce flood risk. The implementation of spatial planning differs from one country to another, depending on economic situation, geographic location, population density and overall policy. The use of land with high potential damage from overflow of the floodplain is often defined in literature with the term "encroachment" (Pottier *et al.*, 2005). If we look at measures that can reduce the risk, measures can be found on the smallest scale, for example making houses more robust against flooding, and on a bigger scale like for instance prohibit urban development in recognized hazard prone areas. The last measure is only possible under the condition that adequate flood hazard maps are derived on local resolution. For measures on both small and bigger scale, focusing on the long term is important, because the city is constantly moving and adjusting. Appropriate measures are very much dependent on the economic situation and the speed of urban movement, for instance in African cities were the budgets are low and urbanization rates are high. In these areas another approach to solve the current and future problem is necessary. Embedding adaptive measures within the urban infrastructure is very costly or very slow, and is therefore economically not possible or only postpone the problem because the situation has been worsened over time. Therefore, preventing this from happening is really difficult. However, even encouraging people to move away from the most risk-prone locations is a step in the good direction. Best possible approach, according to McGranahan *et al.* (2007) is by making people aware of their situation on local scale and to help governments develop urban management policy, because small shifts in settlement location can already make a major difference.

LAND-USE MANAGEMENT

Over the last couple of years, an increasing interest is noticeable for potential link between rural land use management and flood generation. This can play an important role in the integrated approach to wider sustainable land use planning considerations and can help adapting communities to increasing flood risk (Parrot *et al.*, 2009). This can be accomplished by both affecting the flood generation (rates of surface runoff) and flood propagation (rate of water movement). This has the opposite result of urban development, where permeable soils are replaced by impermeable soils with more overland flow and reduced infiltration as limiting factor. This upcoming trend is also induced by the desire of the European Union, included in the Water Framework Directive, to deliver sustainable solutions for land-use management. Using rural land as flood plain can result in a large storage for excess water and reduce water peak flows, while at normal conditions, the land can be used for agricultural purposes. Next to the positive effect to reduce the effects of a flood, flooding of agriculture lands has a much lower unit costs in terms of damage (Wheater and Evans, 2009). Another concept of land-use management worth mentioning is implemented in the last years in The Netherlands with the name 'make Room for the Rivers' ('Ruimte voor de rivier' in Dutch). Land-use management is difficult in the Netherlands, because it is one of the most densely populated countries in the world. The goal of this program is to give the river more room to manage higher water levels and encompasses measures in more than 30 locations varying from deepening the summer bed, dike relocation, removal of obstacles, increase water retention and many more. Implementing 'room for the river' concepts could be a very effective measures for cities with low natural water storage resulting in fast runoffs. Measures could be found on big scale by moving technical structures away from the river to provide more space and on a more smaller scale by designing water retention ponds in new urban areas.

PUBLIC PREPAREDNESS/PERCEPTION

Risk perception is an often overlooked aspect, but plays a significant role in the efficiency of flood management. As authorities and the public perceive risk in very different ways, flood risk management strategies are known to have failed in the past due to this disconnect between authorities and the public (Bradford *et al.*, 2012). Public risk perception can be influenced by a lot of factors; geographical location, personal experience, knowledge of flood threats and individual risk attitudes (Botzen *et al.*, 2009), and can differ widely between countries. Knowledge of public risk perception and influencing factors can be used to develop plans to change this perception in case of unawareness of flood risk. Public preparedness is the transition from becoming aware, perceive themselves at risk to taking precautionary measures on household level. It includes both the measures taking and the awareness of the public how vulnerable people are. Determining the public perception is a difficult task, because relatively little is known about this. Most common technique to know more about risk perception is by making use of a survey. Research of Raaijmakers *et al.* (2008) specified the definition of risk perception as the relationship between three characteristics: awareness, worry and preparedness, as illustrated in figure 3.2. Awareness is defined as the knowledge or consciousness of flood risk. Worry depends on the expected severity and consequences of flood risk, meaning the fear of flooding. Preparedness is the capability of coping with a flood before the flood and the recovery capability after the flood. The figure shows the interactions between the three components, which can be both positively and negatively influenced . An example is the negative relation between preparedness and worry, meaning that a better prepared society will worry less. Another interesting relation is between awareness and worry. If the public is more aware of the risk involved, they are going to worry more and will demand more measures to reduce risk. These relationships can be defined for every arrow in the figure. Especially awareness is important for an effective execution of flood management plans. Individuals living in areas with high risk, but unaware of it, are most vulnerable for flooding. Another founding by Botzen *et al.* (2009) in the public perception of risk was that people living in areas protected by dikes generally underestimate the risk, because they perceive the dike protection as indication that their area is save. Continues provision of information and the participation of the public in local flood management plans could be good measures to raise awareness and insist people to take precautionary measures. Private precautionary measures could be flood prove interior, flood prove windows in cellars, sand bags, but also by just collecting information about flood protection and neighborhood evacuation.

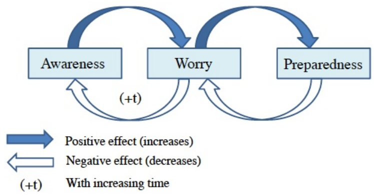


Figure 3.2: Relationships between the three components of risk perception according to the definition of (Raaijmakers *et al.*, 2008)

3.4. EMERGENCY MANAGEMENT

In case of an actual flooding, the structural measures were not sufficient enough the prevent this. The impact of the flood event is for a large extent depending on the mitigating actions taken like warning systems, disaster planning and evacuation scenarios. Absolute protection from flooding is technically unfeasible and economically and environmentally unviable (APFM, 2009). Therefore, increasing effort and interest is observed for effective emergency management next to protective measures in flood prone areas in case of a major flood event. Effective emergency management can result in potential reduction of the number of fatalities, but can be costly in terms of time, money and credibility (Kolen *et al.*, 2012). In figure 3.3, the overall time window in case of an emergency, with specific points in time are shown. Emergency management is the transition from day-to-day live into evacuation, or according to the figure from normal life to the transition phase into the evacuation mode. Therefore different measures could help shorten the times frames and increase the percentage of evacuated people. First the threat is detected and recognized (Td) and warning systems play an important role in this. After that, the decision has to be made whether or not the threat is serious enough to continue into evacuation (Tc). After the threat is recognized and the decision is made to go into evacuation mode, the phase in between these two is the transition phase. In this phase, evacuation planning should be set in place for example by informing the public, adapting traffic infrastructure and re-locating personnel and resources (Kolen *et al.*, 2013). Effectiveness and duration of this phase is mainly determined by the disaster planning provided by governments or city authorities. After that (Tt), the evacuation starts until the expected onset of the Flood (TO) and after that. The evacuation fraction is thus determined by the implementation of evacuation planning. In the same figure, the percentage of evacuated people is displayed in case of no measures presented by the dashed line and in case of coordination and planning by authorities. It can be said, that especially effective planning in the first phases can save a lot of live and damages.

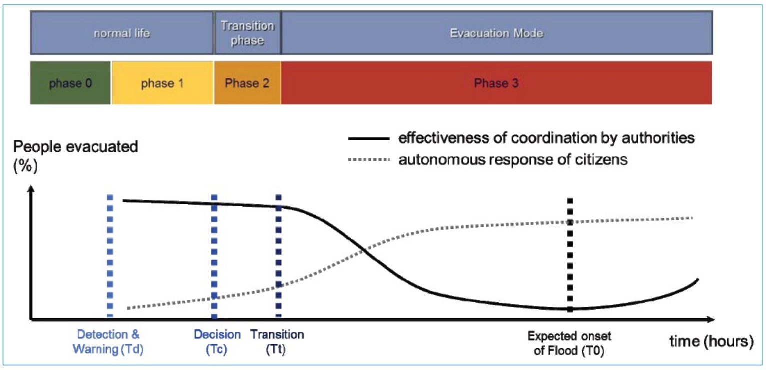


Figure 3.3: Different time frames in case of evacuation and the effectiveness of measures by authorities on these time frames (Kolen, 2013)

EARLY WARNING SYSTEMS

As was mentioned before, especially measures in the early stage of emergency management can have a positive impact on the number of people evacuated, and therefore early warning systems could be a good measure for achieving this. Early warning systems are defined as ' the provision of timely and effective information, though identified institutions that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response' (Alfieri *et al.*, 2012). Effectiveness of early warning is again dependent on the flood characteristics and the time frames. For instance, combining weather predictions with early warning systems makes it able to detect a possible threatening event and gives sufficient time to prepare and respond. Early warning systems can collect data that authorities can use for making the decision to evacuate, but also for the assessment of dike quality (Krzhizhanovskaya *et al.*, 2011). However, it is impossible to rely only on these systems, because a system can fail, do not recognize the threat or gives a false alarm. In developing countries, where governments lack the resources for adequate prevention of flooding, early warning systems can be an effective and cheap solution for people to evacuate and protect their property. However, enough public awareness of the presence of such system and technical know-how about the maintainability of the systems is necessary in order to obtain the maximum benefit out of it. An interesting development in Europe to mention is the establishment of the European Flood Alert System (EFAS), which offers international coordination for floods in large trans-boundary river basins, in close collaboration with national water authorities (Alfieri *et al.*, 2012).

DISASTER PLANNING

Disaster planning is next to the early warning system another aspect that determines the preparedness of a country in case of a flood disaster. It includes planning what should be done in case of a flooding, not taking into account the evacuation mostly in the form of a written document. In most cases, this document contains questions as; who is responsible for what, which resources to use, procedure of steps and many more. Another important aspect is in what way the planning is tested, so are the responsible people capable of doing the job correctly. In absence of an appropriate planning, the execution of plans in case of a real disaster could be very chaotic and time consuming with the resulting negative consequences of this. Therefore, the way countries are prepared for a disaster can be a determining factor for an effective implementation of flood management. Disaster plans could be made on household, company, neighborhood and country level making it a comprehensive measure.

EVACUATION MANAGEMENT

Especially evacuation management is an important measure, because an effective evacuation can result in a larger fraction of people that can evacuate the affected area. In countries where floods are occurring more frequently, evacuation management can be an important pillar in flood risk management. The effectiveness and choice of evacuation measures are dependent on the threat itself, decision making by authorities, environment, infrastructure and citizens' response (Kolen, 2013). The time window of this event, especially the time between observed potential threat and impact, plays a major role in effectiveness. In case of abrupt events, with shorter time windows to impact, evacuation is more difficult and if time and money are spent in evacuation measures, the potential savings can be really big. Different types of evacuation can be identified as was defined by (Kolen *et al.*, 2012), where evacuation management is a combination of these types;

- Preventive evacuation: from a potentially exposed area to a safe location outside this area.
- Vertical evacuation: the organization and the movement of people inside the potentially exposed area; 1) Shelters: buildings that offer protection for people and goods. 2) Safe havens: areas inside the threatened zone that not be affected.
- Shelter in place: from home to upper levels of residential building.

From these three types, preventive evacuation is often the most executed type of evacuation measurement, because it is recognized that removing as many people as possible is the best measure. However, in some situation, the other two types can be more important and effective. Research of Haynes *et al.* (2011) for flash floods events in Australia showed that implementing a 'shelter-in-place' strategy could be a better option, because due to the limited response time, people got injured or became fatalities when they entered flood waters in a vehicle or on foot.

3.5. RECOVERY

INSURANCE

Most important aspect after a flood disaster is the ability to recover from this. One major determining factor is the insurance policy of a country. If we look at the values of insured losses for some of the major flood events, we observe huge amounts of insurance money paid out. For example, the 2011 Thailand flood with overall losses US$ 43000 million and US$ 16000 million insured (37%), the 2002 Central Europe flood with overall losses US$16500 million and US$ 3400 million insured losses (21%), and the 1993 American Mississippi flooding with US$ 21000 million overall losses from which US$ 1300 million insured (6%) (MunichRe, 2014). Looking at this data provides insight in the different insured cover ratios of extreme events and this represents how the insurance policies in a country is regulated. Those two extremes are clearly visible, namely relatively high coverage (France, UK and other western European countries) and relatively low coverage (United States). Clearly, insight in the different insurance policies gives a perception of how countries deal with risk control and where the responsibility lay. In order to do this, an elaboration will be made between the extremes, namely the solidarity principle which is presence in many European countries and the individualism or private interest principle which is presence in a country like the United States. This is done in appendix A, where a few countries are being discussed.

3.6. PRO-ACTIVE

FUTURE ADAPTATION

Future adaptation is necessary for including scenarios of climate change and socio-economic development into urban city planning. Some cities are making their flood risk management plans pro-active by including scenarios into their plans, where other cities are more reluctant doing this. This is by a great extent determined by the government risk attitude. In appendix B, three different government risk cultures are described ranging from pro-active to passive. Including these scenarios demanding management plans to be robust to future threats on one side and flexible to uncertainties on the other side. Overestimation of the future can lead to huge unnecessary investments, where underestimation can lead to small benefit in contrast with the effort taken. Including scenarios into urban planning is difficult and a lot of stakeholders are concerned. For instance, regulations need to be set for building requirements in flood prone areas included in the building codes. This could be a time-consuming process.

3.7. RISK INDICATORS

To evaluate the vulnerability of a city and derive an advice for an appropriate set of measures to focus on, several risk indicators will be used. The economic risk, individual risk and household risk are quantitative indicators. Another indicator is the distribution of the damage over the five land-use classes. These indicators will be discussed shortly with linkage to the derived framework.

ECONOMIC RISK

Economic risk is calculated by FIAT (€/year) with taking into account protection standards. This is the potential economic risk of the city.

INDIVIDUAL RISK

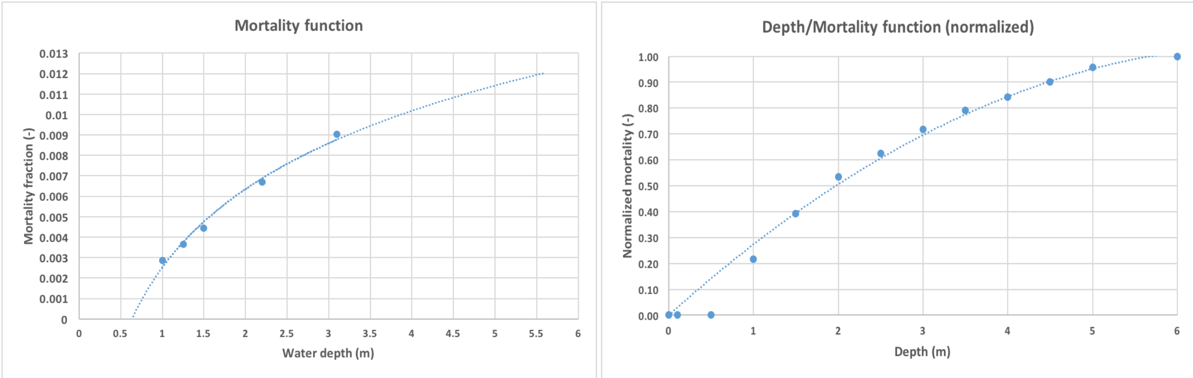
FIAT could only calculate the risk and expresses it in a monetary value, € or €/year. However, measures in emergency management and public perception are difficult to express in a monetary value, because objective of these measures are reduction in fatalities in case of a flooding. The expected number of fatalities due to a flood is assumed to be a function of population density, evacuation and vulnerability of people living in the flooded area (Deltares, 2011). This number is often expressed in number of fatalities or mortality, which is the number of fatalities divided by the number of exposed people. Also the definition individual risk is being used defined as the risk of dying at a place without any protection. For the use of a quick assessment, the definition of the number of fatalities proposed by Maaskant *et al.* (2011) is being used and the risk is derived from that equation by dividing it with urban population.:

$$N_{fat} = N_{exp} * (1 - F_E) * F_D \tag{3.1}$$

$$Risk_{fat} = \frac{N_{fat}}{Population_{city}} \tag{3.2}$$

In this equation, the total number of fatalities N_{fat} is a function of the number of people exposed N_{exp}, the evacuation fraction F_E and the mortality F_D. $Population_{city}$ is the urban population. An suggestion is made for an easy and quick assessment of this based on a few data inputs. However, this assessment does not have the purpose to give an exact value to fatality risk, but more a rough indication of cities with the highest risk.

Method explained For the individual risk assessment, the GLOFRIS method of FIAT is being used. For a detailed description of this method, the study of Winsemius *et al.* (2013) or Nootenboom (2015) could be used as reference. Two land type classes are being considered for this, 'urban-dense' and 'peri-urban'. Cover maps are already available for the whole world, but to give an example of this assessment only the continent Europe is being considered. In contrast with the risk assessment, no damage value is being assigned to the two land-uses but a population density value. The most recent data of the GRUMP(2015) population density map is used, giving the number of people/km2. This map is overlaid with the urban/peri-urban land-use map to assign a value to the two land-use types. By looking closely at the data, an average population density value for the big European cities is assigned. On average, the 'dense-urban' areas corresponded with a value of 6000 people/m2 and the 'peri-urban' areas with a value of 2000 people/km2. To link the number of fatalities to the water depth, a depth/mortality function is suggested. Mortality functions are not available yet, because of lack of empirical data. The function used is based on the research of Jonkman *et al.* (2008) for the individual flood risk without taking into account any kind of evacuation. This research was also the basis of the assessment of the new dike ring standards in the Netherlands (Rijkswaterstaat, 2014). In this research, for some waterdepths, the corresponding mortality rate was given for the function type residential (woonwijk) (Huizinga *et al.*, 2009). These points were extrapolated in excel and vary from mortality rates of 0 to 0.014. This is in line with Maaskant *et al.* (2011), where a mortality fraction of 1% was being assumed for coastal areas. If we assume that this function could be used for all European countries, an assessment could be made. It is very likely that these mortality functions differ from one country to another, but for an easy assessment an uniform function is assumed. This extrapolation and the resulting mortality function are shown in figure 3.4a. After that, the value are normalized given the value 1 to 0.014 and a depth/mortality function in line with the depth/damage functions of the risk assessment (3.4b). FIAT needs a maximum damage value as input value to calculate the risk. In the normal assessment, this value was the maximum damage in €/m2, but for our assessment, this value should therefore be the maximum number of fatalities/m2. This is calculated by multiplying the maximum mortality rate by the population density per square meter. For example, this rate for the 'dense-urban' class is 6000 (n/km2) * 0.014 /100000 = 0.00084(n/m2). Now FIAT can run this and the result will be the risk expressed in number of fatalities per year. Evacuation is not taking into account in this assessments, which could be an input for further research.



(a) (b)

Figure 3.4: a) Extrapolated mortality functions based on mortality fractions of Jonkman *et al.* (2008) b) Depth-mortality function

RISK PER HOUSEHOLD

The overall risk does not say anything about the risk on household level. It would be a logical assumption that the big, densely populated cities are most vulnerable. Quantifying risk on household level could be an indicator how much money should be spend per year per household to reduce the overall risk. If this number is high, convincing people to do this is more difficult, because a larger fraction of their income should be spend of this. More effort should be put in creating awareness on local level in this case. Next to that, the emphasis on risk insurance is more important in areas with high household risk, because households have a higher probability for household damages. Insurance companies can use this to determine city premiums and to assess the insurance risk they face. This risk indicator is calculated by means of three input data; the risk, population and number of people per household in the following relation:

$$Risk_{household} = \frac{Risk}{Population} * N_{household} \tag{3.3}$$

DAMAGE DISTRIBUTION

The damage distribution shows what percentage of the overall risk is allocated to one of the five land-use classes agriculture, commercial, industrial, infrastructure and residential. Based on this, insight in what is located and damaged in the flood prone area can lead to an advice for a set of measures which could lead to the most benefit in terms of risk reduction. For example, in cities where the percentage residential damages are really high, building flood prone buildings and taking precautionary measures are more effective in contrast with cities where this percentage is really low. Also, high residential damages means that a lot of households are located in flood prone areas and evacuation seems therefore really import. Early warning systems and evacuation plans in communities are focus points. The percentage of agricultural damages can give an indication if 'room for the river' measures like changing urban to rural land-use, relocating dikes and making use of retention ponds are appropriate. Little damages mean that relatively less agricultural land-use is located in the flood prone areas and this offers perspective for implementing these measures. If already a lot of agricultural land is in the flood prone area, these measures will be less effective. The percentage of affected infrastructure relates to effective evacuation in case of a large flood event. If a lot of infrastructure is damage, evacuation by means of the road is more difficult. Early warning and evacuation routes safe from flooding are appropriate for cities with high percentage of affected infrastructure. High percentages of commercial and industrial damages means that not only households should be informed about emergency situations but also companies. Having plans for evacuation, relocating valuable company assets to higher grounds and precautionary measures in the office could result in less direct damages and less indirect damages due to inactivity.

4
THAILAND: 2011 FLOOD

In 2011, Bangkok and almost the whole country of Thailand was hit by the worst flooding in at least 50 years. The devastating flood was the result of an accumulation of several factors, which will be discussed later. 69 provinces were affected with a total inundation area of 41,382 square km (Nabangchang *et al.*, 2014). According to data of the World bank, the reported damage was estimated at US$ 46.5 billion (Worldbank, 2012). In total, 815 people were reported death and 3 people missing. Next to the great number of fatalities, the impact on the whole economy of Thailand was very heavy, especially the manufacturing industry. Manufacturing makes up about 38.5 percent of the total Thailand's GDP and the main driver of Thailand's exports, where most manufacturing was located in the affected area (Worldbank, 2012). The manufacturing locations of several brands of automobiles and hard drives were affected so badly, that the supply of this was seeing a decrease in availability worldwide. Therefore the overall economic costs of the interruption were also very big and need to be taken into account. The World bank estimated this at approximately $US 32.5 billion, which resulted in a drop of the economic grow rate from 3.7% to 0.1% in Thailand that year (Komori *et al.*, 2012). The river levels of the Chao Phraya River during the 2011 flooding for the cities Ayutthaya, Bang Sai and Pakret were respectively 5.9, 4.2 and 3.2 meters above mean sea level. This corresponds to a return period of over 100 years in all three places (DHI, 2011), as can be seen in figure 4.1. More details about the river characteristics, reasons of the flood event and the insurance policy are outlined in appendix C.

STATION	Observed Peaks			Estimated Return Period (years)					
	1983	1995	2011	2	5	10	25	50	100
Ayutthaya	4.7	5.1	5.92	3.4	4.1	4.7	5.1	5.4	5.6
Bang Sai	3.1	NA	4.21	2.6	3.1	3.4	3.7	3.8	4.0
Pakret	2.2	2.6	3.20	2.15	2.61	2.72	2.86	2.96	3.07

Figure 4.1: Peak water levels in the Chao Phraya river during the 2011 flood event and corresponding return periods (DHI, 2011)

4.1. DAMAGE ASSESSMENT FIAT

LAND COVER MAP

OpenstreetMap (OSM) data is used for the land cover map of Thailand. Data in and around Bangkok is well defined, where data covering the rest of Thailand are not so well defined. Because OSM is a open source data source, everyone can change and add layers to this map. Therefore, the data consist of a lot of classes, some usefull for our research and some not. Therefore, only the classes considered in our research need to be filtered out the overall data. The land-use class infrastructure is not defined in OSM and therefore not included as land-use type here. Producing of the land-use map is already done for Southeast Asia by Kosters (2015) and therefore her land-use map will be used. An additional map for the 'no-data' cover is also being produced by her, so in total five land-use classes are being considered. These land-use maps were rasterized and converted to the right grid cell size of 1 x 1 km2 and the right extent to make it compatible in FIAT. For a more detailed overview of the procedure, the thesis work of Kosters (2015) contains a description of this process.

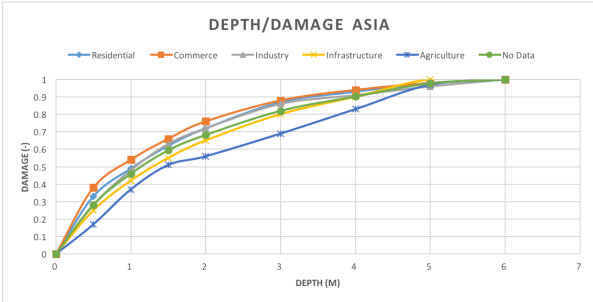
DEPTH DAMAGE FUNCTION

For Thailand, no country specific depth-damage functions are available in contrast with most European countries. Huizinga and de Moel (2015) developed depth-damage function for the continent Asia and this depth-damage will be used for Thailand as well. For the maximum value, the average value of Asia are taken from the same research. The depth-damage values of the five classes in figure 4.2b are almost identical.

Therefore, for the depth-damage function of the 'no-data' layer, just the average of the five classes is taken. However, just taking the average of the maximum value data will be a misinterpretation, because this means that all classes are equally present in the missing data, which is highly unlikely. According to the CIA factbook (CIA, 2011), Thailand consist of 30% agricultural land cover. The maximum damage values of the land-use classes residential, commercial and industry do not differ so much from each other. For this research, an estimation of the maximum damage of the 'no-data' layer is calculated by assuming that the other 70% consist of either commerce, industry or residential. Exactly knowing how much does not matter so much, because the values are so close to each other. The average of these three values are taken and assigned to the overall 70% from which the 'no-data' damage value is calculated by combining this value with the agriculture value. The resulting maximum damage values are shown in figure 4.2a.

Classes	Max Damage 2010(Euro/m^2)
Residential	111
Commerce	138
Industry	114
Infrastructure	17
Agriculture	0.02
No Data	84.71

(a)



(b)

Figure 4.2: a) maximum values of the five land classes and an additional 'no-data' class b)Depth Damage function obtained by taken the values of the average Asian values from Huizinga and de Moel (2015)

FLOOD EXTENT

The flood water moved from the north of Thailand all the way down to Bangkok and eventually debouched in the ocean. Damaged areas are also being found from the top to the bottom. HKV has provided a map with the flood extent at the end of 2011 in Thailand. In QGIS, municipal boundaries were loaded in and overlaid with flood extent. This resulted in all areas affected by the flood extent considered for the calculation. This is shown in figure 4.3 and the input for the boundary file in FIAT.

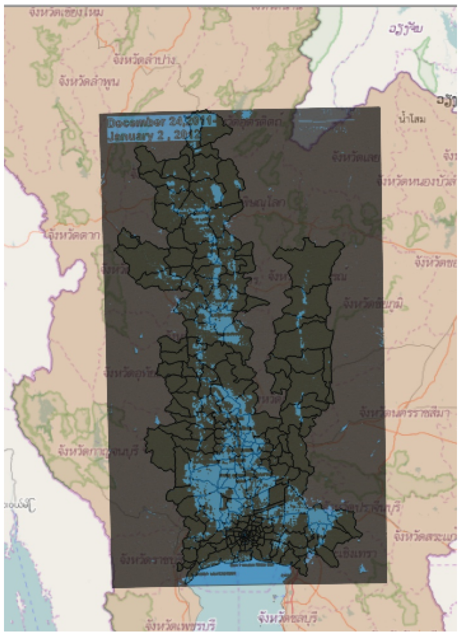
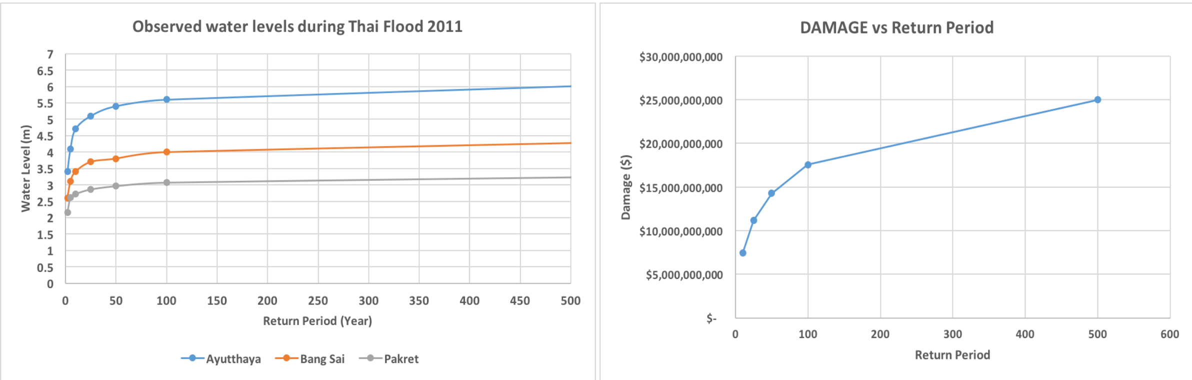


Figure 4.3: Affected areas in Thailand during the 2011 flood event

RESULT

The result of FIAT should be compared with the reported damage of this event. The reported damage of this event was $46.5 billion in total. However, this number contains both damages and losses. Damages were defined as the direct damages of the flood. Losses were defined as the associated losses in economic activity and could not be calculated in FIAT. Therefore, only the direct damages could be compared with FIAT results. According to the official Thai Government Report of the flood event (RTG, 2012), 44% of the total damages are considered damage and 56% losses. This makes up to approximately $20.6 billion in direct damages. The FIAT results are calculated and a detailed overview of the damages are reported in appendix D. FIAT calculates the damages in euros, where the reported damages are in dollars. The exchange rate during the event was approximately 1.4 and this number is being used to convert the euro values to dollar values. For return periods 10,25,50,100 and 500 year, the damage is calculated and shown in figure 4.4b. Which damage value belongs to the flood event is determined by the return period. In figure 4.4a, the water level measures of 4.1 are plotted and extrapolated. If we intersect the reported water level of the flood event for the three places (5.9,4.2,3.2) with these lines, we get a corresponding return period of approximately 300 year for all three places. If we read the damage value associated with this return period, FIAT calculated a damage of approximately $21.5 billion. This number is really close to the $20.6 billion reported damages, just a factor 1.04 higher.



(a) (b)

Figure 4.4: a) Measured water levels with corresponding return periods of figure 4.1 and extrapolation. b)Result of damages ($) in FIAT linked to the corresponding return period

4.2. MANAGEMENT ON CITY SCALE: BANGKOK

Bangkok is the capital and by far the biggest city in Thailand located along the banks of the Lower Basin of the Chao Phraya River. Nowadays, around 15% of the country's population live in the Bangkok Metropolitan Area (BMA). Bangkok's population increased by 74% between 1998 and 2003 (WorldBank, 2010), showing the extreme high urbanization rate of the city. This increase in urban population has put pressure on the urban water resources. Groundwater extraction has increased with the same number, resulting in subsidence making the city even more vulnerable. Bangkok is also the economic and financial heart of Thailand. Bangkok's urban development policy has focused on promoting internal economic growth and livelihood for its citizens (Mar, 2013). This has led to the decrease of agricultural areas and increase of residential and commercial areas, which led to settlements on the floodplains of the city. Zoning regulations were changed or ignored to serve the business development in the city (Poapongsakorn and Meethom, 2012). The city was severely hit by the 2011 flood event, which showed the improper and inconsistent land-use management policy. The main reasons of the flooding of the city were the low efficiency of the urban drainage systems, high discharges from upstream, high sea tides and dike failures due to lack of maintenance. The failure of the urban drainage systems was mainly due to the fact that it was not designed for extreme events of long duration. However, the drainage system reduced the impact on the city center by flooding of the peri-urban and agricultural lands outside the city center (Nair *et al.*, 2014). The inconsistent land-use led to obstruction of the natural flood drainage system (Mar, 2013). Bangkok's flood protection is characterized by the focus on structural measures. However, after much investments it is recognized that the city is in some places not resistant to flood events of 1/10 years (WorldBank, 2010), for instance the King's Dyke protecting the economic center on the east side of city. Also the lack of public communications in the city led to slow evacuation responses, although a flood control center (FCC) monitoring data of the river is in place.

It was recognized that Thailand lacked a comprehensive flood management and that a shift to a more integrated flood management was necessary to prevent a future event with the same or even higher magnitude. It is therefore interesting to see, also in line with the proposed framework, how Bangkok integrated this smart city flood risk management into their city boundaries. A disaster like this is on itself a terrible happening, but it can also give an opportunity to rebuild the whole protection system again and set new restrictions and measures. Right after the flood, a new flood management master plan was derived for the Chao Phraya river basin. This overall plan for the long term, or the "Master Plan on Water Resource Management" consists of the 8 work plans with an allocating budget of approximately $US 10 billion (SCWRM, 2012) containing three main objectives ; 1) to prevent, mitigate and reduce the damage by flooding. 2) to improve the efficiency of the flood prevention and emergency systems. 3) to build public confidence and security (Poapongsakorn and Meethom, 2012) . For Bangkok, a flood management plan was derived by the Bangkok Metropolitan Administration (BMA, 2012) admitting to failures in 2011 and aiming to improve the robustness of the city. This plan consists of measures implementing on the short, middle and long term set from 2011 to 2017. The drainage systems, both the urban and natural, were improved by increasing the capacity and initiate warning systems. Extra drainage pipes were built under the city and drainage canals were being dredged. The flood control center was being updated by improving the information and warning systems for better monitoring and earlier detecting of floods. Three new drainage tunnels will be constructed to discharge water from Bangkok to the Gulf of Thailand. Also the development of retention ponds to store water is planned. But the biggest emphasis of the plan is strengthening and elevating the flood walls and dikes. Upstream, middle and downstream flood walls will be elevated by respectively +0.5, +0.2 and +0.3 m. The aforementioned King's dike will be elevated from +1.5 MSL to +3.0 MSL. Measured water level during the 2011 flood event in Bangkok was +2.53 MSL (BMA, 2012), meaning that the King's dike could withstand an event like the 2011 event when finished. In appendix C, information about insurance policy in Thailand before and after the flood is listed showing that change of policy did not had the expected result. Still after recognition of the failure in spatial-planning, character on structural measures are visible and lack of broader legislative, regulatory and planning framework. Also, emergency measures are scarce, where a study of Kampanartkosol (2013) showed that the value of preventable damages significantly exceeds the costs of proposed emergency measures in case of a similar event in Bangkok. Based on the information given and the failure recognized during the 2011 flood, the suggested smart city framework can be made for Bangkok before and after the flood event giving an indication how management plans changed. Based on all information, the following smart city flood risk framework is suggested in figure 4.5 for Bangkok for the old and the new situation.

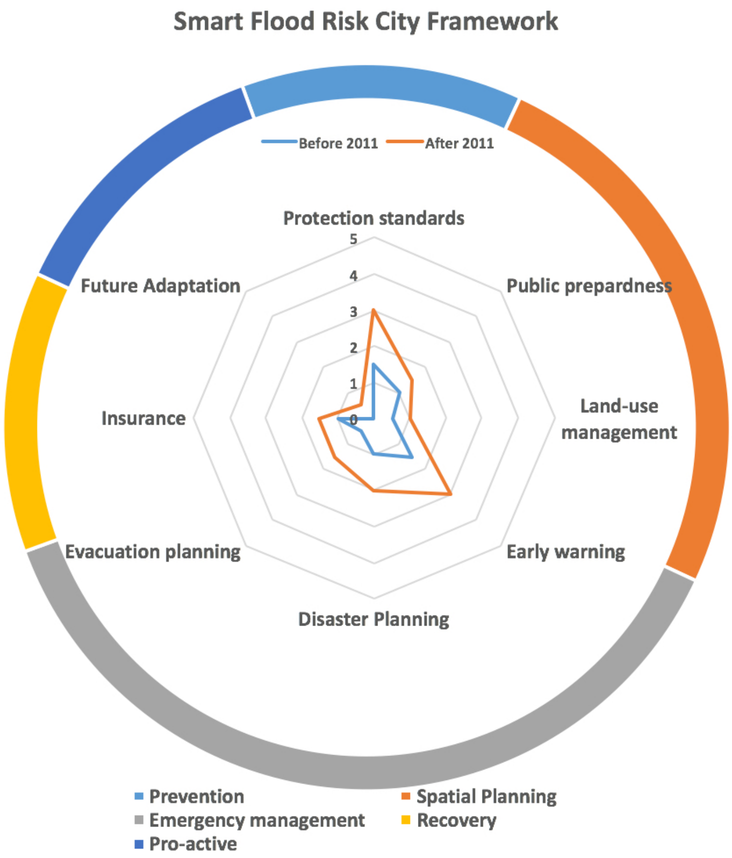


Figure 4.5: The smart flood risk city framework of Bangkok before and after the 2011 flood event and introduction of the new flood management plan

5
Individual Risk Europe

To give an indication of the individual risk and show the result of the suggested method, an assessment is performed for Europe following the method described. However, as mentioned before, this assessment is more a quick and easy indication than an assessment where conclusions can be drawn from.

Result

In figure 5.1 and 5.2, the results of the individual risk assessment indicating the number of fatalities and the fatality risk per year are shown for Europe without taking into account flood protection or evacuation.

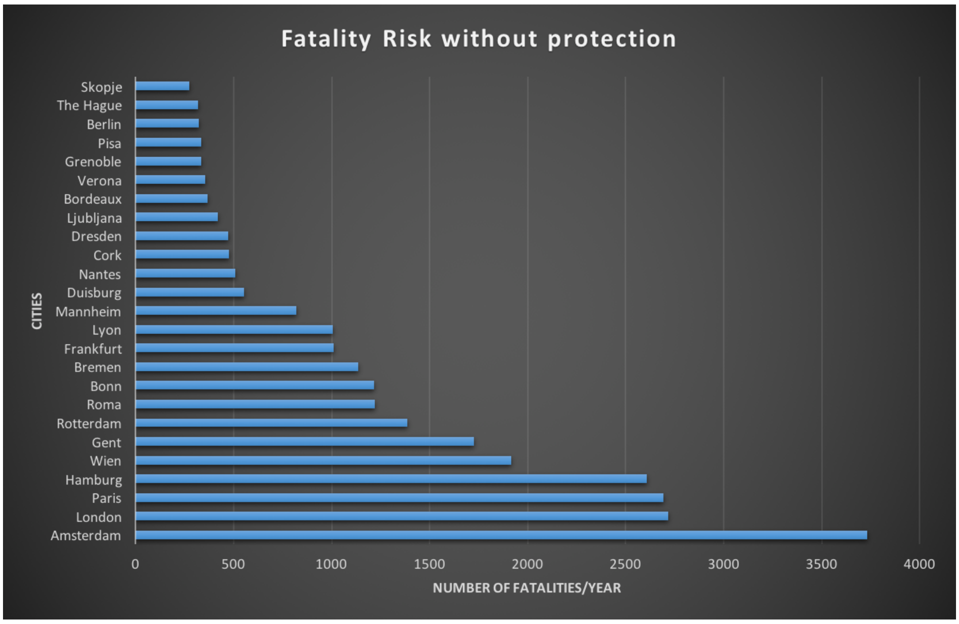


Figure 5.1: Results of number of fatalities/year

Both graphs show a lot of similarities, but also some shifts in the results. Just looking at one of the two assessments could be misleading. Not only cities with high exposure (high population), but also smaller cities show up in the results. Amsterdam is by far the city with the highest individual risk with almost 3750 fatalities per year as risk indicator. Number of fatalities for cities like London and Paris are really high as well, however the risk per person is just less, because both cities have high population. It is interesting to look also at smaller cities that show up at the results like Cork, Bonn, Pisa, Nantes and Sunderland. By only considering economical damages, these cities will most likely not show up, because of low direct economic exposure. Therefore, looking at risk from another angle, in this case fatalities, is so important to show that measures in these cities more focused on reduction of individual risk are more appropriate.

It is now interesting to see how these risk results will change in the future. As mentioned before, this assessment does not include any evacuation fraction that could reduce the number of fatalities. Based on non-technical measures in place in cities, the risk could be adjusted. By looking at the cities more closely and making frameworks of each cities, this measures could be included in a risk assessment like FIAT.

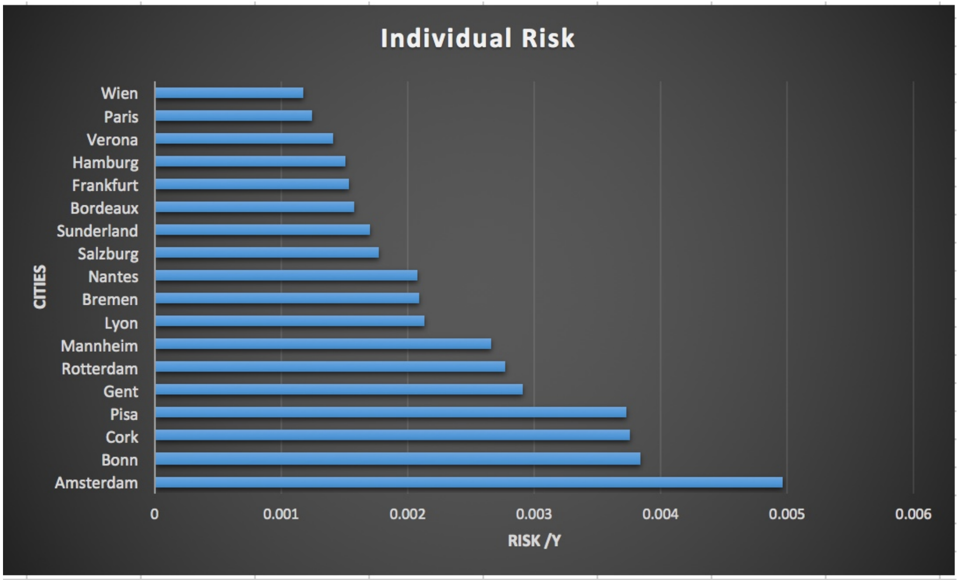


Figure 5.2: Results of individual risk/year

How this will look can be best illustrated by an example including three cities A(blue), B(orange) and C(grey). City A has no measures undertaken at all. City B has some non-technical measures in place resulting in an evacuation fraction of 20% for every event. City C has recently derived a new flood management plan. They invested in early warning systems, disaster planning, local projects to increase public awareness resulting in the transition of taking precautionary measures by households and companies . This resulted in an evacuation fraction of 80% for every event. This is shown graphically in figure 5.3, where it is clearly shown which benefit the measures could have. If more research to the effects of these measures is conducted, this could be included in the flood risk assessment leading to a more proper identification of vulnerable cities to individual risk.

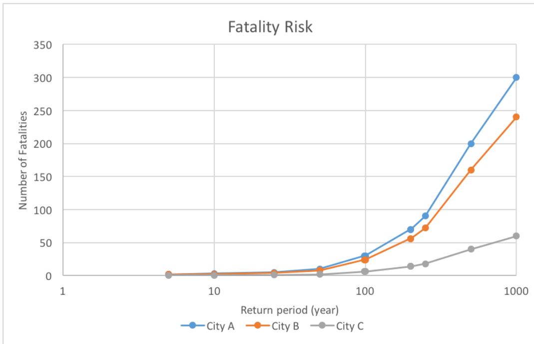


Figure 5.3: Effect of different emergency measures on fatality risk for city A, B and C

6

German city evaluation

By looking at the three risk indicators combined with distribution of the risk over the five land-use classes, an evaluation of the city specific risk can be made. These indicators can be compared to the average of the 25 cities by population in Germany (figure 6.1a) given if the city is at high, moderate or low risk compared with other cities. More importantly, it can give insight what measures should be most appropriate for risk reduction, or where the biggest benefit could be achieved. The European Flood Directive obligates cities to implement measures from all layers into their policy. However, focusing on the most beneficial measures could result in less time and resources to achieve an acceptable flood risk level. All of this can be combined in an advice for the implementation of flood risk measures in a city based on the components of our smart city framework. This is done for all 25 top cities in Germany. However, five of them will be discussed based on differences in risk indications and thus different appropriate advises. The five cities are Düsseldorf, Bochum, Bonn, Essen and Hamburg. For this purpose, flood protection standards are included in the economic risk assessment to see the damage distribution after reaching the threshold of preventive measures.

Düsseldorf

Overall, Düsseldorf is at moderate risk compared to the cities average, meaning that effort must be put in effective risk management (figure 6.1b). What really stand out is the percentage of residential damage in case of flooding. This means that a lot of households are located in flood prone areas or close to the river banks. Flood management measures of the city should therefore be focused on the aspects of residential buildings, but it gives also an indication that a lot of people living in the flood prone areas. By making flood prove buildings or by taking private precautionary measures, the share of residential damage could be reduced drastically. By moving residents away from the flood prone areas and setting regulations of building in these areas, the share of residential damage could be reduced in the future. Also, a lot of people in prone to flooding means that focusing on emergency management is important. However, the affection of the infrastructure is low, meaning that evacuation by car is relatively safe. A focus on early warning systems is most appropriate.

Bochum

In contrast to Düsseldorf, the characteristics of Bochum are just the opposite. The overall risk, individual risk and risk/household are really low compared to the average (figure 6.1c). Not much gain is reached in insurance and taking precautionary measures. The share of residential damage is the lowest of all German cities considered. Focusing on flood prove buildings and spatial city planning will not result in must benefit. Also, the percentage of affected agricultural areas is the highest of all cities. This means that already a lot of water storage in rural areas is available, which is already a good sign. However, a lot of commercial and industrial areas are located in the flood prone areas. Focus on making companies aware of their risk by taking precautionary measures like sand bags, evacuation planning and moving valuable company assets to dry places could lead to the highest risk reduction in the future. Because non-structural measures are not considered cost-effective, budget could be best spend on structural measures like enhancing the dikes and installing pumping stations.

BONN

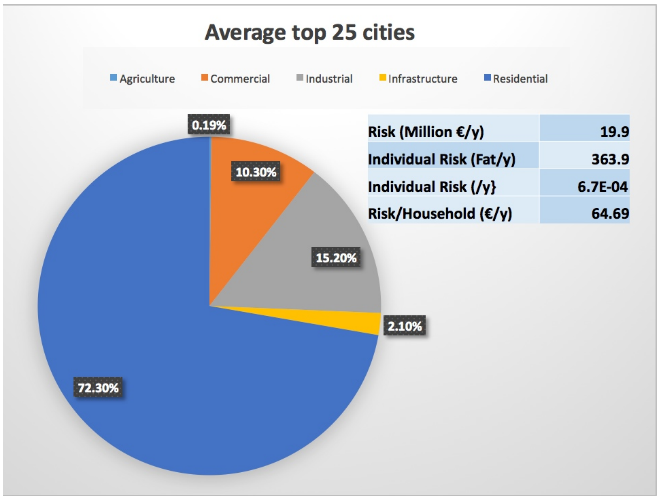
Bonn is located near Bochum and Düsseldorf, however risk characteristics are really different. Overall flood risk and individual risk are considered high compared to the average. Moreover, the risk/household is considered extremely high and the highest in all of the 25 cities as shown in figure 6.1d. Given all this, the emphasis of flood risk management in Bonn should be on household level. From all measures, encouraging people to take private flood insurance and taking precautionary measures are to utmost importance. This could be achieved by improving the public awareness of the risks involved. Projects on local level involving the community and rewarding initiatives of communities improving their neighborhood are very important. This could be difficult, because relatively a lot of their household money should be spent on this to reduce the risk per household to comparable levels. Also, the share of agricultural damage is the lowest of all cities. This means that there is room for improvements in land-use management by increasing the number of retention ponds, flood polders, and changing urban areas back to rural. This does not mean that other measures should not be taking into account, but this is where the most progress could be made.

ESSEN

The same as in Bochum, Essen is a German city focused primarily on the industry represented by the high share of industrial and commercial damage in the overall damages (figure 6.1e). Residential damage is below average and the individual risk and risk/household is relatively low. It is therefore relatively easy to convince the citizens to take precautionary measures, because little of their overall income should be spent on this. This in contrast with Bonn as mentioned before, where high risk per household is present. By looking at the numbers, it is best to invest in preventive measures that could reduce the overall risk. It is likely that the city economics largely dependent on the industrial activity and interruption of running business could be a huge cost driver. Therefore, protecting the most valuable operations from flooding should be top priority.

HAMBURG

The last city that will be discussed is the city of Hamburg, taking the top place in most vulnerable cities in Germany. The potential damages are calculated at almost €136 million per year, with additional high individual risk and risk per household (figure 6.1f). Finding the appropriate set of measures for this city is comprehensive. Investing in protection only is not enough. Agricultural damages are really low creating room for improvements in rural areas for water storage. The flood management should include measures from all layers; prevention, spatial planning, emergency management, recovery and a shift towards a more pro-active approach. Also, infrastructural damages are above average meaning that a lot of infrastructure will be hit during a large scale flood. This makes evacuation of densely populated areas difficult. A lot more effort should be put into flood risk management to end up at the same level of risk as other German mega cities like Berlin, München or Köln (number 1,3 and 4 by population).



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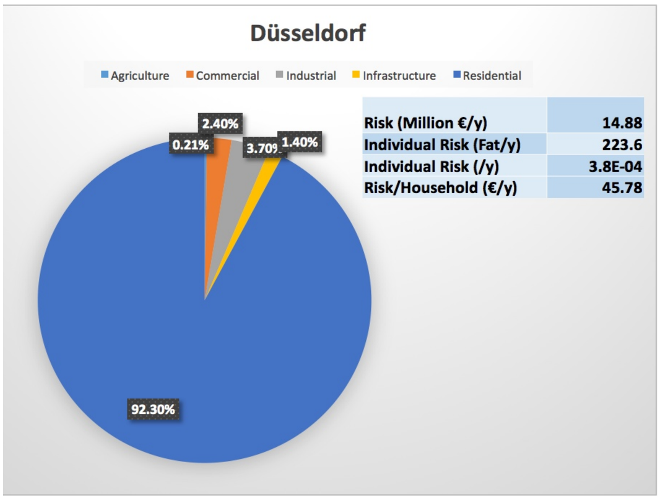

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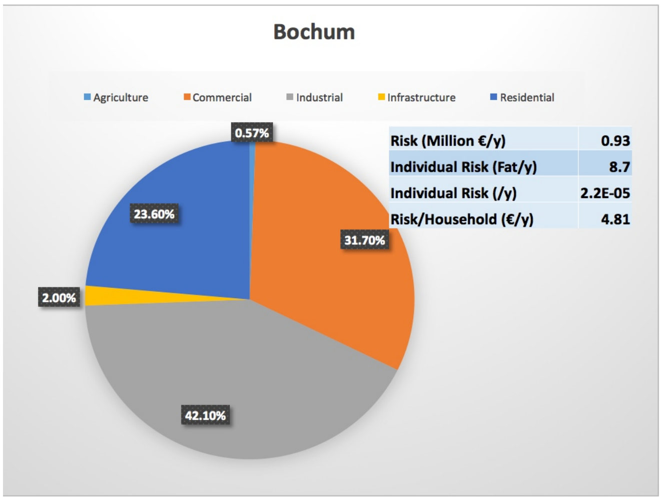

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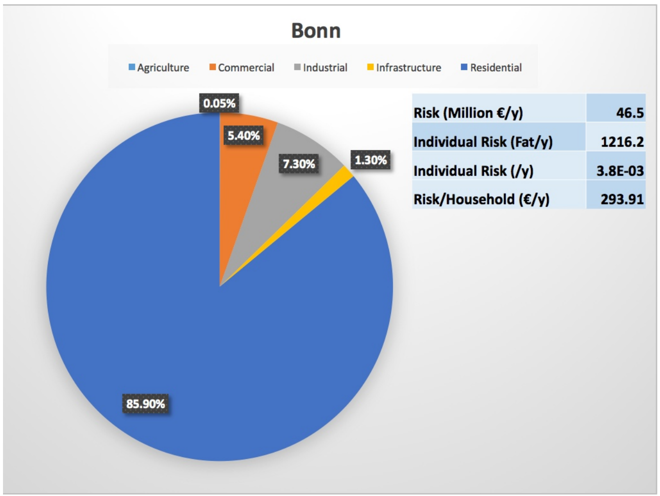

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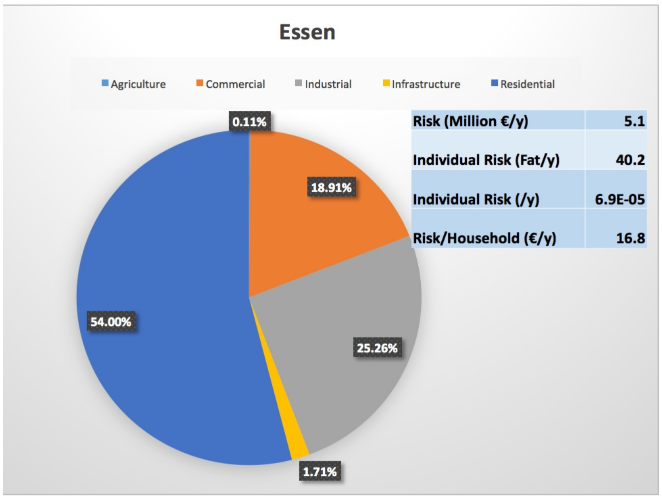

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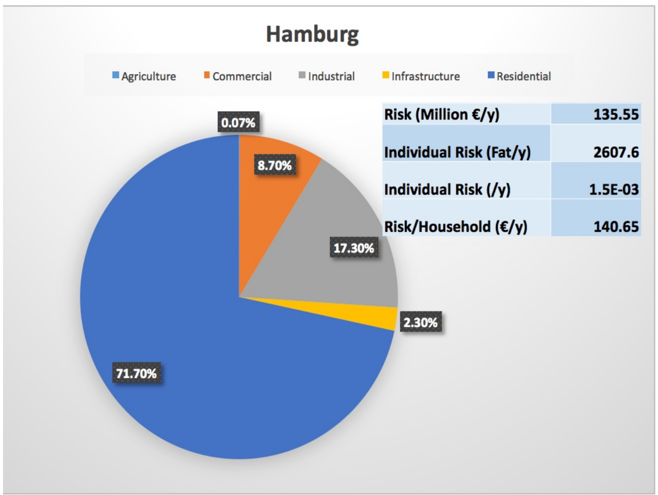


(f)

Figure 6.1: Closer look at the risk characteristics of the average of the top 25 German cities(a) and the cities Dusseldorf(b), Bochum(c), Bonn(d), Essen(e) and Hamburg(f)

7

GERMANY: 2013 EUROPEAN FLOODS

In June 2013, a major flood event affected parts of Austria, Switzerland, Czech Republic, Poland, Hungary, Slovakia, Croatia, Serbia but particularly Germany was affected. We will look closely at Germany, because it was affected most severe and the most information is available. The flood was caused by a combination of two major factors; a heavy rain persisting for several days and strong earlier rainfall that has led to a very high soil moisture in large parts of Germany (Merz *et al.*, 2014). This high soil moisture content, resulting from persistent rain in May earlier that year, led to problems with the water absorption of the soil and together with the above-average initial stream flow levels, high flood peaks resulted in the upper catchments of the rivers Rhine, Wesser as well as the rivers Danube and Elbe (Thieken *et al.*, 2016). This all resulted in observations of flood discharges of historical levels, for example the city center of Passau where a flood level similar to the highest recorded flood in 1501 was observed (Bloschl *et al.*, 2013). The flood event resulted in 25 fatalities in all affected countries. The reported economical losses vary from €12 billion to €16 billion, where Germany took the biggest hit with economic losses of approximately €10 million (CEDIM, 2013). Insured losses were estimated on €2.4 billion to €3.8 billion (PERC, 2014). Looking back at the flood event for Germany only, it can be said that this event is the most severe large-scale flood since at least 6 decades in hydrological terms (Merz *et al.*, 2014). However, looking in terms of economic losses, the flood event of 2002 was more severe than this event. More information can be found in appendix F

7.1. DAMAGE ASSESSMENT FIAT

LAND COVER MAP

For the land cover map of Germany, the CORINE land cover is being used. As mentioned before, this land cover map is a very detailed map consisting of 44 different land-use classes. In the end, 28 out of the 44 class types were part of one of five land-use classes based on the LUCAS survey. These 28 are included for a certain percentage in one or more of the five land-use classes. The CORINE map is widely available and the reduction to the considered land-use types is done by Nootenboom (2015).

DEPTH-DAMAGE FUNCTION

To assign a value to the exposed assets, we had to derive a depth/damage function for Germany. Fortunately, the depth damage function for the five classes are being made by Huizinga (2007). They are combined and shown in figure 7.1. However in our situation, we do not want a total risk in terms of damage, but a total damage value for our event. Therefore, we need to calculate the damage for the measured inundation depths in Germany. The depth on the vertical axis corresponds to a certain return period in our hydrological model, and therefore the damage values will be taken at that depth. From the same research, the maximum damage values of the five classes are obtained for the year 2007. Our event discussed happened in 2013 and therefore the maximum damage values need to be adjusted to the values corresponding to the year 2013. To do this, inflation rates (CPI) of Germany are obtained from inflation database and the total inflation increase over the years is calculated. In figure 7.2b, the final maximum damage values are calculated and these values will be used for the validation of the event in FIAT.

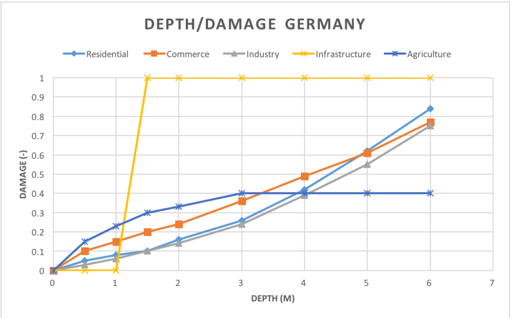


Figure 7.1: Depth-Damage function of Germany based on values of (Huizinga, 2007)

Year	Inflation rate(%)
2008	1.13
2009	0.81
2010	1.31
2011	1.98
2012	2.04
Total	4.84

(a)

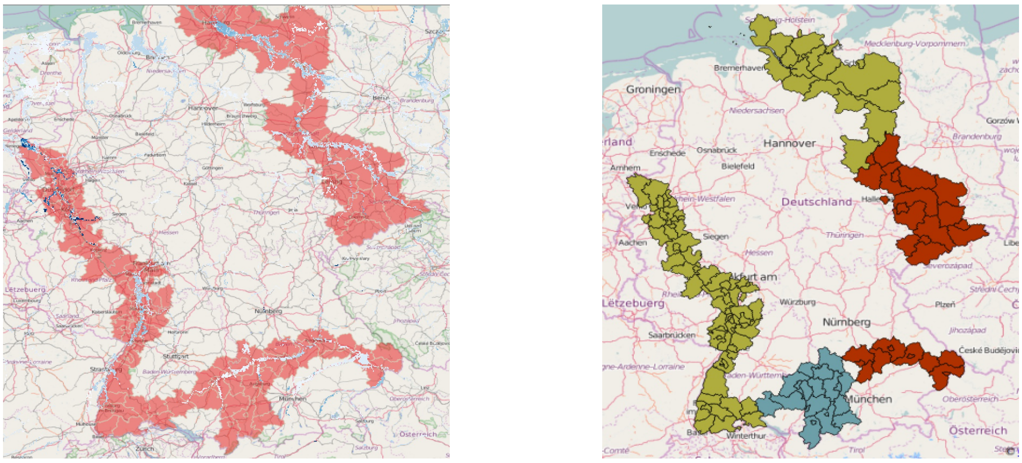
Classes	Max Damage 2007 (Euro/m^2)	Max Damage 2012(Euro/m^2)
Residential	520	545.18
Commerce	400	419.37
Industry	200	209.69
Infrastructure	6	6.29
Agriculture	0.1	0.10

(b)

Figure 7.2: a) Historical inflation rates of Germany obtained from inflation database b) Maximum damage values for the five land-use classes obtained from Huizinga (2007) and the adjusted values for 2013.

FLOOD EXTENT

The land-use map must eventually be overlaid with our hydrological model linking the inundation depths to the damage. Because a total damage is the goal of the validation, an inundation depth need to be assigned to the right areas. In figure7.3a, all affected German municipals are showed. To every municipal, an inundation depth is being assigned according to the measured return periods of figure F.1 in the appendix. However, FIAT can only calculate return periods of 5,10,25,50,100,500,1000 year. Therefore, the municipals are assigned the return period closest to the measured ones and this resulted in areas with respectively 5, 50 and 100 year return periods. This is shown in figure 7.3b, where the three different areas are displayed. The damage for each area will be calculated in FIAT for the right return period and eventually the three areas will be combined to get an indication of the total damage according to FIAT.

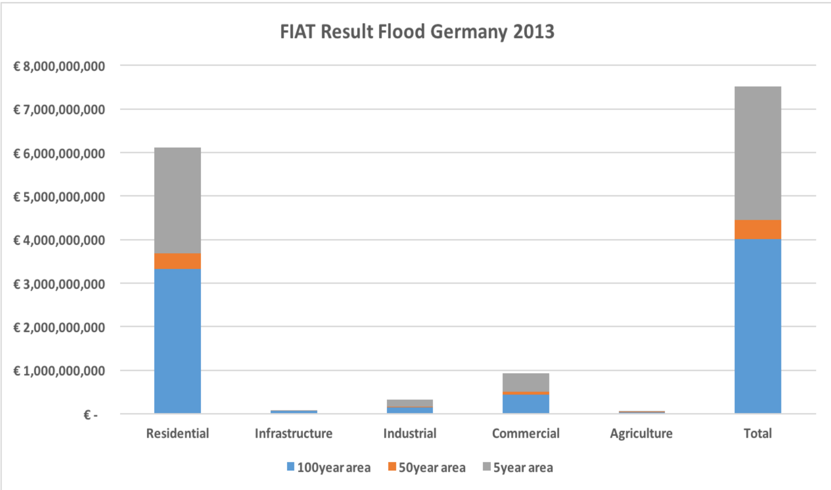


(a) (b)

Figure 7.3: a) River extent of the Danube, Elbe and Rhine rivers in all affected German municipals b) Subdivision of the affected German municipals in return period areas of 100 year (red), 50 year (Blue), 5 year (Green)

RESULT

After processing in FIAT, the damages of the three areas and the combined areas are being calculated. In this calculation, flood protection standards are not taking into account. This because the flood protections were apparently not sufficient to withhold the river from inundating the hinterlands. This in contrast with the GLOFRIS database and literature that stated that Germany has protection standards in place of 100 year or even higher. These protection standards could have significantly reduced the extent of the flood, but not prevent it from happening. The results of FIAT are shown in figure 7.4a, where especially the residential land-use class accounted for the most damages. By combining the total damages of all three areas, the total damages add up to approximately €7.5 billion. The results for the five most affected states are shown in figure 7.4b. Reported total damages vary from 10 to 12 billion euros. The aid allocated for federal and state relief fund was approximately €8 billion and is close to the FIAT damage. By looking at the results, FIAT gives an indication of the total damages but not close to the total reported data in Germany. However, FIAT calculates the direct damages of an event, where reported damages often include indirect damages like damages for hindrance of economic activity. According to Thieken *et al.* (2016), the reported direct damages are still not accurately processed, but the overall losses as reported by the Federal Ministry of Finance (BMF) was €8.15 billion. This number is less than the first estimates of 10 to 12, because many estimates of State damages were reduced in the end. For example, the state Saxony first estimated their damage on €2.7 billion, but this was reduced to an estimate of between €1.5 and €2.0 billion. Compared to the €8.15 billion, the FIAT estimation of €7.5 billion is not so far away from this. However, looking at state level, result vary from over to underestimations. Especially in the Baden-Württemberg, where observed return periods were low, overestimation takes place by neglecting protection standards. However, the calculated damages in Bavaria and Saxony are in the same order of magnitude.



(a)

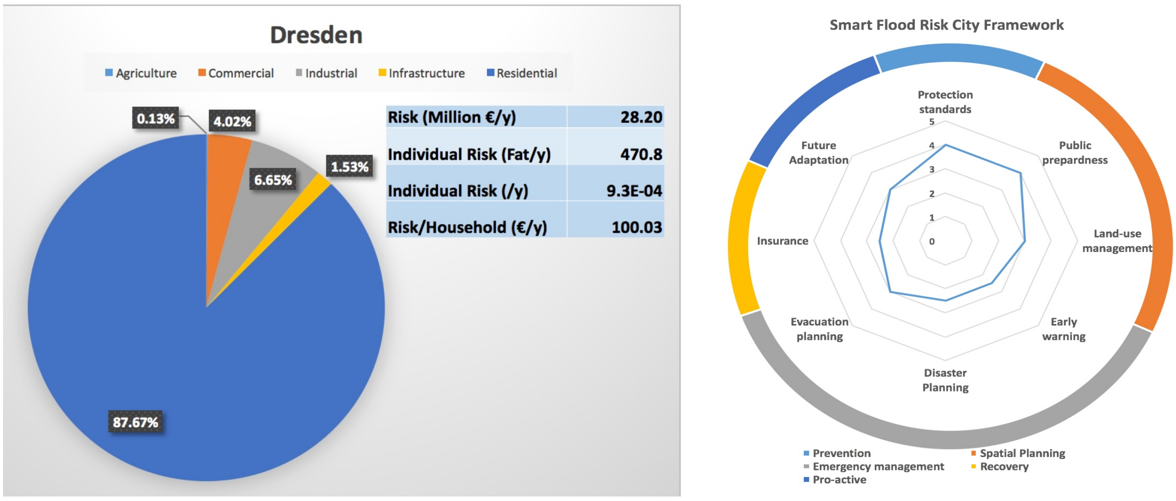
State	Reported(m€)	FIAT(m€)
Baden-Württemberg	74	501
Bavaria	1308	1648
Brandenburg	92	144
Saxony	1923	1416
Saxony-Anhalt	2699	1224

(b)

Figure 7.4: a) Results FIAT for the European Flooding of 2013 in Germany b) Reported damages and calculated damages in FIAT for five most affected German States(Thieken *et al.*, 2016)

7.2. MANAGEMENT ON CITY SCALE: SUCCESS STORY DRESDEN

Dresden was severely hit by the flood event in 2002, however managed to achieve considerable improvements in flood prevention resulting in significantly less losses and saving of flooding of the city center in 2013. Comparison between the flood events can give useful insight how the proposed flood risk management succeed. First we look at the flood management in relation with our framework. First of all, Dresden invested a lot in technical structures; floodgates, mobile flood protection and flood protection to at least 1/100 per year (Jonkman *et al.*, 2013). The city shifted to a more risk-based approach by increasing some thresholds to a 1/500 per year level (PERC, 2014) protecting the historical center. Next to that, communication of the flood was better, quicker and more effective compared to 2002 making the evacuation process run more smoothly. Dresden has focused for some years on land-use measures along the river flood plains. The city increased retention areas and proper run-off pathways for flood water. The 2002 flood in Dresden was the first flood since years and most citizens had not experienced any flood in their lives making them unaware of the risks. Only 3% had experienced a flood before and 23% knew that their household was located in a flood-prone area (Kreibich and Thieken, 2009). After the flood event, the city authorities encouraged the citizens to take private precautionary measures and insure themselves. The study of Kreibich and Thieken (2009) showed that in 2006 precautionary measures taken by household was increased from 13% in 2002 to 67% in 2006. Besides that, 75% knew the current flood risk situation of their household and 43% of the household had insured their property for flooding which is significantly higher than the German averages. What this number is nowadays is not known, but it could be expected that these number have increased over the years and helped Dresden managed the 2013 flood so well. This information led to the following flood risk city framework in figure 7.5b. By looking at the risk indicators, two important aspects pop up. First, the share of residential damages is really high for this city and the risk per household is almost twice the average, where the overall risk is just 1.5 times the average. Most appropriate measures where the most benefit could be made is on household level by taking precautionary measures, flood prove buildings and taking risk insurance. Surprisingly, this is where the city of Dresden mainly focused on as non-structural measures. This could be the reason why the vulnerability of the city is so much lower than a few years ago as will be explained in the next paragraph. However, Dresden still is one of the cities with the highest risk and other measures should not be forgotten. Because Dresden is located on the upstream part of the Elbe, threat of flash floods as a result of climate change are expected for the future, meaning that focus on future adaptation and emergency management are still important for the future.



(a) (b)

Figure 7.5: a) Risk indications and distribution for the city of Dresden b)Smart city flood risk management implemented by the city of Dresden

VULNERABILITY ASSESSMENT OF DRESDEN

Information about the historical events can give an indication of the vulnerability of Dresden and the change of this over time. This can be done based on information about the return periods and reported damages of both events. The vulnerability assessment is based on the proposed indication of vulnerability by Jongman *et al.* (2015) by rewriting the risk equation:

$$Risk = Hazard * Exposure * Vulnerability \quad (7.1)$$

$$Vulnerability = Risk/(Hazard * Exposure) \quad (7.2)$$

	2002	2013
Return Period(Years)	200	50
FIAT (Million €)	4023	3239
Reported Damage(Million€)	1000	137.1
Vulnerability	24.9%	4.2%

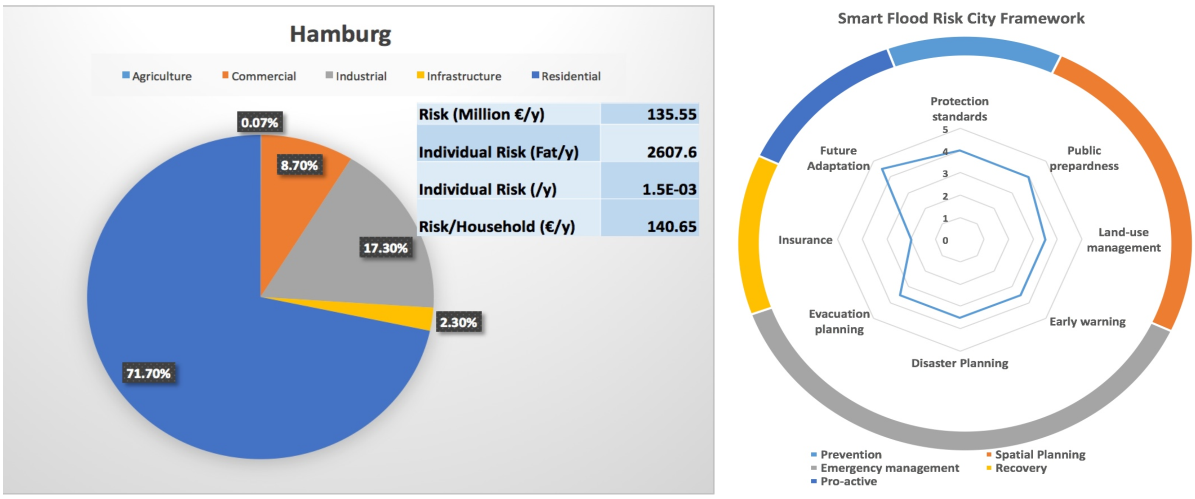
Figure 7.6: Comparison of reported damage, FIAT damage and vulnerability

$Risk$ in this equation if measured by the reported damages in € and $Hazard * Exposure$ by taking the damage calculated in FIAT for the right return period. In 2002 the reported damages in Dresden were approximately €1000 million (Jonkman *et al.*, 2013) compared to damages of only €137.1 million reported by Sachsen (2013) in 2013. Return period in 2002 was 200 year and in 2013 approximately 50 year (Jonkman *et al.*, 2013). By taken FIAT calculation of the damage, the vulnerability of Dresden has decreased from 24.9% to only 4.2% in 2013. To what extent each measure contributed is not clear, but the overall flood management plan has worked well for this city.

7.3. MANAGEMENT ON CITY SCALE: FRONTRUNNER HAMBURG

Hamburg is located at the most downstream part of the Elbe catchment area at the mouth of the North Sea. Because of this location, Hamburg is prone to both coastal flooding and river flooding influenced by the tides which makes it difficult to cope with both. According to our risk assessment, Hamburg is the most vulnerable city in Germany and one of the most vulnerable in Europe. Next to that, high economic development makes Hamburg an attractive city to live and work putting a huge pressure on urban planning in the city. Despite all this, Hamburg is considered a frontrunner on urban flood risk management making it a good source of inspiration for other cities facing the same conditions in the future. Fortunately, Hamburg was spared during the 2013 flood event, but developed a flood management plan to prevent losses in future events.

The city of Hamburg changed to a more adaptive approach taking into account future scenarios in urban planning and water management leading to high protection standards expressed in a flexible protection system for the city (Gonnert and Muller, 2014). The main part of the city is protected by a main dike line with high protection standards of 1/400 years. Because of growing demand for housing and working space, expansion of the city outside the main dike ring was inevitable. Hamburg has made the shift from structural to non-structural quiet early, because raising and building dikes to acceptable risk level would be far too expensive.Therefore, urban planning in Hamburg takes into account flood risk by means of emergency management. This new urban area in front of the main dike line is named 'Hafencity'. Instead of physical protection, the area consist of elevated ground, flood proof buildings and evacuation routes above flood level. Responsibility lays at the private owners, who are obligated to make their buildings flood prove to protection standard of main dike line (Goltermann *et al.*, 2008). This to make the private owner aware of the risk of living in this area. Study showed that awareness in Hamburg is indeed really high, but this awareness does not translate in taking precautionary measures for a part of population. Therefore, Hamburg is currently busy to implement building requirements and standards for such areas in new and adjusted laws. Hamburg has also established a disaster communication system for the city. Another project, named 'leap across the river Elbe', shows the emphasis on emergency management. This new urban island is constructed in the middle of the city. The urban areas are provided with warning and evacuation schemes, distributed in the form of information sheets in different languages to the households concerned. These sheets show the evacuation routes, available shelters and meeting points (Restemeyer *et al.*, 2015). Throughout the island, an open water drainage system is responsible for water retention. Figure 7.7a shows the risk indicators of the city, where in figure 7.7b the smart flood risk city framework is shown. As mentioned before, the risk indicators show high overall risk, individual risk and risk per household. Given the socio-economic situation, the focus on emergency management and urban planning looks like the most appropriate way to reduce risk. Also, really low agricultural damage in contrast with really high infrastructure damage shows that the city has little storage possibility and that a large fraction of the infrastructure necessary for evacuation will be affected in case of a large flooding. However, plans for room for the river projects are not yet found in the city, maybe because of the fact that there is just no space for that. The construction of elevated evacuation ways above flood level is a great initiative to reduce infrastructure damage and at the same time provides unhindered evacuation possibilities. Looking at the city of Hamburg, the city is on the right track recognizing the vulnerabilities and shortcomings and becoming more robust to flooding. However, the urban flood risk management is a continues process by constantly adapting flood management plans to future scenarios.



(a) (b)

Figure 7.7: a) Risk indications and distribution for the city of Hamburg b)Smart city flood risk management implemented by the city of Hamburg

8
Towards a better assessment

The objective of our framework is first to give a quick overview how cities implementing various measures and where the focus is laid. But this framework can also lead to a better risk assessment in the future and a way to communicate with each other. It could lead to some sort of competition to make your city as safe as possible by creating new innovative and sustainable solutions. Therefore the framework is made for two other European cities, Rotterdam and Vienna. This because those two cities have approximately the same economic risk expressed in damages as Hamburg and Dresden. Looking at the four cities gives an indication with city scores the highest in each category on a scale from 0 to 5 by taking the average of the components or in a qualitative way. For the economic risk, the risk without taking into account protection standards is used.

8.1. Rotterdam

Rotterdam is located in the Netherlands with its whole urban footprint below sea level. Rotterdam is the second largest city of the country with the port of Rotterdam as a major economic center. Despite the location and future climate change threats, the city is one of the safest deltas in the world. Rotterdam is for a large part protected with a system of dikes, closure dams, and storm surge barriers with a protection level of 1/10000 years. In the city and port area, flood mitigating measures are embedded into urban planning. A water square in the city with recreational purposes turning in water storage reservoir during rain and drained into the river. Making use of underground parking lots for water storage and green and blue roofs in the city heart. However, large port and urban areas are situated outside this protection system in need for other protective solutions. The development of the Rijnhaven district shows how flood management is embedded into urban planning in these parts of the city. This district is a playground for innovative urban flood management measures. Industrial buildings are located above sea level and the city is experimenting with floating houses to make living next to the river available instead of moving away from the river (RCI, 2014). Also innovative smart solutions are currently under development. Tools like smart gaming, apps and decision support systems have the goal to increase risk perception and make emergency management more efficient. Emergency management is nowadays not developed like in for instance Hamburg. Disaster plans and evacuation mapping are scarce and according to the research of Maaskant *et al.* (2009), only 15% of the city could be evacuated preventive. In the dikes around the city, an early-warning and monitoring system is embedded that calculated dike failure probability and simulate dike breach scenarios. Despite the location and risk situation, risk perception in Rotterdam and the whole country is low. For Rotterdam, especially for people living outside the dike systems, this plays an important role in order to prepare for a flooding. Research of de Boer *et al.* (2015) showed that a large percentage did not know if their household was located outside the main dike line. However, this group had a higher level of prevention-focused responses, but the flood preparedness on household level is still very low. A climate change adaptation strategy includes stakeholders from all different levels and groups working together to make the city safer for future changes. Insurance of the Netherlands is discussed in appendix A.

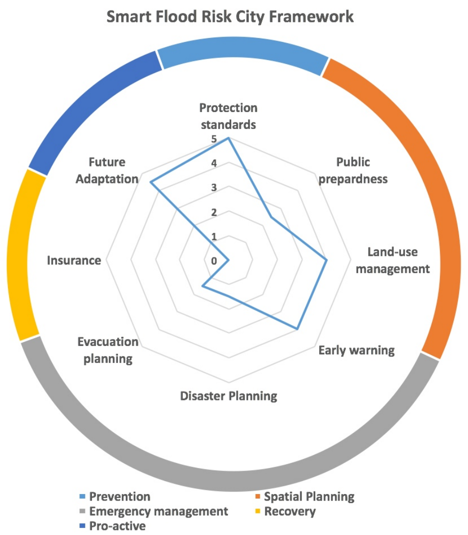


Figure 8.1: Smart Flood Risk City Framework of Rotterdam

8.2. VIENNA

Figure 8.2: Smart Flood Risk City Framework of Vienna

Vienna is the capital of Austria along the Danube river. A Danube river branch, the Vienna river, flows through the most densely populated districts of the cities. Due to large number of impervious surfaces, low infiltration capacity, little natural retention and large slopes, the city is prone to both flash and pluvial river floods (Compton *et al.*, 2009). The Vienna flood protection system can manage flood with a return period of 1000 years in most parts of the city and up to 10000 years in most hazardous areas (Kryzanowski *et al.*, 2014). The focus of city flood risk management next to dikes is on flood relief canals in the Danube river, with a large bypass-channel controlled by five weirs as result. In the city, an early warning system with 48-hours forecasting is installed. Over the last couple of years, the Vienna watercourses have undergo restructuring and revitalization measures if compatible with technical flood protection (ICPDR, 2009), however much water retention plans are still under development. The citizens are informed by brochures and folders about flood risks to increase awareness together with training sessions and instructions to protect buildings. How this translates in awareness and taking precautionary measures could not be found. The area north of the Danube, which was unused and outdated, is currently under development making room for new urban areas with some signs of urban flood management measures. Evacuation and disasters planning is still underdeveloped and recognized as major improvement in the future. Also, climate adaptation is not fully integrated in urban flood management like was found in Rotterdam. Flood Insurance in Austria is on a private basis with an estimate of country's cover rate of 10-25% (Lamond and Penning-Rowsell, 2014), which is assumed to be representative for the city of Vienna as well.

8.3. RESULT

By comparing the four cities, something can be said about how each city scores for each subtotal and on the overall risk reduction. Looking at economic risk, Hamburg face the highest risk, where Rotterdam face the highest individual risk. Protection standards of Rotterdam and Vienna are the highest in the world in contrast with Dresden and Hamburg where less emphasis is put on extreme high flood protection standards. All cities have managed to make spatial plans to reduce damages in case of an actual flooding. Dresden and Hamburg are more focused on preparedness and emergency management on household level, where this is less present in Rotterdam and Vienna, leading to the fact that citizens of the last two cities are less aware of the risks and what to do in case of a flooding. Despite that, Rotterdam and Hamburg are considered the front runner of implementing smart flood management measures into urban planning. This is necessary, because of increasing urbanization rates and need to built homes and commercial places outside the main dike protection. Insurance cover rates are not high in all cities, due to the private flood insurance policies in Vienna, Dresden and Hamburg and absence of flood insurance possibilities in Rotterdam. Which city is most vulnerable or the safest is up to a personal interpretation, but it is clear that all cities have managed to implement components of the multi-layer flood management concept on city scale. Each city could be a inspiration for other cities and by constantly developing new plans, each city plans to stay ahead of the upcoming flood threat.

City	Eco. Risk (€/y)	Ind. Risk (/y)	Prevention(scale)	Spatial Pl.	Emerg. Mn.	Ins.	Pro-Act.
Rotterdam	7.37E+09	2.77E-03	1/10000 (5)	3.25	2	0% *	4.5
Vienna	7.36E+09	1.18E-03	1/1000-1/10000 (4.5)	3.25	2.6	10-25%*	2.5
Dresden	3.00E+09	9.28E-04	1/200- 1/500 (4)	3.5	2.6	43%	3
Hamburg	1.13E+10	1.50E-03	1/400 (4)	3.75	3.5	10-35%*	4.5

Table 8.1: Comparison of smart flood risk city managements of the cities Rotterdam, Vienna, Dresden and Hamburg scored on a scale from 0 to 5. *country average

9
Discussion

PCR-GLOBWB The PCR-GLOBWB is being used for the hazard component in our flood risk assessment. This global hydrological model produces output with a resolution of 50 x 50 km. Because FIAT only works with a spatial resolution of 1 x 1 km, the output values are scaled down based on assumptions. The model contains only information about inundation depth related to return periods. It does not take into account river changes of time. Also, factors like flow velocity, water level rise, flood duration are really important in real flood event but are not taken into account in this model

Land-use maps Land-use maps derived from the Corine land cover map are considered quite accurate. However, considering only 5 land-use classes covers approximately 80% of the total coverage. For land-use maps outside Europe, OSM data was used. In Thailand, this data was scarce and only well defined around Bangkok. That is the reason why the no-data layer has the highest share of the total damage. This layers is based on assumptions of land distribution in Thailand, which is questionable. The risk evaluation is also not conducted for Thailand for this reason, because a solid damage distribution could not be made.

Depth-damage functions The depth-damage functions already include some uncertainties regarding maximum damage and damage impact for different inundation depths. These depth-damage functions are also really sensitive. For example, taking the average function of Europe instead of the depth-damage functions of Germany led to a total damage of 2.5 times larger. For Thailand, the depth-damage functions of the continent Asia are being used. Therefore, to what extent this function is representative for Thailand as country is uncertain.

Flood protection standards First of all, flood protection standards were not included for the validation studies. This result in an overestimation, especially in the areas where low return periods were observed. This can be seen by looking at the state validation in Germany. Because inundation of land was due to dike breaches, including protection standards result in a underestimation. Comparing the results with the FLOPROS database raise skepticism about this database. In Germany for example, standards were known on state level representing a 1/100 year standard. However, during the 2013 flood event it came clear that these standards were met at a lot of places. Also, standards can differ between cities in the states. For example, Dresden has protection standards of 1/500 year in place for large part of the city where the city of Passau had almost no standards in place. The state Baden-Wuerttemberg has set a goal for enhancing flood protection standards in the whole state from a 1/100 to 1/200 protection level. For Thailand, no information for the first two layers in FLOPROS was present making information already less reliable. By looking at the data, the standards differ from 1/5 to 1/35 throughout the whole country. The flood event showed that a lot of place could not even withstand a return period of 1/10 year. The protection standards for Rotterdam, Hamburg and Vienna agree with the FLOPROS values.

FIAT The FIAT tool requires input data with a spatial resolution of 1x1 km. For a quick global comparison assuming uniformity between cities, this resolution is fine. However, for assessments on city scale this resolution is really coarse leading to a lot of information that is being lost. A 0.1 x 0.1 km resolution could be more suitable for looking at for instance damage distributions of cities.

Validation Giving a conclusion of the validity of the FIAT model is difficult. Both validation studies showed that damage calculation were close to reported damages. However, on a lower scale, variations are larger raising the question if the outcome is not just luck. FIAT is also not meant to give exact damage estimations but more a course risk quantification. Results in the same order of magnitude as the reported damages shows indeed that this objective is met.

Individual risk The suggested method for individual risk is far from perfect. Mortality function are until now not validated yet and not much information is available on this. Also, average population density estimation are not representative for all European cities, leading to overestimation in less densely populated cities and underestimation in high densely populated cities. Evacuation fraction are also not taking into account yet. The GLOFRIS method used for this assessments uses only two land-use classes; urban and peri-urban. The assumption is made that for the urban land-use type 75% of the raster size can be appointed to this class and for the peri-urban 25% of the raster size. How accurate this is is not clear, but earlier research of the bachelor students showed that comparison between both methods were not to far apart from each other.

Damage distribution If the damage distribution is a valid way to give a reasonable advice for measures is not sure. Damage to residential building for instance does not give insight if the damaged object is a small house or a flat. Also, surface elevation are not taken into account. If the average of the top 25 cities of Germany is a good reference to compare with is also not clear. Agricultural damage fraction are really small in all cases and it could be better to look at the actual damage than the percentage.

Smart flood risk city framework The proposed smart flood risk city framework could be made for five cities in this research. However, not much information about all components could be found and some interpretation of other information was needed. It is therefore difficult to make this framework for cities where even less information is available. However, especially in European cities with obligation of the European Directive to make flood management plans, information about future project will be more and more available. This enables easier information distribution between cities themselves and scientists looking for this information.

10
CONCLUSION

The objective for this thesis project was to validate the FIAT model and extend the flood risk assessment with other components to come to a more proper assessments of the vulnerability of cities and to translate this in an advice for the implementation of appropriate structural and non-structural measures for flood risk management. The different measures are included in a smart flood risk city framework consisting of five different layers; prevention, spatial planning, emergency management, recovery and pro-active. Two case studies are being discussed; the 2013 flood event in Germany and the 2011 flood event in Thailand.

Case study; 2011 Flood event Thailand The validation of the Thailand flood event resulted in a difference of only 1.04. Calculated damages were $21.5 billion compared to the $20.6 reported direct damages. Looking closely at the flood management of Bangkok before and after the flood event gave insight in the measures taken. Bangkok derived a new flood plan, however it seems that they did not recognize the weaknesses of the city and still rely to much on technical measures.

Flood Risk Indicators The flood risk assessment is extended with an individual risk component, household component and damage distribution. This makes the flood risk assessment more comprehensive by not only looking at economical damage. A quick assessment of the individual risk in Europe showed that Amsterdam is considered the most vulnerable city to become a victim of flooding. Also smaller cities like Bonn, Cork, Pisa and Nantes, which would not show up in damage assessments, are high in individual risk.

Flood Evaluation and advice This risk indicators are being produced for the top 25 German cities by population to give an idea how these indicators could translate into an advice for appropriate measures. The cities Dusseldorf, Bochum, Bonn, Essen and Hamburg are evaluated in detail. Dusseldorf has a moderate overall risk, individual risk and household risk. However more than 90% of the damage is accounted to residential damages. This means that taking precautionary measures, building flood prove houses and require building regulations for flood prone areas are appropriate measures, which could have the highest benefit for this city. Bonn is characterized by really high household risk, high residential damages and low agricultural damages. Measures focus on household level, insurance and 'room for the river' measures are therefor most beneficial for Bonn.

Case study; 2013 Flood event Germany The damage validation of Germany resulted in an estimate of €7.5 billion calculated by FIAT. The early reported damages vary from €10 to 12 billion, however this number is lowered later to an estimate of approximately €8.15 billion. The overall result is in the same order of magnitude, however on German State level differences are higher. In Bavaria, the difference is considered accurate with €1648 million calculated compared to €1308 million reported. In Baden-Wurttemberg, the comparison is inaccurate with €501 million and €74 million. The city of Dresden managed to achieve a vulnerability reduction from 25% to 4.5% over the years. They identified the city's weaknesses and took the appropriate measures.

Towards a better flood risk assessment The earlier mentioned cities of Hamburg and Dresden are compared to the cities Rotterdam and Vienna. Last two cities have protection standards up to 1/10000 years, which are the highest in the world. In contrast with the German cities, preparedness on household level and emergency management is still underdeveloped, making room for improvements available. Each city managed to implement spatial management measures into the city boundaries. Hamburg and Rotterdam are leaders in their pro-active approach to include climate change scenarios into urban planning and prepare the city for future changes.

11
Recommendations

Some improvements to the models used could decrease the uncertainties and ideas giving in this thesis could lead to further research. This includes:

Flood risk assessment The flood risk assessment could be more accurate with less uncertainties in different ways. The hydrological model could be extended with other parameters or even another model could be considered with higher spatial resolution. Depth-damage function for more countries could be derived. If land-use maps as CORINE were available for other continents, the assessment of cities outside Europe will lead to a better land-use coverage resulting in less uncertainty of the 'no-data' layer. The FLOPROS database is a step in the good direction for including flood protection standards, but improvements could be made. For instance, standards on city level and more information in the more reliable layers for countries where this information is not available yet. The FIAT model could be improved by running it on a higher resolution, for instance 0.1 x 0.1 km, but is the question if this is worth it considering the intention to give a risk indicator instead of accurate damage assessment.

Flood risk indicators The suggested flood risk indicators could be further improved or additional indicators could be added to this. Especially the individual risk components could be a research on itself. Indicators like societal risk, social vulnerability index, climate change and socio-economic indicators on city scale are ideas for additional components.

Smart city flood risk framework The suggested framework could be made for more cities in Europe of outside Europe. Scoring methodologies for assessing the measures could be made so every city could be scaled to this. Additional measures could be added as well.

Quantitative effectiveness of non-structural measures Assessing the risk or damage reduction is really difficult, because information about the effectiveness of non-structural measures are not well defined. If this was done, for each cities the risk reduction could be made for the measures taken to come to a more realistic indication of the risk. Insight in the effectiveness of different measures could also lead to a better decision making for city authorities to decide which measures to pick out of the handful of available measures.

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A
INSURANCE POLICIES

SOLIDARITY PRINCIPLE

The solidarity principle is deeply embedded in the flood policies of many EU countries. This principle is defined as *'the principle that the society as a whole should cover certain flood-related costs'* (Hegger *et al.*, 2013) . For example, in the flood management policy of France, this principle keeps returning in many different ways. Every citizen with an building property or car indirectly contribute to this principle. First of all, insurance solidarity ensures that the damage can be repaired and that society can return to normal life after a dramatic event, thanks to the so-called "CAT-NAT" insurance system (DGPR, 2014). This means that in case of a presidential recognized natural disaster, every affected household can file their losses. This approach involves every partner to contribute in the flood management.

PRIVATE INTEREST

The other possibility is to cover the cost of a flood disaster is by private insurance regulations. In Europe and the rest of the world, the existing flood insurance products differ widely in scope and reach (Bouwer *et al.*, 2007). An example of a country with private insurance is the UK, where the insurance market is an extremely competitive one. Flood insurance is in most cases part of your building and contents insurance if you buy a house and mortgage providers are expecting you to have one before providing you with a mortgage. However many differences between insurances exist about what to cover. Premiums of this insurance are based on the assessment of flood risk by the insurer. This means that people in flood risk areas must pay higher premium and in some cases insurance companies consider the risk unacceptable and they will not guarantee full recover (DEFRA, 2012). This policy makes it necessary to provide citizens with information and make them aware of their current flood risk. This policy has resulted in high cover rates in case of a flood event, for instance the 2007 flood in the UK with a 75% insurance coverage (MunichRe, 2014). In countries like Sweden, Portugal and Ireland where flood insurance is voluntary, the government does not offer insurance or financially back the insurers. Portugal and Ireland apply, next to the UK, a risk-based premium system, where private insurers in Sweden do not apply this system. However, even if flood insurance is voluntary, mortgage provider often require any insurance before providing the mortgage except for Portugal where this is not the case. An alternative and interesting flood insurance policy is being applied in Spain, where there is a mix of public and private insurance. In order to promote private insurance, a deductible over public compensations applies and private insurance is offered in a bundle system, which makes flood insurance compulsory if you are insured against other risks (Surminski *et al.*, 2012). If we look oversea to the policy of the United States, we observe some differences in perception and regulation. In the United State, flood insurance is possible from a government program named the National Flood Insurance Program (NFIP). Because flood insurance is not covered in the standard home insurance, an additional insurance is needed for flooding and other disaster. The NFIP provides insurance against disaster to homeowners if their community is participating in the program. Premiums are based on the zones depicted in the Flood Insurance Rate Maps (FIRM). These government premiums are often less expensive that private insurance would be by providing communities with deficits and subsidies. Another interesting arrangement is the exception from flood insurance for property owner living in an area protected by a structure that provide protection against a flood event happening once in every 100 years (Glick *et al.*, 2014). In current debates in the United States, some skepticism is present about the subsidies and insurance exception, because it encourages people to live in flood prone area and these people are often least capable of recovering from a flood event, often associated with the adverse selection principle.

Absence of insurance policy

Another possible insurance policy for the recovery of flood damages, is not having any public or private insurance policy. This is for instance applied in the Netherlands, where standard home and home contents insurance policies exclude coverage for damage caused by flooding. Moreover, there is no legal obligation for the government to compensate flood damage, what makes it uncertain whether households are eligible for compensation in case of damage caused by flooding (Surminski *et al.*, 2012). However, tax money or ad hoc payments should compensate affected household in case of a flooding, but to which extent is uncertain. Introducing an insurance policy system is considered to be complicated as a result of the extreme-low probabilities/high-impact nature of flood risk in the Netherlands (Surminski *et al.*, 2012).

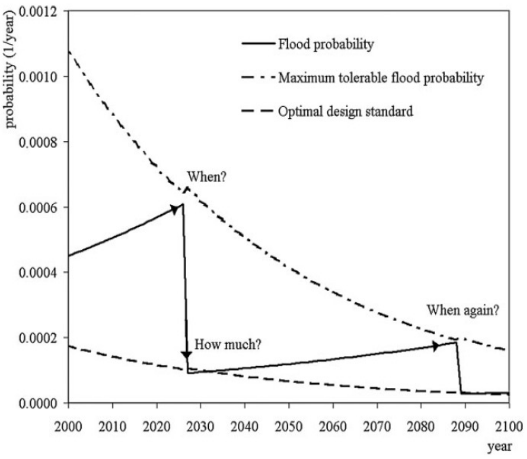
B
Government Risk Cultures

Pro-active approach; new Dutch Delta Program

After years of using a cost benefit approach to determine protection standards, the Dutch Government revised the flood protection for the new Delta Program (Deltaprogram, 2016) and will come into effect in 2017. The revision include a re-evaluation of the current flood protection system in the Netherlands. The height of the new standards are based on the individual risk of becoming a victim flooding(also called basic safety), the societal disruption due to large scale flooding and the economic efficiency of investment in flood protection (Klijn *et al.*, 2014). As can be observed, the new approach is therefore next to a cost benefit analysis expended with a analysis of casualty risk and implemented for different 'dike rings'. This new law is the result of policy project 'Flood Protection 21st Century' , which takes into account the effects of climate change and economic development. Another difference compared to the current standards is the perspective towards flood risk. The current standards are expressed in the exceedance probability of extreme events in contract with the new standards which are expressed in the probability of flooding, because of misinterpretation of flood risk in the current definition and better definition of the real probability of flooding. The new principles include the following points, obtained from Klijn *et al.* (2014):

- A basic level of safety for everyone living behind dikes, to be achieved by enhancing the safety in areas with large individual risk.
- Societal disruption due to large scale flooding. To counteract the societal disruptions and large flood can cause, additional investment in protection next to basic safety will be made for ares, which may experience large groups of casualties and/or economic damages.
- Protection of vital and vulnerable infrastructure. Special attention will be required for the impacts of flooding of certain utilities, as this infrastructure is of vital importance for the functioning of an area during and after a flood.

Basic safety in this context means that individual risk should not exceed the value of 1 in 100.000 years. Next to individual risk, it is relevant to look at the risk of a large number of casualties in a flood event, or group risk. The group risk is related to the probability of many fatalities during a single event, which depend on the location, number of breaches and interaction in flood defences. The number and location of breaches in a flood event is affected by the river discharges, strength of the defences and the outflow into the flood prone area (de Bruijn *et al.*, 2014). The economical assessment differs from earlier approach, because flood probability will increase due to climate change and economic development, and therefore should be taken into consideration in the optimization process. With increasing probabilities and consequences in time, a decision to invest in flood defences is not a one-time decision but a recurring one (Kind, 2014) and because a large proportion of the costs are fixed costs, it is economically most efficient to take longer time interval between investments. Important question to ask is thus when to take the new investment and how much this investment should be. This is represented in figure B.1a . The probability is low after and investment (jump in figure), changes in time and is high right before a new investment. So after an investment the probability increase in time until a new economical optimum is reached. In the end, the new analysis led to new flood protection standards. Standards in dike rings with relatively low probability of a flood event are determined by the protection standards of the basic safety principle, where dike rings with relatively high probability of a flood event are predominantly determined by the economic optimum and societal risk with higher standards as result. An indication of the new standards is presented in figure B.1b . By implementing this new Delta Program, The Netherlands has changed over the last couple of decades from a reactive approach, by strengthen the levees to the highest observed point, to the current pro-active approach (Rijkswaterstaat, 2014).



(a)

(b)

Figure B.1: a) Flood probability over time and change due to periodic investment. Graph consist of components when investment is needed ('when'), how much this investment will be to optimal design standard ('How much?') and over which period follow up investment is needed ('When again?') (Kind, 2014). b)Overview of the flood protection standards in the different dike rings for the Netherlands based on the approach discussed in the new Delta Program 2017 (Klijn *et al.*, 2014).

1% FLOOD STANDARD; BASE LINE APPROACH

For over 50 years, many developed countries uses the 1% flood standard as a basis for identifying, mapping and managing flood hazard and used this standard for design of structural and non-structural flood protection (ASFPM, 2004). The 1% flood standard is in use for several decades based on experts, historical perspectives and an overall accepted probability. Before this standard, flood standards were being set based on historical records, but after some time it was recognized that occurrence of floods were more a matter of chance. Next to the 1% standard, or 100-year flood standard, well known standards widely used are the 50-year flood standard and 25-year flood standards, based on governments perception of the most appropriate level (ASFPM, 2004). A benefit is the efficient administration and implementation, because in big countries with many states or provinces, a national adopted standard is useful. This standard is especially being used for identifying the hazard area subject to inundation by the 100-year flood, where areas able to cope or protected to this inundation are considered hazard-free. Over the last couple of years, there has been some discussion about this standard aiming at future changes like climate change, urbanization, floodplain encroachment and erosion. However, in many countries were this approach is being used, the standard is deeply embedded into policies, programs and insurance what makes changes to this extremely costly. Therefore, it is expected that this base line standard will be used for quiet some time in the future. Another point of interest surrounding this standard is the definition of this standard and the perception of the inhabitants. In order to achieve an efficient implementation and to avoid an ambiguous use of a standard like this, a definition is needed with the same public attitude, perception, and understanding of uncertainty towards risk (Bell and Tobin, 2007). A definition like a the 100-year flood standard can give the perception that areas, which are not situated inside the 100-year hazard area, are risk free , which can encourage people to settle in this perceived risk free area and to decide not taking an insurance. Also, people have in most cases no idea about the uncertainties involved with this standard. In order to achieve an effective implementation, flood risk communication is important to avoid ambiguous perception of a flood policy.

PASSIVE APPROACH

In contrast with the aforementioned pro-active approach of the Netherlands, a government could also chose to follow a more passive approach in flood risk policy. Such a policy acts as a result of a flood event by restoring the damaged protection measures, but does not adequately anticipate on the occurrence of a new event.

This approach arises from the perception that the occurrence of a disaster event is inevitable and protection against such an event shall not prevent it from happening. An example of a government which follows this approach is the United States. This results in no uniform flood-control policy in the whole country, but leave it up local community policy to decide upon a flood-control policy. Vulnerability of this approach was concluded after analyzing the storm surge induced by the hurricane Katrina in New Orleans in 2005. First, the system of levees and floodwalls in place was not an integrated, coordinated, and well-maintained system. Second, flood protection strategy in at-risk areas such as New Orleans must be based on an integrated risk-based system that rejects the expectation that complete structural protection against extreme events is possible (Tarlock, 2012). In the last couple of years, Federal Governments expenses on flood-control projects are limited and local projects are generally initiated by local communities. But the lack of government controlled national flood projects also results in communities shifting flood risk to upstream or downstream communities (Tarlock, 2012). Implementing this approach in America is also the result of the perception of the so-called ' safe development paradox'. The safe development paradox, or land use management paradox is the perception that making hazardous areas safer by taking flood-control measures resulting urban encroachment in this areas, which in fact substantially increases the potential economic losses (Burby and French, 2007). While much skepticism exist about the effectiveness of this approach, time will learn the appropriateness of this.

C
Details Thai Flood 2011

River characteristics and causes of the flood

The Chao Phraya River Basin has a length of approximately 700 km, and flows from the top of Thailand downwards until it debouched in the Gulf of Thailand. The basin can be divided into two parts, the upper watershed and the lower watershed. The upper watershed is a conjuncture of four rivers flowing down out of the mountains. For purposes of irrigation and power generation, two big dams are constructed, namely the Bhumibol Dam and the Sirikit Dam (Komori *et al.*, 2012). In the lower watershed, the Chao Phraya Dam is located, which controls the discharge of the river and the dams serve as storage in case of flooding. The slope of the lower water shed is more gently and extensively used for agriculture purposes out of history. Floods are a natural phenomenon in the lower Chao Phraya River Basin and the local populations has historically adapted their lifestyle to those repeating events. Those returning flood events are normally the result of monsoon rainfall in the upper watershed and during a long period of rainfall at the end of the year. Due to the gentle slope, water rises quite slowly and peak discharges from these events occur after several days (DHI, 2011). Therefore flood events seldom results in loss of lives. What makes this event a devastating flood event was a mix of natural causes and man-made mistakes. *1) The highest recorded rainfall together with five consecutive tropical storms*: The first half year 2011 was already a wet season for Thailand in contrast with normal conditions. Moreover, from the end of June to the beginning of October, five tropical storms contributed to heavy rain in the Northern and Central part of Thailand, which resulted in extremely high accumulated rainfall since the beginning of the year. Also, several flash floods were reported in the Northern part (Worldbank, 2012). *2) Water runoff from major rivers exceeded the river capacity*: The four rivers in the upstream part, the Ping, Wang, Yom and Nan rivers all drained their runoff in the Chao Phraya rivers. Next to that, the Bhumibol and Sirikit dams began to discharge water as the dam reservoirs could not manage the level of water that was building up (AON-Benfield, 2012). This resulted in overflow of the river banks and flooding of the flood plains. The main cause of the flooding was the low flow capacity of the river, which resulted in overtopping of river dikes and breaches in many river arms (Poapongsakorn and Meethom, 2012). Especially in Bangkok, located at the downstream part of the river, the high discharges in combination with proceeding rain, caused exceeding of the city's drainage network. *3: Rapid urbanization and unsuitable land use in the flood plain areas*: Over the past decades, rapid urbanization in especially Bangkok. Next to that, wrong land-use management resulted in expansion of cities and industrial location on flood plain areas. Except for Bangkok, no land use zoning is used in any of the provinces (Poapongsakorn and Meethom, 2012). Therefore, in these provinces development of housing and industrial estates were allowed in the flood prone areas, also because land prices were the lowest in these places. However, in Bangkok where restrictions of land zoning were established, the law was changed to serve business development and flood plain areas were changed so it could be used as building site. *4) Man-made mistakes*: Skepticism exist around the political intervention and executing of the right management during the flood event. The mismanagement includes; weakness of operations and intervention in reservoirs and dams, ageing structures and delayed maintenance, lack of flood forecasting and early warning systems and lack of emergency management (Poapongsakorn and Meethom, 2012). A main reason for overflow and major flooding of some areas was due to breaches and failures of many flood protection structures, which was for some

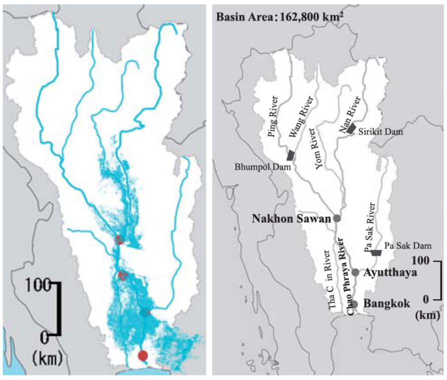


Figure C.1: At the right an overview of the Chao Phraya River basin with location of dams and on the left the inundation situation on October 18, 2011 (Komori *et al.*, 2012) cases caused by the lack of maintenance. Another argument that claims the mismanagement is the operation of the dams, because too much water was retained behind the dam and after release of this, huge discharges reached the downstream part. The responsible minister acknowledged that this decision to delay the water release was with hindsight not the best possible decision, however predicting the late season storms was difficult (Meehan, 2012). Also the lack of emergency management was due to coordination problems between central government and local governments. It was claimed that the central governments reacted to slow and actions to divert the river into other rivers and canals had a counterproductive effect.

Insurance

Since flood events are commonly occurring in Thailand, insurance is an important tool that can positively influence the recovery of a country like Thailand. As a response to the 2011 flood event, the government set up the National Catastrophe Insurance Fund (NCIF) to provide flood insurances, because private insurance was already possible but these insurers suffered from the many events and were not able to cover the full damages (Nabangchang *et al.*, 2014). Before this flood event, only around 17% of the households in the most vulnerable areas had insurance, and it is interesting to look how this changed after this event and after introduction of the NCIF. It is therefore also important to look how the different households were compensated by the government after this event, and how they perceive the risk of occurrence of a future event. Because this event was a national recognized natural disaster, all affected household were entitled some form of compensation of the damages from the central government. Households in areas that were officially declared as flooded got 5000 Baht. Next to that, household were entitled with compensation up to 30000 Baht depending on the list of damages and pictures they sent with it. The 5000 Baht were provided rather fast in contrast with the additional compensation that was time consuming and limited, because the available resources were limited. A research of Nabangchang *et al.* (2014) suggests that especially the middle income and higher income households were affected the most in terms of damages and refunded money. This same research showed that less people than expected were interested in buying insurance after the event considering that flood insurance coverage would have resulted in a higher compensation than the compensation they got. Despite this, a large majority expect that an event like this will happen again. Concrete conclusions can not be drawn upon this, but some assumption can be made about the perception of the people towards flooding. This can be partly verified with the evacuation rates that were low. Especially the lower income household stayed behind. This was not because they had no time, because the duration of the flood was several days, but more likely because they perceived themselves not being at risk or were not aware enough about the size of the risk.

D
Results Thailand flood event

Return period	Residential	Commercial	Agriculture	Industry	Nodata	Total
10	€ 303,360,780	€ 200,679,600	€ 28,519	€ 109,777,440	€ 4,702,263,564	€ 5,316,109,903
25	€ 426,748,384	€ 310,097,040	€ 44,702	€ 150,409,320	€ 7,091,763,140	€ 7,979,062,586
50	€ 543,582,544	€ 404,483,520	€ 58,450	€ 181,490,280	€ 9,059,875,972	€ 10,189,490,766
100	€ 665,425,020	€ 485,660,640	€ 73,392	€ 205,608,120	€ 11,193,957,008	€ 12,550,724,180
500	€ 958,611,536	€ 656,052,000	€ 104,572	€ 258,533,760	€ 15,985,303,624	€ 17,858,605,492

Figure D.1: Result of the damage distribution in euros calculated for the 2011 flood event for different return periods

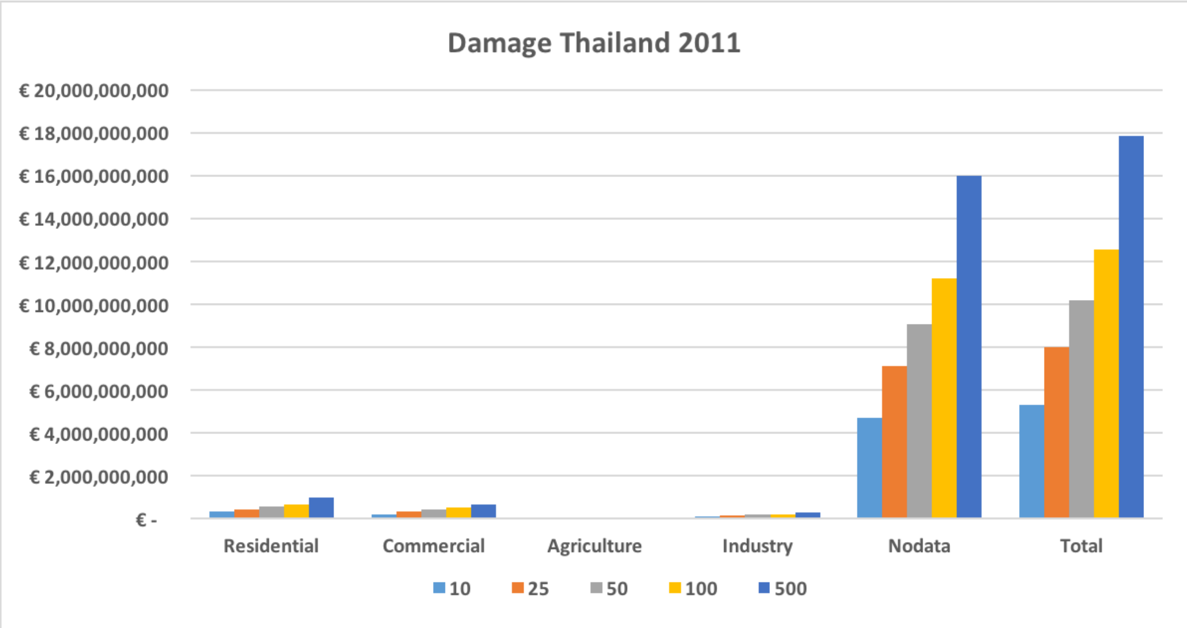


Figure D.2: Result of figure D.1 shown graphically

E

RESULTS RISK INDICATORS GERMAN CITIES

Name	Household	Population	Total (€/y)	Ind. Risk(Fat/y)	Ind.Risk(/t)	Risk/househ(€/y)	%agr	%comm	%indu	%infra	%resid
Berlin	1.7	3420768	22765126	324.1	9.5E-05	11.31	0.10%	7.90%	10.30%	2.60%	79.00%
Hamburg	1.8	1734830	135554352	2607.6	1.5E-03	140.65	0.07%	8.70%	17.30%	2.30%	71.70%
Mnchen	1.8	1311573	9803861	181.5	1.4E-04	13.45	0.07%	4.10%	3.40%	2.60%	89.90%
Kln	1.9	995397	27739074	268.9	2.7E-04	52.95	0.23%	8.00%	12.70%	2.00%	77.00%
Frankfurt	1.9	659021	42820036	1009.7	1.5E-03	123.45	0.13%	8.60%	13.00%	2.50%	75.80%
Stuttgart	1.9	591000	3585859	35.0	5.9E-05	11.53	0.12%	11.30%	20.30%	2.70%	65.60%
Dsseldorf	1.8	585054	14879942	223.6	3.8E-04	45.78	0.21%	2.40%	3.70%	1.40%	92.30%
Essen	1.9	580751	5145130	40.2	6.9E-05	16.83	0.11%	18.90%	25.30%	1.70%	54.00%
Bremen	1.8	545932	53288140	1137.4	2.1E-03	175.7	0.13%	6.10%	10.20%	2.40%	81.10%
Hannover	1.8	515841	3832987	45.5	8.8E-05	13.38	0.49%	0.00%	0.00%	1.20%	98.30%
Dresden	1.8	507513	28203448	470.8	9.3E-04	100.03	0.13%	4.00%	6.60%	1.50%	87.70%
Duisburg	2	504403	36837132	553.3	1.1E-03	146.06	0.15%	7.50%	20.70%	2.20%	69.50%
Nrnberg	1.9	503110	13651433	105.0	2.1E-04	51.55	0.40%	3.20%	4.30%	1.50%	90.60%
Leipzig	1.8	498491	839863	4.2	8.5E-06	3.03	0.06%	0.60%	0.00%	1.90%	97.40%
Bochum	2	388179	933116	8.7	2.2E-05	4.81	0.57%	31.70%	42.10%	2.00%	23.60%
Bonn	2	316416	46499264	1216.2	3.8E-03	293.91	0.05%	5.40%	7.30%	1.30%	85.90%
Mannheim	2	307640	38913308	817.9	2.7E-03	252.98	0.15%	6.80%	15.50%	3.00%	74.50%
Karlsruhe	2	283959	10341846	41.0	1.4E-04	72.84	0.06%	22.50%	29.90%	2.00%	45.50%
Strasbourg	2	272700	10684121	188.4	6.9E-04	78.36	0.07%	7.60%	11.20%	1.60%	79.50%
Gelsenkirchen	2	270107	802269	4.0	1.5E-05	5.94	0.07%	0.20%	0.30%	1.80%	97.60%
Augsburg	2	262368	11500154	243.1	9.3E-04	87.66	0.08%	11.10%	14.70%	1.40%	72.70%
Braunschweig	2	245872	659970	7.1	2.9E-05	5.37	0.04%	12.30%	14.70%	2.80%	70.20%
Krefeld	2	238270	669524	6.6	2.8E-05	5.62	0.79%	31.50%	41.90%	2.30%	23.40%
Magdeburg	2	230140	10291310	211.4	9.2E-04	89.44	0.08%	8.10%	11.60%	1.80%	78.40%
Lbeck	2	212095	1940563	6.0	2.8E-05	18.30	0.18%	12.30%	24.90%	3.30%	59.30%
Erfurt	2	202450	3762736	59.2	2.9E-04	37.17	0.06%	5.00%	5.50%	1.70%	87.80%
Rostock	2	200500	483033	8.1	4.1E-05	4.82	0.66%	30.90%	43.00%	2.50%	23.00%

Figure E.1: Result of the risk indicators for the top 25 cities by population in Germany

F

DETAILS 2013 FLOOD GERMANY

DETAILS OF THE EVENT

As mentioned before, one of the reasons of the flood event was the wet period in May earlier in the year 2013. Due to meteorological conditions, several low pressure systems reached the catchment areas of central Europe and induced an long period of intense rainfall. The month May 2013 was the second wettest May since 1881 and showed 180% of the long term monthly mean precipitation (CEDIM, 2013). Next to the heavy rain in May, lower than average air temperatures hindered the evaporation of the rain of the soil surface. This combination of events in May led to extreme soil moisture, which can easily generate fast and high runoff. However, the most intense rainfall occurred between 31 May and 4 June, which can be characterized by a large spatial extent covering most parts of the Danube and Elbe catchments (Merz *et al.*, 2014). Germany has a extensive system of gauge stations that can measure the water levels along the rivers. Looking at these measurements, an indication of the return periods of this event could be made. In figure F.1, the return periods are subdivided in four domains ; >100, 100-50, 50-10, <5 years. It can be concluded, that especially the upstream areas have observed the high flood level of over 100 years. As a result of these extreme water levels, several embankments were unable to withstand the floodwater resulting in dike breaches and inundation of the hinterland (Thieken *et al.*, 2016). During the whole event, more than 52000 people had to be evacuated throughout Germany, which was a major event on its own. Next to damages to houses, especially a lot of agricultural land and industrial locations of large car manufactures were inundated and production of these manufactures stopped after the flooding. What is interesting about this flooding is to compare it with another major flood event that struck Germany, namely the 2002 flood event in almost the same catchment areas. This flood event was more worst in damages, however less severe in water levels measured in the same gauge stations. This event was a wake up call that flood management needs to be changed in Germany and in the whole catchment area. It is therefore assumed that improvements in flood management since 2002 have prevented higher damage, but this can off course not be proven or further investigation is needed.

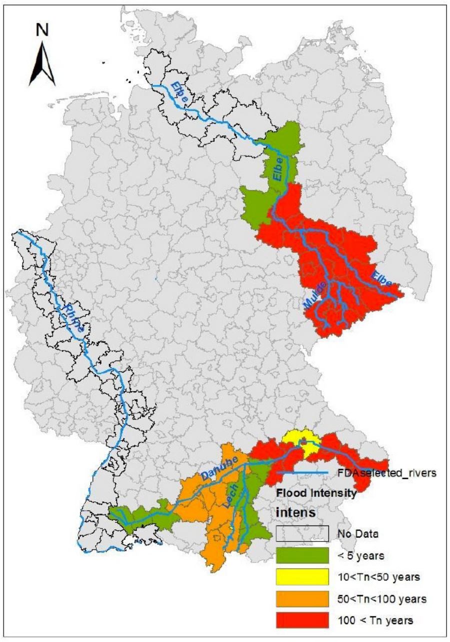


Figure F.1: The observed return periods from the gauge station in states of Germany during the period of 31 May and 7 June 2013 (CEDIM, 2013)

INSURANCE

With two major flood events in the 21 century in Germany, it is important to look how Germany have recovered from this by looking at the role of insurance. Evaluation of this is also important for a potential future event. Insurance is a big issue in Germany, for instance in the 2002 flood, only 15 percent of the damages was covered by insurance. Nowadays, the reported insurance penetration for natural hazards is only 35 percent, where this number is even lower in the most hazardous areas (PERC, 2014). Because of the low insurance penetration, the government established a national flood fund of €8 billion to cover most of the insured losses and the rebuilt the damaged infrastructure. This low coverage ratio gives also an indication that the German people consider themselves not being at risk, or underestimates the risks they are dealing with. There is some discussion around about the effectiveness of the German insurance policy, particularly a change to a different structure is being discussed that eventually could result in a higher cover ratio of insurances. In Germany, people can insure themselves for flood damages by taking a insurance from a private insurance company. This is optional insurance next to the normal building insurance and does not only cover flooding, but includes natural disasters as a whole meaning the risks of flooding, earthquakes, land subsidence, landslide and avalanches. However, not all damages are being refunded to a certain extent depending on the exposure location of the households, divided in four zones. The majority of the properties are located in zone 1 (with probability of flooding lower than 1/200 years) means that they are considered insurable. The other extreme are properties located in zone 4 (probability of flooding of 1/10 years) and these properties are considered uninsurable (Seifert *et al.*, 2013). Several surveys and researches are done over the last years in Germany and the research of Seifert *et al.* (2013) combined these researches with his own study and concluded some characteristics of the German inhabitant towards insurance and risk perception. This research showed that risk perception in Germany is substantially higher than in a country as the Netherlands, which was the comparison in this study. More than 50% of German people perceived themselves at high or very high risk, and especially those people were willing to pay for insurance. This high percentage was also the result of the fact the many German people had experienced one or more severe flood events in their life. Therefore, why the coverage rate of insurance of natural disasters is so low is not clear, but it could be possible that people rely on the expectation of compensation from the government in case of a new event and therefore restrained in taking private insurance for their properties.

Decentralized decision making

In Germany, flood management plans are realized by the German States for their state, because Germany has a decentralized decision making policy for flood risk management. This means that the central government sets out the legal framework for all issues, but the detailed provisions are under authority of the states (Muller, 2013). This decentralized structure can have advantages, but a disadvantage could be that differences exist in the implementation of the measures between states, and the rivers do not take state boundaries into account.

Early flood warning is an important measure for a successful evacuation of people and mitigating the damages of a possible flood event. After the 2002 the German government realized how important this could be, because in 2002 27% of the people and 45 % of the companies did not get early warning of the flood event. In 2013, after some improvements in early warning systems, this number decreased to both 7% for people and companies (Kreibich *et al.*, 2016). This was not only because of the improvements, but also because the 2013 event was spread out over several days. Therefore a closer look is needed to objectively compare both events and find out if the expected increase in effectiveness in reached. Kreibich *et al.* (2016) studied this particular development and concluded that indeed the warnings received and emergency measures undertaken in 2013 showed an improvement compared with the 2002 flood event. However, there is enough space for further improvement when it comes down to this. For instance, the percentage of companies having an emergency plan in place has increased from 10% in 2002 to 26% in 2013, but this is off course not an impressive share. These emergency plans made it able for these companies to protect their valuable equipment and for instance to place sandbags in front of their property or the deployment of pumps to help mitigate the damages.