Flood Safety in Delta Cities

Development of a comprehensive risk-based model to support decision making on measures against pluvial, riverine and coastal flooding in urban area, with the application to Hoboken, New Jersey

Defne Osmanoglou
MSc graduation thesis
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Author:

Defne Osmanoglou
MSc graduation thesis
Faculty of Civil Engineering and Geosciences
Department of Hydraulic Engineering
Delft University of Technology
Student number: 1354264
Royal HaskoningDHV
The Netherlands
March, 2015

Graduation committee:

Prof.dr.ir. M. Kok (supervisor)	Faculty of Civil Engineering, TU Delft
Ir. B.J.T. van der Spek (daily mentor)	Royal HaskoningDHV
Dr.ir. M. van Ledden	Faculty of Civil Engineering, TU Delft
Ir. A.L. Nillesen	Faculty of Architecture, TU Delft

Photo on title page: View on Hoboken and the Hudson River (Marchetto, 2014)

General note to the reader:

Each MSc track of the Faculty of Civil Engineering at the Delft University of Technology culminates in a graduation project: the 'thesis project'. This is an individual project in which the student must demonstrate that he or she is capable of solving an engineering problem independently and at a suitably academic level. This graduation project is in the field of Hydraulic Structures and Flood Risk (Hydraulic Engineering) and is done in cooperation with engineering consultancy Royal HaskoningDHV. The graduation project caries a value of 40 ECTS credits.

After the storm-attack of Hurricane Sandy in October 2012 at the East Coast of the United States, President Obama's government responded in a plan to rebuild Sandy-affected areas by making the region stronger and better protected against floods. The new Rebuilding Strategy that was introduced by 'President Obama's Hurricane Sandy Rebuilding Task Force' in 2012 is chaired by the secretary of Housing and Urban Development (HUD) and focusses on helping Sandy-affected regions to rebuild and making them more resilient. One of the recommendations of the strategy was to set up a design competition: the Rebuild by Design competition. One of the teams involved in the Rebuild by Design competition is the OMA team. The OMA team consists of OMA (architects and urban designers), Royal HaskoningDHV (water management and engineering expertise), Balmori (landscape and land-use planning experience), HR&A (economic understanding) and 2x4 (digital know-how).
"The OMA team presents a '*comprehensive flood defence strategy*' for the City of Hoboken, New Jersey. A combination of political, ecological, and economic factors are considered to create a comprehensive flood strategy – resist, delay, store, discharge – that defends the city and assists in commercial, civic, and recreational amenities to take shape" (OMA, 2014). This graduation thesis further elaborates on this strategy.

"While coming into being for the sake of living, the city exists for the sake of living well."

-Aristotle

From *The Nature of Urban Design* - Alexander Washburn

Preface

For a school project in grammar school on my thirteenth, I interviewed Mr. Van der Weele, the grandfather of a very close childhood friend. The project was about the 'Watersnoodramp van 1953', the flood in Zeeland in the Netherlands. (At that time we recorded the interview on cassettes, and I still have this cassette.) Before that time I never realized the meaning of words like *uiterwaarden* and *dijkdoorbraken*. His stories were impressive, but very sad because many people lost their lives during the night of January 31, 1953. Mr. Van der Weele was only 19 years old during this flood and his family lived in Brouwershaven. He remembered that there was a storm, but that was normal for that time of the year; there was also spring tide, neither was anything strange about that. That's why not only Mr. Van der Weele's family, but all the villagers went to sleep that Saturday night as they were used to do so. But that night the water got higher and higher and when everybody awoke, it was too late. The water overflowed the sea dikes and the inland dikes and immense flood waves rolled into the polders. Mr. Van der Weele survived the flood but he was in suspense all the time because he couldn't reach his fiancée, living in Bruinisse, due to broken telephone connections. Luckily all ends well for him, but because the broken lines it takes days before in the rest of the country everybody gets informed of the drama that took place in Zeeland. I would like to thank Mr. Van der Weele for his story which made me realize the meaning of this flood.

When people would tell me at that time, that twelve years later I would go to New York, to consider possible flood protection in the New York area, by using Dutch water knowledge, gained from the best teachers at Delft University of Technology, I would have never believed it. At that age, I dreamed of becoming an architect, or a lawyer.

Neither would I ever have believed that I would walk among prominent engineers and architects from all over the world in a skyscraper in Manhattan with beautiful views on the Hudson River during the Rebuild by Design competition for protecting the New York area against floods. But so did happen, and this graduation thesis is the result of a year of intensive work on flood protection in Hoboken, New Jersey, a project which has been carried out by Royal HaskoningDHV. With this thesis I conclude my Master of Science of Hydraulic Engineering at Delft University of Technology.

The team behind this graduation thesis includes most of all the professionals of Delft and Royal HaskoningDHV, my graduation committee, who I would like to thank for their knowledge, guidance, concern and support. I am grateful to Professor Matthijs Kok for his personal involvement during the project. He encouraged me with his positivism and he stimulated me to see not only the details of the model which I developed, but also to think about the relevance of my model in the context of flood risk assessment. I am thankful to Bart-Jan van der Spek, who is a friend, but also my daily supervisor, for his enthusiasm and support during my project. He continually shared his knowledge, especially about modeling and statistics. I am thankful to Mathijs van Ledden for his input and encouragements. He did not only accompany me during my trip to New York, but he also kept accompanying me academically by his positive criticism by building up this thesis. Together with Bart-Jan he kept challenging me to investigate thoroughly and achieve the best I can. I am grateful to Anne Loes Nillesen for sharing her views on flood protection issues in urban environments. She stimulated me to think over the frontiers of hydraulic engineering and she freshened my interest in architecture. I thank Marten Hillen and Nanco Dolman for involving me in the Rebuild by Design competition and sharing their knowledge about Hoboken. I am thankful to Caleb Stratton and Stephen Marks of the City of Hoboken for showing me around in Hoboken. I want to thank my colleagues and the graduate students at Royal HaskoningDHV for their assistance and the nice time at the office. I thank both Tim and Derrick for taking their time to discuss subjects in my graduation work. I thank all my friends for the joyful moments and mental support during my graduation project. I had a great time!

However, above all I want to thank my mother, father, brother and Jan, who all supported me during this period in which I worked intensively. I want to thank Jan for his trust, his help with my graduation works, and most of all for his endless patience and encouragements. I would like to thank my brother for his bright advices and listening. I am grateful to my parents for their always loving support and care. Thanks to them I was able to reach this milestone in my life.

Defne Osmanoglou
Delft, March 2015

Summary

Flood safety in low-lying delta regions has been a challenge of all ages. Societies worldwide have been trying to protect themselves against flood hazards for centuries. Floods in vulnerable urban regions are often caused by heavy rainfall, high river flow, extreme sea levels, or combinations of those three. Currently, there is a lack of tools and experience in assessing the effects of combined pluvial, riverine and coastal flood risk reduction measures for delta cities. The objective of this study is to develop a comprehensive risk-based model, which supports decision making in delta cities on measures against pluvial, riverine and coastal floods.

An idealized hydrologic model has been developed to evaluate flood extent and frequency due to combination of these three factors in urban environments. The model quantifies pluvial, riverine and coastal flooding and identifies the contribution of different weather events to floods in a delta city. The city is schematized by a typical lay-out, in which different elements of a city's flood protection system are connected. The city was drafted as a storage basin with varying areal sections as a function of the city's elevation levels; incoming and outgoing water fluxes; and different strengths of flood protection elements, including waterfront resistance, discharge capacity and storage capacity. By calculating the hydrological budget of water, flood levels in the city can be computed as a function of precipitation and water levels in time. The computed flood levels are coupled with stage-damage relationships to define the direct economic damages. By comparing the economic damage and the investment costs, an optimal mix of measures (river flood defences, water pumps, storage areas) can be defined. The model serves as a practical tool that can be used in the search for an optimal combination of flood risk reduction measures.

This study has adopted the City of Hoboken in New Jersey (United States) as a case study to apply the idealized risk model. Because of Hoboken's history as an island, the low-lying area inundates when water levels in the Hudson River increase due to storm surges. In combination with severe rainfall, the impermeable surface and a lack of drainage, floods also occur during high rainfall events, especially when the excess water cannot be drained into the river. The consequences of a flood can be very large because of Hoboken's economic valuable character and central location. Flood levels were computed as a function of historical observations of precipitation and river water levels. The simulations prove that the model gives a first realistic quantification of the contribution, scale and frequency of historical flood events in Hoboken. Floods due to pluvial events were observed more often than coastal flood events, as rainfall events exceeded the capacity of water management system more frequent than high water levels occurred. However, flood extents due to coastal events were much larger.

As Hoboken flooded frequently in the past and *Hobokenites* desire safe living environments, it has been investigated if flood risk reduction measures are interesting for the City of Hoboken. Synthetic time series of precipitation and water levels of 1,000 years were created by means of extreme value analysis of historical observations, in order to investigate extreme flood levels in Hoboken. As a result the computed flood events over 1,000 years give insight in the expected frequency and magnitude of pluvial and coastal floods in the area. Floods have been defined as inland water levels higher than one 2.5 cm uniformly spread over the total area of the city. The calculated flood levels are considered as mean water depths in the corresponding areal section of the basin and are dependent on the incoming and outgoing fluxes. In reality, locally much higher flood depths could occur, as routing due to urbanization and varying elevation levels, are not included in the model.

For the time interval of 1,000 years, it was found that in Hoboken pluvial events resulted in maximum flood levels of 0.27 meter and that approximately 96% of the flood events can be contributed to pluvial flooding. This means that flooding in Hoboken can occur every year due to pluvial events and the current safety level of the water management system is approximately 1 year. 4% of the flood events were due to coastal flooding and had maximum values of 1.72 meter. This means that the current safety level of the waterfront protection is approximately 23 years. The flood risk level of the current situation in Hoboken has been determined and expressed in terms of expected value of economic loss. For this purpose a damage assessment was completed in which flood characteristics, information on land use and economic data and stage-damage functions have been studied. The present value of risk for the current situation in Hoboken over the entire future converges to $ 817 million. It can be concluded that 66% of the flood damage in the current situation is caused by pluvial

events and 34% of the damage by coastal events. The results show that the consequences of coastal floods are much larger, but the higher frequency of the pluvial – much smaller – floods results in more expected flood risk for the future.

Following the integrated water management strategy from team OMA of Rebuild by Design, different combinations of flood risk reduction measures were included by the model: *Resist* for waterfront protection; *Store* for increasing storage capacity within the city; and *Discharge* for increasing discharge capacity. For every combination the reduced flood risk, compared to the current situation of the city, has been calculated. The sum of the investment costs and the expected damage or risk, are the total costs for the combination of the system. The investment costs of each combination have been balanced with its corresponding benefit (i.e. risk reduction). In this study the economic optimum is defined as the combination with the lowest total costs.

For the optimal combination of Hoboken the waterfront defence has been exceeded two times in 1,000 years, which means that the coastal flood protection of the system has a new safety level of 500 years. The pluvial safety level has been upgraded towards a safety level of 25 years. This means that the total safety level of the optimal system is 25 years. In practice for *Resist* this means that flood defences at the Weehawken Cove and Hoboken Station waterfront are constructed, with a total of 3.5 km in length and increased elevation levels to 3 m + NAVD88. For the internal water management system it means 25,000 m^3 of green infrastructure in the City (*Store*) and a total pumping capacity of 100,000 m^3/h (*Discharge*), which equals building 12 more pumps like the current water pump in Hoboken. For the optimal combination, the present value of the risk is $363 million and the investment costs are $232 million. This corresponds to a flood risk reduction of $686 million compared to the current situation. The cost-benefit ratio of this solution is reasonable in terms of constructing flood infrastructure in the United States.

For Hoboken the elements for computing the present value of the risk and investment costs in this study were a preliminary estimation. Recommended areas for further improvement of the model are: uncertainty and sensitivity analyses for improving robustness of the model; a study to the dependency of input variables and system elements; and investigation to the effects of correlated surges and precipitation on the model results. Despite its assumptions and limitations, the model functions as a convenient tool which gives first-order insight in flood extent and an optimal mixture of flood risk reduction measures in a delta city. It can quickly identify the different flood events and it can quantify their frequencies and scales. For this matter it offers realistic insight in the rates between pluvial, riverine and coastal flooding. It can be concluded that the recommended types of flood risk measures give a useful impression of the frequency and scale of flood issues and required flood protection elements (pluvial, riverine, coastal and/or combinations) within the city. In short, the presented comprehensive flood risk model in this study is an effective and efficient tool for urban planners, decision makers of cities and engineering companies as they can estimate pluvial, riverine and coastal types of flood risk reduction measures for a delta city.

Contents

1. Introduction

Societies across the planet have been dealing with floods for centuries. Since the beginning of civilization, human beings are trying to protect themselves against flood hazards (Jonkman, 2007). From more primitive methods like building houses on stilts to impressive flood defenses like the storm surge barriers of the Delta Works in the Netherlands and Lake Borgne Surge Barrier in the Mississippi River in New Orleans; flood safety is an issue of all ages. In this study the effects of pluvial, riverine, coastal and combined events and different types of flood risk reduction measures on flood safety in urban environments are investigated.
The context of the study is described in this introducing chapter. The main problem, objective and research question are defined and it is explained how the issues are tackled in this research proposal.

1.1 Context

Nowadays, more than half of the world population lives in cities, especially coastal cities (Bosboom, et al., 2013). As coastal zones are expanding and their economic values are growing, the consequences of flood hazards in these regions are continually growing. It is expected that coastal cities are exposed to rising sea levels, increasing frequency, intensity and duration of heavy rainfall events and extreme water levels due to storm events. In combination with land subsidence, vulnerability of cities will increase further in the future (Aerts, et al., 2012).
Due to the intensifying usage of coastal zones and the concerns for climate change, people are getting more aware of the increasing risk of floods. Societies in developed cities aim to guarantee flood safety, while they also desire pleasant living standards and working environments. As flood risk reduction measures frequently have high investment costs, the level of protection against floods is mainly a matter of political choice. This choice is the basis for a risk-based design, in which flood risk reduction measures are usually expressed in terms of risk and acceptable probability of failure (Vrijling, et al., 1998). *Risk* may be defined as “a function of the probabilities and consequences of a set of undesired events” (Jonkman, 2007) or more general as *probability x consequence* of failure of a system, in which the probability of an event is often expressed as the probability of an event per unit of time. Failure of a system can be described in terms of *loads* and *strengths*: when the *strength* of the system is exceeded by *loads*, failure of the system will occur.

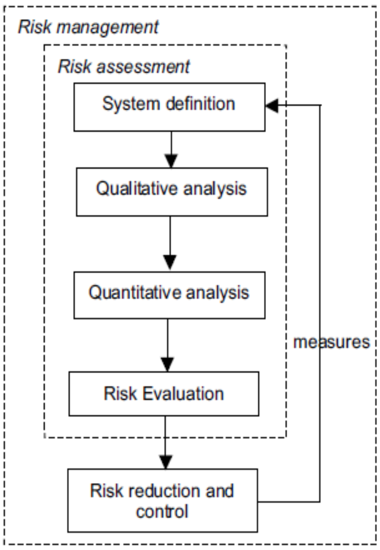


Figure 1 Risk management and risk assessment (Jonkman, 2007)

In projects, a *risk assessment* may support decisions about required safety levels of systems. It is about the identification, quantification and evaluation of risks within a given system. If a flood protection system for a city is considered, risk assessment may be applied to choose for instance the required height of a flood defence, by investigating probabilities and consequences of floods in the area that has to be protected. If the flood risk in the region turns out to be too high for accepted standards, decisions can be made about measures to reduce the risk, in order to achieve the required safety level in the future (Jonkman, 2007). Based on a comparison of flood risk and investment costs for the lifetime of the structure, an economical attractive decision can be made.

1.2 Problem description

Floods in vulnerable urban regions are often caused by precipitation, river flow, high sea levels, or any combination of those three. This may be due to extreme weather events when heavy rainfall takes place and water levels in riverine or coastal waters increase. Precipitation may cause problems when waterways or drainage systems do not have the capacity to discharge the water and when the excess water cannot be stored. High water levels in coastal and riverine waters may result in inundation of large parts of land when they exceed the height of flood defences. These pluvial, riverine or coastal floods may have high economic and social consequences.

When precipitation falls during a period of high water in the adjacent river or at the coast, consequences may be even larger. The coincidence of high water and rainfall may also be the reason of a flood. This was the case in Jakarta in 2013, when large regions were flooded because high water levels restricted the drainage of excess water, caused by heavy rainfall, to open waters. In the Netherlands urban floods are generally a result of hydrological extremes due to a combination of anomalous conditions: storm surges prevent the ability to discharge water to the open sea, and local precipitation generates excessive water levels in the inland area, as happened in January 2012 (van den Hurk, et al., 2015).

Hoboken, a small densely populated city right across the Hudson River from Manhattan (New York), also floods frequently because of this problem. When high rainfall events occur during high tide, the city cannot drain on open water. In some cases, the inflow exceeds the available storage in the city's water housing system, resulting in flooded streets. However during Hurricane Sandy in 2012, eighty percent of Hoboken was flooded due to coastal flooding, because storm surge increased water levels in the adjacent Hudson River to a much higher level than the waterfront. Consequently the city was inundated and suffered loss was estimated between $300 million and $750 million (OMA, 2014).

Figure 2 Historical boardwalks in Hoboken (City of Hoboken, 2013); bird view Hoboken and Hudson River (Marchetto, 2014); Hurricane Sandy Hoboken, 2012 (Photo copyright: observer.com)

Many rainfall, river discharge and tide events do not result in flooding when they occur as an individual event. However, in some cases a combination of events does lead to an extreme load or impact on the city's drainage system. This is called a compounding event (Seneviratne, et al., 2012). Not only a combination of meteorological circumstances, such as the coincidence of precipitation and storm surge, may lead to an extreme event, but also the combination of meteorological and non-meteorological circumstances may increase the impact of an event. For instance when a flooded region has a highly dense population, consequences of the event may be larger.

Large consequences of weather extremes challenge the adaption to climate conditions. Since the magnitude of the impact is often a combination of causes, it is important that the contribution of compounding conditions is considered in the analysis of flood risk reduction measures (van den Hurk,

et al., 2015). However, in the design of flood protection systems, the coincidence of precipitation and high water levels is rarely investigated and pluvial, riverine and coastal flood risk reduction measures are often designed separately (e.g. (Miller, 2011), (Jonkman, 2007)). Where pluvial floods may be answered by increasing drainage capacity and storage areas, flood barriers are frequently a solution for riverine and coastal floods.
The question arises whether it is attractive to design flood risk reduction measures in a comprehensive way, by combining the solutions for pluvial, riverine and coastal floods. To answer this question it is necessary to investigate how different weather events contribute to flooding of a city and its consequences. This information will provide parties like urban planners, decision makers of cities and engineering companies insight in different combinations of flood risk reduction measures from a safety and economical point of view. This allows them to design an optimal flood risk reduction strategy, in which both pluvial, riverine as coastal flood measures are integrated.

1.3 Objective and research questions

The objective of this thesis is to develop a risk-based model, which supports decision making in delta cities on measures against pluvial, riverine and coastal floods in a comprehensive way.
The aim is that for a given delta city following questions are answered with the use of model computations:

1. How can flooding and flood risk in urban areas due to pluvial, riverine and coastal events be identified and quantified?

2. What are for a given delta city most effective measures to take to reduce pluvial, riverine and coastal flood risk?

3. Will comprehensive modeling of pluvial, riverine and coastal floods lead to more effective decision recommendations for flood risk reduction measures in urban area?

1.4 Methodology

Currently, an integrated risk model to define the effects of combined weather events and to evaluate the effectiveness of a mix of measures is missing. In this study an idealized model has been developed to assess flood extent and volume due to combination of riverine, pluvial and coastal flooding in urban environments. The model has the aim to simulate pluvial, riverine and coastal flooding and to identify the contribution of different weather events to floods in the city by including combined precipitation and water level events. The model serves as a practical tool that can be used in the search for an optimal combination for flood risk reduction measures.
The optimal choice for flood risk reduction measures, i.e. improving the flood protection system of the city, is supported by a flood risk assessment, as described in section 1.1. The risk assessment is coupled to the model results (flood levels). The approach of (Jonkman, 2007) is followed in this study, in which the flood risk assessment includes a system definition, qualitative analysis, quantitative analysis, risk evaluation and risk reduction analysis. In the system definition and qualitative analysis the considered city and its elements are defined and described. Historical flood hazards and possible flood scenarios due to pluvial, riverine and coastal causes over the last couple of decades will be discussed, simulated and tested, by applying the developed model. *Loads* and *strength* of the region will be determined by analyzing historical data and the characteristics of the region. In the quantitative analysis flood probabilities over a longer future period will be assessed by model computations for the given city. As a result, *probabilities* of extreme flood events can be calculated, which will give insight in the frequency of different types of floods in the area. Furthermore a damage assessment will be done by analyzing the *economic consequences* of floods in the area. By quantifying flood damage in the area, the *risk* of floods can be calculated by multiplying the consequences with corresponding flood probabilities. Consequently the current flood risk level of the city can be determined. Dependent on the outcome of the risk evaluation, measures can be taken to reduce risk and optional measures will

be investigated. It will be determined how the city can invest in flood reduction measures, such that in the lifetime of the recommended measure(s), construction is attractive both from a safety as from an economical point of view. Finally the question is answered whether it is economically attractive to start designing a comprehensive flood design from the early design stage.
The City of Hoboken (United States) has been chosen as a case study area for applying the model and risk assessment and answering the research questions. As mentioned before, Hoboken suffers from pluvial, riverine and coastal floods frequently.

1.5 Outline of report

The research thesis is divided into five chapters in which it is aimed to answer the research questions by following the methodology as described. Chapter 2 and 3 cover the system definition and qualitative analysis of the flood risk assessment that has been applied. First the case study area, Hoboken, its flood protection system and the possible flood hazards are considered in chapter 2. In chapter 3 the principles of the developed model are described and it is explained how flood levels in a given city can be calculated. It is shown how the lay-out of the system within the model and its specific components are determined and computed. Finally it is described how the model is tested and verified and how flooding in Hoboken due to pluvial, riverine and coastal causes may be simulated by using historical data and characteristics of Hoboken.
In chapter 4 the economic flood risk analysis covers the remaining steps of the flood risk assessment. The required safety level against floods in Hoboken is investigated from an economic point of view. For this purpose historical data is analyzed and by means of extreme value analysis, synthetic data is generated to simulate future flooding in Hoboken. Furthermore damage due to flooding is assessed and the current risk level of Hoboken is determined. The chapter concludes by investigating different combinations of flood risk reduction measures and comparing the investment costs of these measures with the risk of each combination.
The thesis ends by concluding the four chapters in chapter 5. The research questions are evaluated in the concluding chapter and it is aimed that the objective is fulfilled for providing insights in supporting decision making in delta cities on measures against pluvial, riverine and coastal floods in a comprehensive way.

2. Case study: Hoboken, New Jersey

Hoboken is a vulnerable city to pluvial, riverine and coastal flooding. Because of its economic valuable character and central location, the consequences of a flood can be very large. This was shown during Hurricane Sandy, when the city was flooded for large parts. In this chapter the characteristics of the City of Hoboken, the flood protection system and the main flooding threats are described.

2.1 Urban environment of Hoboken

Hoboken is a city in Hudson County, New Jersey, United States. The City is part of the New York metropolitan area as it is situated adjacent to Manhattan across the Hudson River. It lies on the west bank of the Hudson River between Weehawken and Jersey City. Although it has the Mile Square City as its nickname, Hoboken actually covers twice as much as space when under-water parts in the river are included. It encloses a total area of 5.3 km^2.

Like other communities of Hudson County, Hoboken consists of urbanized land. It is the fourth densest city in the United States and has a high growth potential: since 2000 the amount of inhabitants increased with 30 percent. In 2010 approximately 50,005 people lived in Hoboken (New Jersey Department of Labor and Workforce Development, 2012). Hoboken is highly vibrant as it has the highest public transportation use in the United States (Vardi, 2011). Around 50,000 people make use of the train terminal, Hoboken terminal, every day. The terminal, owned by New Jersey Transit, Port Authority of New York & New Jersey and Port Authority Trans Hudson, is a major transportation center for the region due to its connection to New York Waterway, three airports and local transportation services.

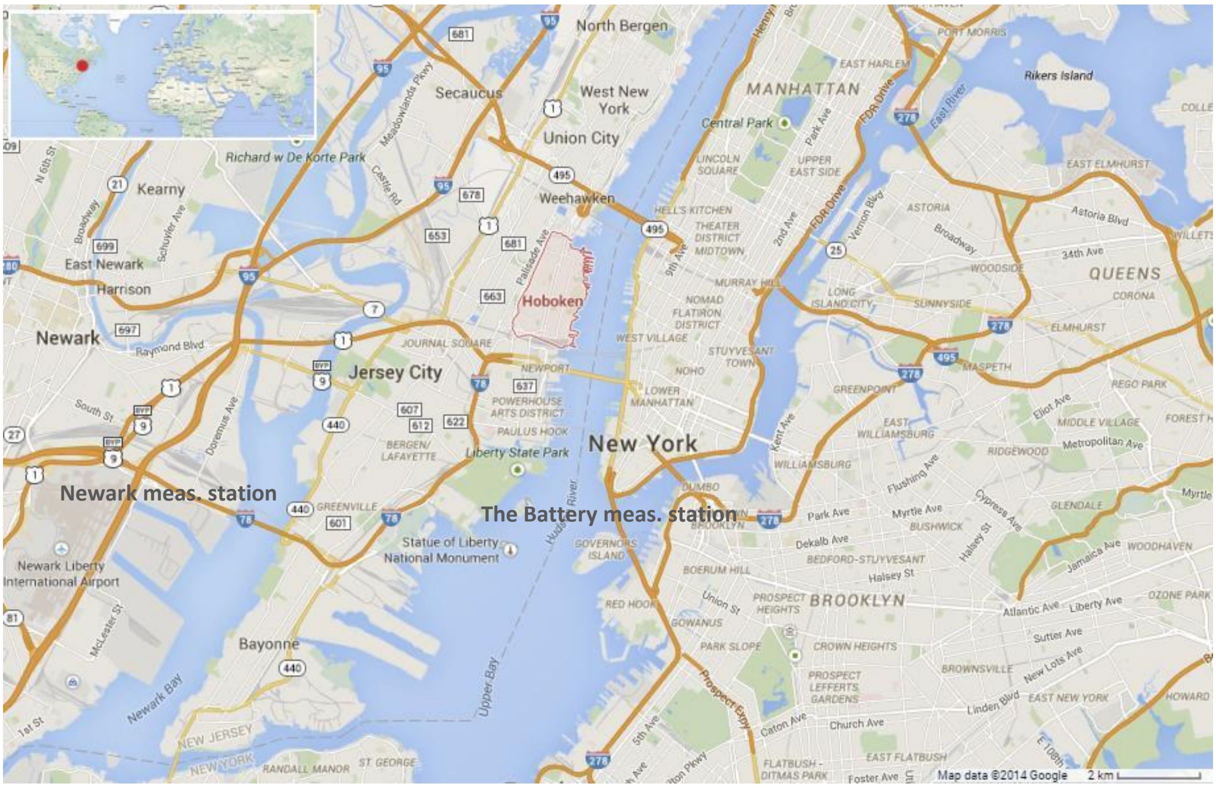


Figure 3 Location Hoboken, New Jersey (Google Maps)

Hoboken was incorporated as a city in 1855, but its growth was already guided by Colonel John Stevens in 1804 (Hoboken Planning Board Master Plan, 2003). The City was in that time planned in an orderly way, which resulted in its unique character, as well as the historic districts of today, still visible in Stevens Institute of Technology, the mansions on Castle Point around the highest point of Hoboken, its neighbourhoods of rowhouses, and the classic design of Washington Street, the main street of the City. The character of Hoboken is enhanced by this rich heritage and historic quality, but the City has experienced a lot of demographic and physical changes ever since the incorporation. This urban development is still ongoing nowadays.
As the population of the City grew intensely during the second half of the Nineteenth Century, its building environment grew with it, and numerous civic buildings, parks, and transportations improvements were constructed, of which large parts are still existing. In the 1950s and 1960s other urban areas were transformed by “urban renewal”, but in Hoboken this only took place on small scale. Most buildings were structurally sound and existing neighbourhoods and buildings throughout Hoboken were stabilized and reused (Hoboken Planning Board Master Plan, 2003). Redevelopment of the City started in the 1970s and lasted until the 1990s. The redevelopment of the last decades resulted in the growth of the population of Hoboken since the 1990s. Hoboken in its original setting was covered by a lot of manufacturing operations, but these moved out of Hoboken during the redevelopment in the mid-Twentieth Century. The containerization of ship cargo along the waterfront resulted in a cycle of disinvestment and population through the 1970s, but nowadays this is seen as an important feature of the City’s character (Hoboken Planning Board Master Plan, 2003).



Figure 4 Bird view (Google Maps); historic character; Stevens Institute of Technology (photos taken by author)

In its essence, Hoboken is nowadays fully developed. The City contains a mix of land uses including residential, commercial, industrial, public and institutional. The City can be divided into five general land-use areas: the terminal area, the business districts, the central city neighbourhoods, the waterfront area and the redevelopment area in the west and northwest (Hoboken Planning Board Master Plan, 2003). The terminal area, in which Hoboken Terminal is located, lies in the southeast corner of the City. It is surrounded by dense primarily commercial area, in which bars and restaurants are concentrated at street level and with offices and residential uses on upper floors.
Furthermore Hoboken has several business districts. The main commercial backbone is Washington Street, which is long and fully developed. There are other commercial concentrations throughout the City and retail clusters located in a few places elsewhere in the City, often remnants larger business districts from the past, as well as some small shopping centres and supermarkets. The businesses are often shared with residential uses on upper floors. This is true for most buildings along Washington Street’s entire length, with some entirely residential buildings in some locations (Figure 5).
A large portion of Hoboken’s land is developed with residential neighbourhoods, especially positioned in the center of the City. As an older urban community, most of these neighbourhoods are not only residential, but mixed with other uses among the rowhouses. Most residents live combined with some types of retail or other service uses. Some areas have a unified character, such as blocks of brownstones, or rows of five story walk-up tenements. Other areas have ranges of heights and building styles in a single block. Traditional Hoboken residential buildings are low- to mid-rise, generally between two and five stories. Many have stoops in front, with a ground floor halfway below grade. The ground level is either devoted to residential or commercial uses, not parking. Fences in front of a small, generally paved, yard are common in Hoboken (Hoboken Planning Board Master Plan, 2003).

Figure 5 Washington Street; typical buildings (photos taken by author)

The Waterfront area is nowadays less industrial than it was in the past. The industrial waterfront has changed into open space, and factories, warehouses and railroad track have been redeveloped for housing and offices. Parks have taken over piers and a waterfront walkway exists along a large portion of the waterfront, which passes Stevens Institute of Technology near Castle Point. The only active industrial use left is Union Drydock.

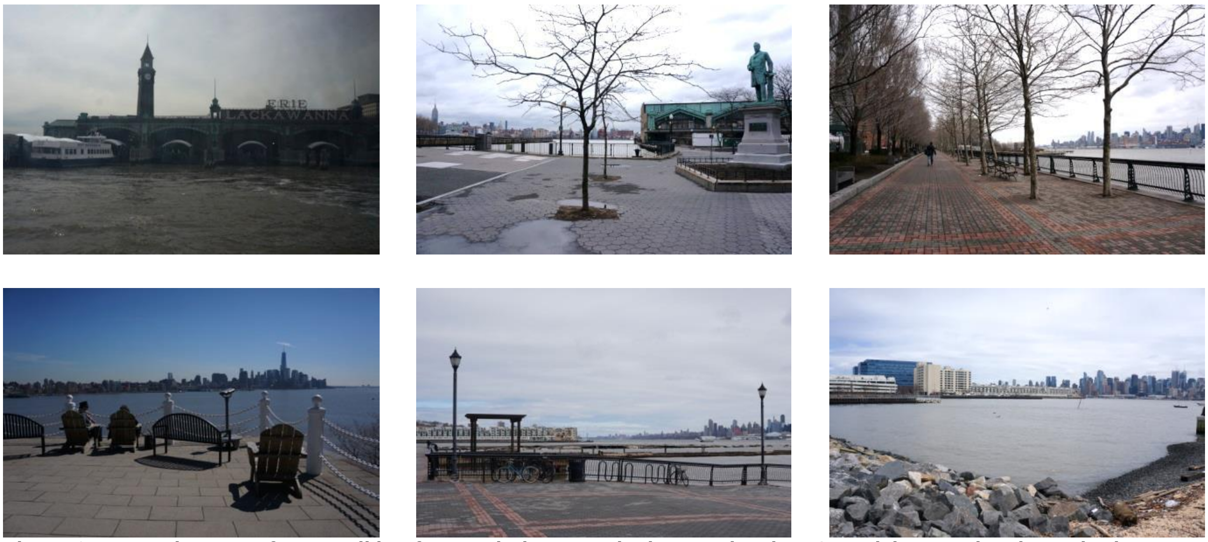


Figure 6 Impression waterfront: walking from Hoboken Terminal to Weehawken Cove (photos taken by author)

Most of the last remaining large industrial parts in Hoboken are located in the west side or northwest of the City, considered as a redevelopment area. The Hudson-Bergen Light Rail Transit is located along the western edge of the City, with two stations in Hoboken. In this area the North Hudson Regional Sewerage Authority treatment plant and electrical substations are located. Also blocks of surface parking for buses and mostly vacant industrial buildings can be found. Affordable housing, shops, and cultural facilities are developed in this area (Hoboken Planning Board Master Plan, 2003).

Figure 7 Industrial and redevelopment area in the west and northwest (photos taken by author)

Hoboken is nowadays a compact, walkable, strategically-located community with a historic character and a mix of land uses. Its typical resident is often characterized as young, well educated, upwardly mobile and transient. It benefits from its location directly adjacent to New York and people can drive to the suburbs or shore almost as easily as take a train, bus, or ferry into Manhattan. Since its incorporation in 1855, the City transformed from an industrial region into a vibrant, liveable, residential area, attracting a lot of people.

2.2 Flood protection in Hoboken

Most communities along the Hudson River are at very low elevation. Hoboken was originally an island in the east central portion of the City, surrounded by tidal marshes to the south, west and north of Hoboken Island (Figure 8a). The marshes in western Hoboken were at that time crisscrossed with boardwalks and buildings on pilings (Figure 8b).

Figure 8 a) Historical situation Hoboken around 1500 (left) (OMA, 2014); b) Boardwalks historical marshes western Hoboken (right) (City of Hoboken, 2013)

In the present situation this topography is still visible. The outcroppings of serpentine rock near the Stevens Institute of Technology campus and along the western border of the city are remnants of the island (Figure 9). Hoboken's topography varies from a high elevation of approximately 21 meter around Castle Point, to less than one and a half meter in a few areas in the western half of the City (Hoboken Planning Board Master Plan, 2003).

Figure 9 Present situation higher grounds: Castle point and western border (photos taken by author)

Due to this position and geography, Hoboken is vulnerable to flooding when the water level in the river increases. Nowadays as a result of land settlements and sea level rise, the area is even more vulnerable. The most low-lying areas in western Hoboken remain below the river at high tide. In Figure 8a the elevation levels of the area are illustrated and the weakest spots, with the lowest elevation levels, become visible. The weakest spots near the waterfront are close to the borders of Hoboken with neighboring municipalities, Weehawken in the north and New Jersey City in the south. Especially the southern spot is vulnerable, because Hoboken Terminal is located at this location at a flood would have high consequences.

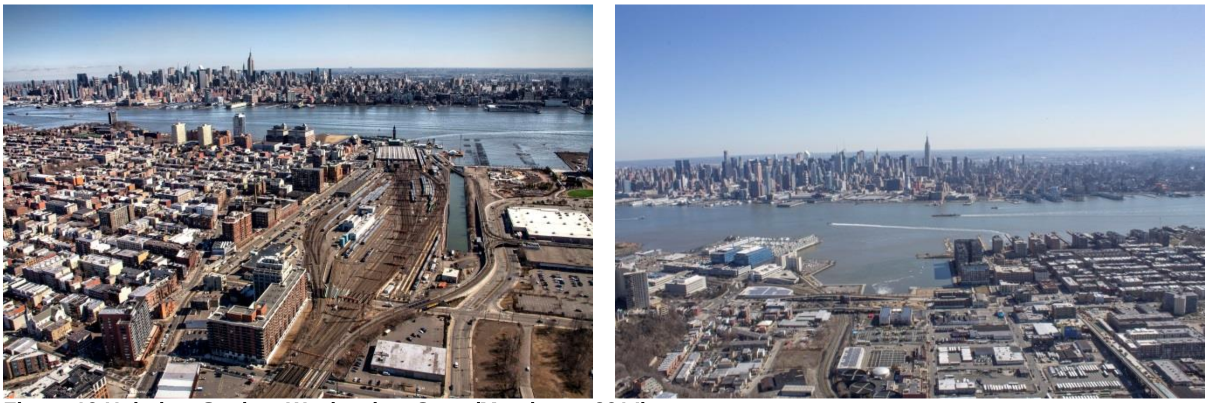


Figure 10 Hoboken Station; Weehawken Cove (Marchetto, 2014)

In Figure 11a the digital elevation model of Hoboken is illustrated and the vulnerable low lying (blue) areas are clearly visible. Figure 11b shows the elevation levels of the city as function of the area in a hypsometric curve.

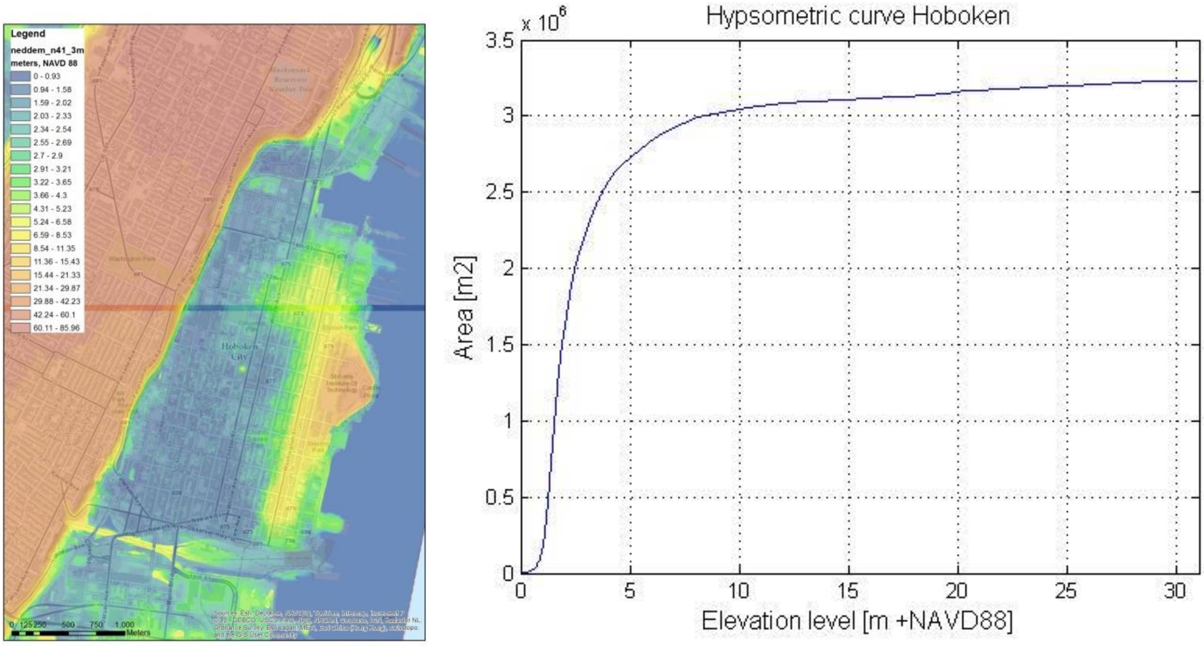


Figure 11 a) Digital Elevation Model Hoboken (left); b) Hypsometric curve Hoboken

In Figure 12a and b a longitudinal cross-section of the waterfront is visualized. The longitudinal cross-section is drawn along the border behind which buildings or other vulnerable objects within the city are situated. The waterfront may clearly be divided into three parts: from 0-2,000 m in longitudinal direction, around Hoboken Terminal, the mean elevation level is 2.2 m + NAVD88; between 2,000-3,200 m, around Castle Point, high elevation levels around 17 m + NAVD88 can be found; from 3,200-4,700 m, around Weehawken Cove, the mean elevation level is again 2.2 m + NAVD88.

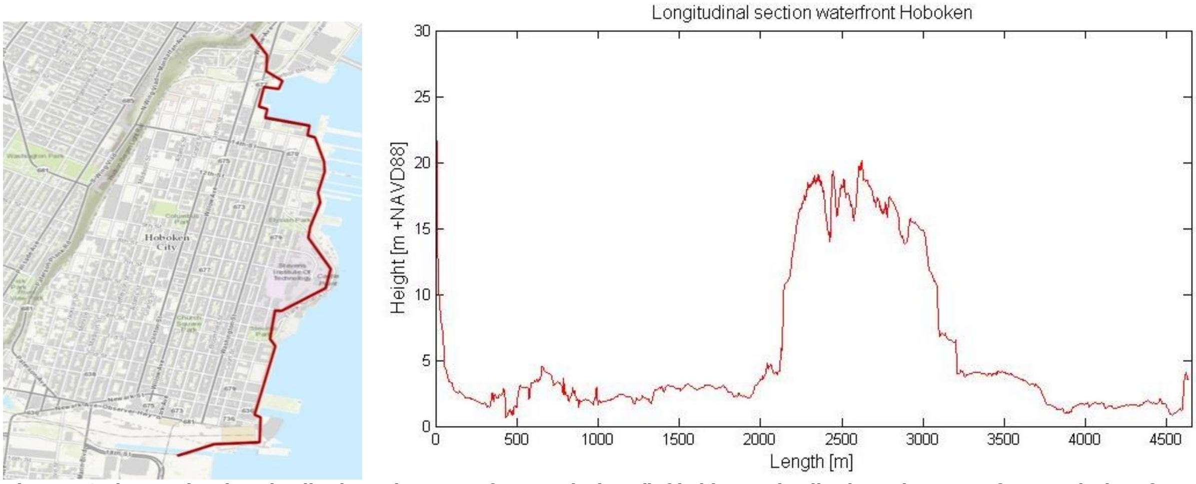


Figure 12 a) Location longitudinal section waterfront Hoboken (left); b) Longitudinal section waterfront Hoboken from south to north (right)

Although Hoboken developed a lot during the last century, the City has a lot of old infrastructure and a lack of flood protection structures. At the most vulnerable, low-lying, locations near the river, flood defences are missing and when water levels get too high, parts of Hoboken are inundated. Furthermore the urban water management system is aging considerably. During the development of Hoboken in the 1800s, the area was expanded into the west of the marshes. Roads were built just above the level of high tide and sewers were built even lower with the bottoms of the pipes just a few decimeters above the level of low tide. When a large storm occurred, the water level exceeded the land elevation level and streets were sometimes covered by half a meter. At that time a study was done and it was found that for the sewer system to drain correctly by gravity during wet weather, roads would had to be raised to at least three meters above high tide. The plan was considered to be too expensive and it was decided to drain and fill in the western marshlands, but it was completed lower than recommended (City of Hoboken, 2013).
As Hoboken is characterized by high impervious area, such as concrete, bricks and asphalt, the urban water management system of Hoboken is mainly based on drainage. In 2003 the estimated amount of parks was a total of approximately 121,000 m^2, which means that 94% of the area consists of impermeable ground. This contributes to Hoboken's pluvial flooding, as rain water cannot be stored in the area and remains on the streets. Besides, the amount of green zones in Hoboken is below New York City's standard of 2.5 acre for every 1,000 residents (Hoboken Planning Board Master Plan, 2003). However, new parks for Hoboken are planned and some already are being realized.

Figure 13 Impermeable ground northwest Hoboken; flood protection in front of liquor store; newly developed park (photos taken by author)

The current drainage system in the City consists of a collection of interconnected pipes, mainly closed canals and discharges sewage (dry weather flow) and stormwater (wet weather flow). Runoff takes place by pumping stations to the wastewater treatment plant in the north of Hoboken and by gravity flow through valves on the Hudson River. The old sewer system, now owned by North Hudson Sewerage Authority, is of the type of a combined sewer overflow (CSO), which means that sanitary sewage and stormwater runoff are collected in a single pipe system.

The Hoboken basin is divided in seven sewer sheds or storm water catchment areas (Figure 14). During extreme rainfall events the drainage system will use the CSO by a storm water regulator for each sewer shed. The sewers do not have enough drainage capacity during extreme weather. This means that they do not drain into the Hudson River through the valves when the drainage capacity of the sewer system is exceeded and when water levels are too high for the valves to drain by gravity. As a result the sewers fill during these conditions and water flows back into the streets causing flooding of the lowest-lying areas. The maximum discharge capacity of the sewer system is approximately 17,000 m^3 per hour. The sewer storage capacity is half an inch per m^2 for the whole city, which is approximately 420,000 m^3. An additional problem is that because the sewer system is of a combined type, during extreme events the sanitary wastewater can flow back on the streets together with the stormwater runoff, which affects the environment and may cause bad smell in the city (OMA, 2014).

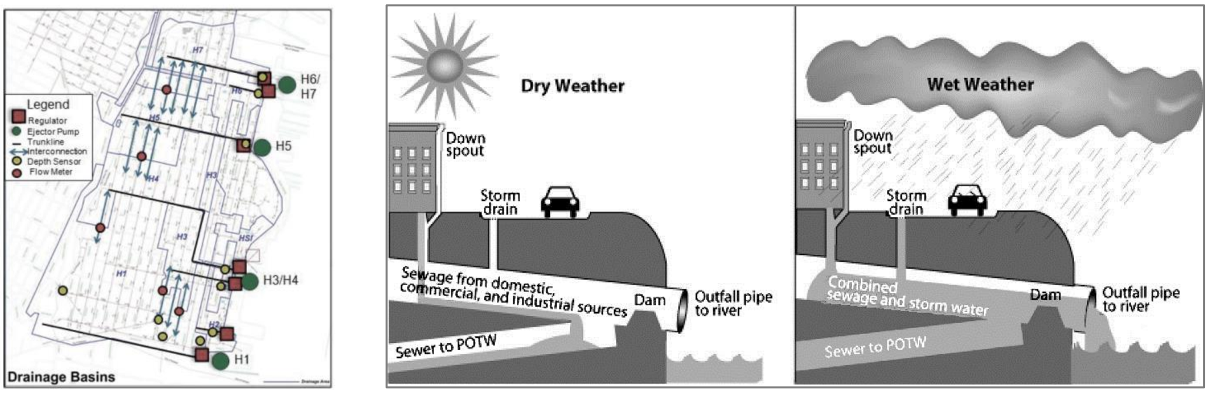


Figure 14 Drainage basins (EmNet, 2011); Combined Sewer Overflow Hoboken (OMA, 2014)

In 2011 Hoboken's first wet weather pump was completed, which can pump out 50 million gallons of water per day, which is approximately 7,900 m^3 per hour. It has reduced flooding during smaller rainfall events, but it still cannot withstand larger ones. From the past it followed that the internal water management system is severely exceeded during high water or storm surges like Hurricane Sandy. As a result Hoboken is not only consequently at risk from coastal inundation, but also suffers from insufficient storage and drainage of stormwater runoff when high precipitation events take place (City of Hoboken, 2013).

2.3 Flood hazards in the region

Since Hoboken is located in northeastern New Jersey, a humid mesothermal climate is dominant with typically hot and humid summers and cold winters. On average precipitation falls 120 days a year and average annual precipitation ranges from 1,100 to 1,300 mm uniformly spread through the year. During fall usually the driest months occur with an average of 8 days with rainfall and other seasons vary between 9 to 12 days per months (Ludlum, 1983). Westerlies are the main feature of the atmospheric circulation over North America and they affect the weather in the region as they vary in strength. Coastal storms, including Nor'easters, tropical storms and hurricanes can cause extreme weather. During Nor'easters continuously strong northeasterly winds from the ocean come ahead of the storm and affect coastal areas when they blow over the land. These low-pressure systems generally affect the Mid-Atlantic States and New England (Ludlum, 1983). They cause powerful winds and heavy rain, snow, blizzards and large wave attacks on Atlantic beaches. Flash floods often occur during nor'easters (Blumberg, et al., 2006). Hurricanes can be classified as tropical cyclones, which are low-pressure systems that are generated most commonly in the tropics. Often they bring extreme rainfall, strong winds and storm surges. The latter can result in hazardous coastal flooding. Atlantic hurricane season is between June and November with on average eleven tropical storms each year, of which six turn into hurricanes (Ludlum, 1983). Hurricanes and tropical storms are a concern along the coastline of New Jersey, but are rare in the region surrounding New York City, including Hoboken. Most likely they occur between August and October (National Climatic Center, 1982).

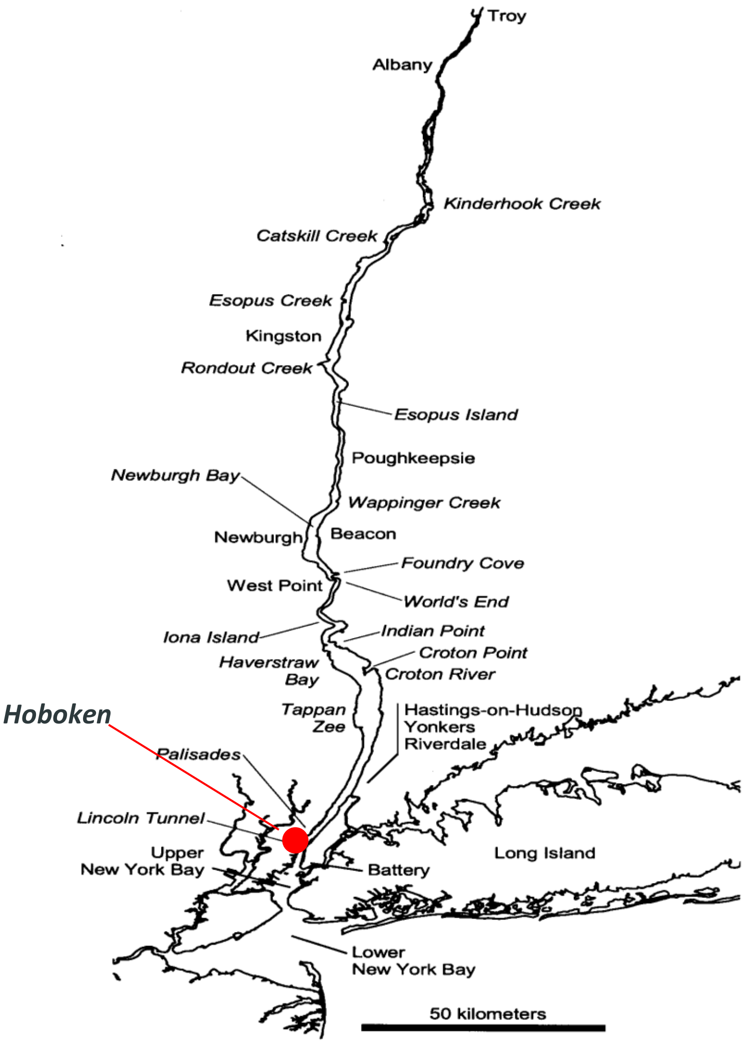


Figure 15 Hudson River Estuary (Blumberg, et al., 2006); red dot indicates location of Hoboken

The Hudson River has a length of 247 km and extends from Troy to the Battery at the southern tip of Manhattan Island, as shown in Figure 15. It has its mouth in Upper Bay, which connects the river to the Atlantic Ocean. The hydrodynamics of the Hudson River Estuary are primarily driven by the upstream river inflows, the oceanographic conditions at the downstream end (tide), and meteorological conditions at the water surface such as storm surge. Both fluctuations in water surface elevation due to tide and storm surges can easily propagate along the entire estuary (Blumberg, et al., 2006). The dominant tidal constituent in the Hudson River Estuary is the semidiurnal principal lunar constituent with a mean tidal range of 1.38 meter (NOAA). Near Hoboken the water levels in the river are primarily driven by tide and storm surges while upstream river inflows and wind waves do not influence the water level in Hoboken (Blumberg, et al., 2006).

Figure 16 Hurricane Sandy flooding (observer.com); Hoboken PATH station Sandy flooding (abcnew.go.com); Flooding parking Hoboken (dailymail.co.uk)

Although Hoboken does not suffer from hurricanes often, Hurricane Sandy hit the metropolitan region in October 2012. The origin of Hurricane Sandy was in the warm waters of the Caribbean Sea. Slowly it moved towards the Atlantic Ocean and on its way it hit Jamaica, eastern Cuba and the Bahama's; at that time it had become a tropical cyclone. Generally most hurricanes turn east towards the Atlantic Ocean without causing any damage. Because of a high pressure area in the north and a low pressure area in the east however, Sandy turned towards New Jersey and New York and made a landfall in New Jersey. After this, Sandy turned to the north and moved away towards Lake Erie and caused severe rainfall in several states located nearby. Wind speeds of 185 km per hour were observed when Sandy arrived on land, but this is not exceptional for Atlantic tropical storms (van Verseveld, 2014).
Hurricane Sandy became exceptional due to a coincidental combination of several factors, like the perpendicular landfall orientation, the very high forward speed, the size which covered almost the complete East Coast, an extreme low air pressure in the eye and the fact that Sandy arrived on land during high tide and spring tide (van Verseveld, 2014). Increased water levels due to storm surge and tide concentrated into the New Jersey shoreline, Long Island Sound, and New York Harbor, inundating areas of Staten Island, southern Manhattan, Hoboken and adjacent communities in Hudson County (van Verseveld, 2014). The highest storm surge level in the region that was measured had a value of 2.5 meter (PlaNYC, 2013).
Millions of people were affected by Hurricane Sandy by its track starting in the Caribbean, including 60 million people across 24 states in the United States. Sandy caused 113 fatalities in the US and damaged 200,000 homes. Costs have been estimated at $50 billion, making it the second nation's costliest natural disaster after Hurricane Katrina (PlaNYC, 2013). The City of Hoboken suffered a lot because much of the land was flooded due to water in the river was so high that the land was flowed over and the whole system was flooded for almost 80%. Much of the population of Hoboken had to deal with several difficulties; people were denied access to public (emergency) services and were out of power for a week or more (OMA, 2014).
However, in the past Hoboken did also frequently flood when water levels in the river did not exceed the waterfront level, but because of flash flooding. During Hurricane Irene water accumulated in the streets of Hoboken as rainfall occurred during high water. In April, 2014 flooding due to rainfall was also the case. On the next page an article is shown, in which the desperation of people in Hoboken about these kinds of floods becomes clearly visible.

Same old song and dance with Hoboken Flooding

Hoboken flooding is a GIVEN any time there's an extended period of moderate rain. Even more so when it coincides with **high tides**, certain wind direction and so on. **Pumps are useless**, and are a blatant waste of property taxpayer funds (no matter where they were "re-directed" from).

The type of flooding we're having tonight is of the "standard" type. Not storm surge related, but due to the antiquated infrastructure in town, coupled with the below sea-level aspect of certain areas of the city. We've talked about and "covered" this so many times – it should be burned into the brain of everyone. Doesn't deserve the "coverage" that other people get hard-ons for. It's a **fact of life** here in this dense, over-populated and over-developed city.

It should only become "news" when it is life-threatening. Like a tsunami. Or tidal wave. Or filled with sharks and stingrays.

Other than that – stay dry Hoboken!

Figure 17 Web article "Same old song and dance with Hoboken Flooding" (nytimes.com)

As Hoboken is an attractive city for people to live in, its population has been growing for a couple of decades and this growth is still ongoing. In the past however, Hoboken flooded frequently because of flash floods during high waters, caused by the lack of capacity of the water housing system and its impermeable streets. In addition Hoboken is at risk of coastal or riverine flooding, when storm surges or increase the water level in the Hudson River, as the waterfront is not protected against these high levels. It is expected that flooding in Hoboken will continue and economic losses will be high. Therefore it is aimed that these floods are being quantified and investigation is being done about how Hoboken may be protected from flooding in the future.

3. Comprehensive flood model for delta cities

For the purpose of investigating the effects of water level variation and precipitation due to a combination of pluvial, coastal and riverine events in urban area, an idealized hydrologic model has been developed. The model identifies the contribution of the different weather events to floods in the city and includes compounding precipitation and water level events in order to get insight in an optimal combination for flood risk reduction measures. The model gives a good impression of the scale and frequency of floods due to the different weather events.
In this chapter at first the principle of the model is described and it is explained how flood levels in a given city can be calculated. Secondly it is shown how the lay-out of the system within the model and its specific components are determined and computed. With the help of different model scenarios the theory behind the model is clarified. Finally the model is tested for two extreme events for Hoboken so it is illustrated how the model functions and it is verified using historical events and data.

3.1 Model principle

The model is an application of the water balance equation to an urban environment. It simplifies, describes and quantifies the hydrological budget of water in cities that are lying adjacent to open waters and have a high risk of pluvial, riverine and coastal floods, by considering inflow and outflow components. The purpose is to compute flood levels in these cities.
The water balance equation follows from the principle of conservation of mass, often referred to as a continuity equation. This equation states that for given volume of space and during any time period, the difference between the amount of water entering the volume of space (inflow) and amount of water leaving the volume of space (outflow) is equal to the change of water storage within the volume. A larger inflow than outflow, results in an increase of the total volume of water that is stored (ΔV). When the inflow is less than the outflow, the volume of water that is stored decreases. The water balance equation in its simplest form can be written as:

$$\text{Inflow (I)} - \text{outflow (O)} = \text{change in stored volume } (\Delta V)$$

This means that the water balance equation includes both fluxes and storage. For the purpose of calculating flood levels in a city, a given confined area represents the area of the city in which water can be stored. The model area extends as far as the areal city limits. The main inflow and output components are selected for the purpose and are based on the volume and period of time for which the balance equation will be applied. The selection of the components is explained in section 3.2.
The components of the water balance equation can be expressed as the volume of water (V in m^3) or as the mean water level in the system (h in m) when the volume of water is divided by the corresponding storage area. For the variation of storage ΔV in a specified period of time Δt, the hydrologic budget can be expressed as a *difference equation*. Where $\bar{I}$ and $\bar{O}$ are the average in- and outflow for the time interval Δt. If I and O vary continuously with time t, the equation can be written as the *differential equation,* in which the rates of I and O are expressed in m/s or m^3/s:

$$\frac{dV(t)}{dt} = I(t) - O(t)$$

In the equations, I and O do not vary in space. The storage volume V varies in space, because of the geographic variation in a city. A flat region is for instance filled more constantly than a mountainous region. The area A that is filled with water in the region is a function of the water depth h within the system. The volume of water stored in the system, is the area A multiplied by the mean water depth h within that area. When it is written as a function of time, this becomes:

$$V(t) = A\big(h(t)\big) * h(t) = A(t) * h(t)$$

The maximum value of *A* is the total available area of the city. This means that when the inland water depth *h* has reached the highest elevation level in the city, the whole city is filled with water. Above this level *A* is assumed to be a constant value. The water balance equation now becomes:

$$\frac{dV(t)}{dt} = \frac{d\ (A * h)}{dt} = A(t)\frac{dh}{dt} + h(t)\frac{dA}{dt}$$

Since

$$\frac{dA}{dt} = \frac{dA}{dh} * \frac{dh}{dt}$$

it can be written as:

$$\frac{dV(t)}{dt} = A(t)\frac{dh}{dt} + h(t)\frac{dA}{dh} * \frac{dh}{dt}$$

or as:

$$\frac{dV(t)}{dt} = \ Qres = \frac{dh}{dt}\left(A(t) + h(t)\frac{dA}{dh}\right)$$

in which the incoming and outgoing fluxes $\frac{dV(t)}{dt}$, are written as the resulting flux Q_{res}.

The expression $\frac{dA}{dh}$ follows from a digital elevation model of the region or from a hypsometric curve, which represents the storage area as function of the elevation levels in an *A*-*h* curve. This function is dependent on the geometry of the given region. In the model the *A*-*h* curve is approached as a linear function, so the derivative of the function is reduced to a constant value *C*.

For discretization of differential equations, numerical methods can be used. These methods can be used to find numerical approximations to solutions of the differential equations. As a constant value is maintained for $\frac{dA}{dh}$, the water balance differential equation can be classified as a first-order ordinary differential equation and may be approached as an initial value problem. For approximation of the equation the Euler method is used, as it is a simple explicit method for approximating solutions to differential equations with a given initial value and consequently has a fast computation time. The method uses the initial derivative of the differential equation to extrapolate and predict future values.
If the differential equation is an initial value problem of the form:

$$h'(t) = f\big(t, h(t)\big), \quad h(t_0) = h_0$$

and if Δt is the step size and $t_i = t_0 + i\ \Delta t$ (for i=0, 1, ..., ∞), one step of the approximation from t_i to $t_{i+1} = t_i\ \Delta t$ can be computed with:

$$h_{i+1} = h_i + \Delta t\ f(t_i, h_i)$$

When the water balance differential equation is described likewise, the numerical approximation of the inland water levels *h* for every time step, can be calculated by:

$$h_{i+1} = h_i\ \frac{Qres_i\ \Delta t}{A_i + h_i C}$$

If the water depth h has exceeded a certain alarm level, a flood occurs. This level is generally dependent on the allowed storage level and emergency level within a city.
The calculated values h_i are approximations of the solution to the ordinary differential equation at time t_i, so: $h_i \approx h(t_i)$. The numerical approximation may get unstable, when approximation errors get too large. In this case the numerical solution for instance oscillates and grows very large where the exact solution does not. The step size is one of the elements that influence numerical stability: for a smaller time step the calculation is generally spoken more stable. A more accurate approximation on the other hand will require more computation time. It is aimed that the approximation is robust, which means that is does not produce a large different result for very small change in the input data. A practical solution to choose the relevant time scale for providing stability is to look at the typical time scale of the equation, which is for this case:

$$\Delta t = \frac{A_c \, h_i}{Qres_i}$$

3.2 System lay-out and model scenarios

The inflow, outflow and storage components may respectively be seen as the loads and strength of the flood protection system of the given city. For the loads this means incoming water. The strength of the city is split into three parts: *waterfront resistance*, *discharge capacity* and *storage capacity*. A typical lay-out for a given city is schematized in which the loads and strengths within the city are represented, as illustrated in Figure 18. The input and output are measured values, for which a reference level is of importance. All values refer to this level.

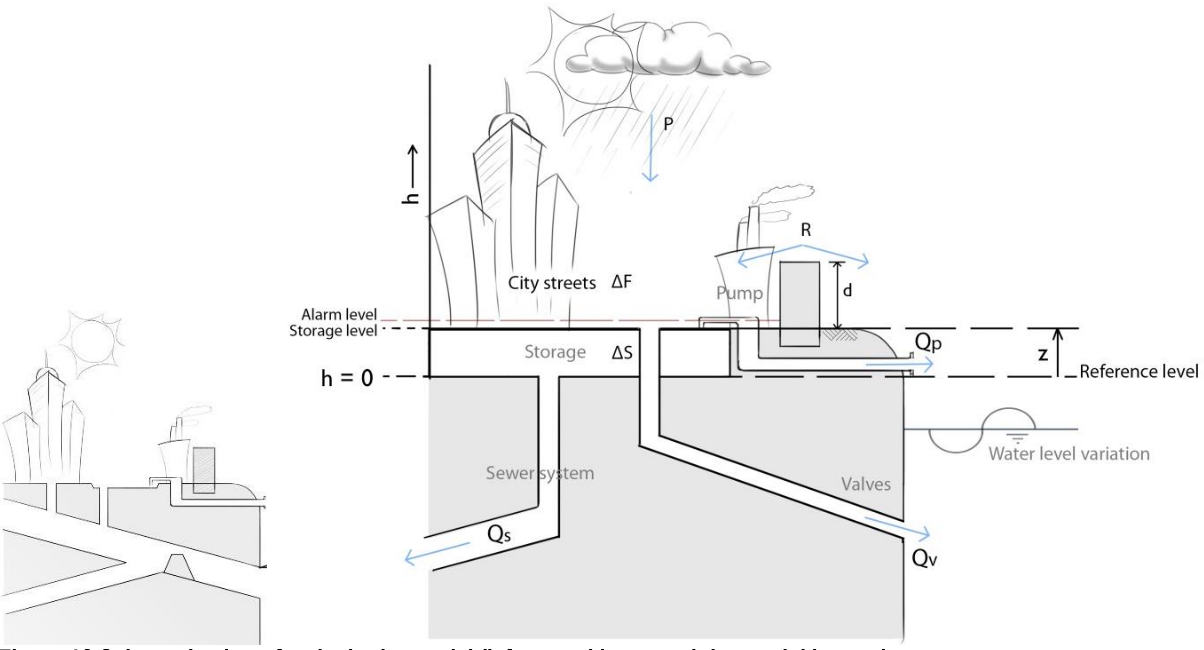


Figure 18 Schematization of a city in the model (left: actual lay-out; right: model lay-out)

The *inflow* components or *loads* include precipitation (P) and river inflow (R), of which the latter is related to the shape of waterfront protection and to the water levels in the open waterbody. Therefore the river inflow includes water level variations due to both coastal and riverine effects, such as storm surge, tide and river discharges. The input in the model consists of time series of precipitation and water level data. The *outflow* or *strength* part of the equation contains drainage components in the possible ways the given city is designed for. In the model a typical lay-out is chosen in which three general measurable factors that determine the *drainage* capacity of a city are defined: the drainage capacity of a sewer system (Q_s) and its maximum value ($Q_{s,max}$); the drainage capacity by gravity on

open waters (Q_v) and its maximum value ($Q_{v,max}$); and the discharge capacity of wet weather pumps (Q_p) and its maximum value ($Q_{p,max}$). Furthermore river outflow (– *R*) may occur, again dependent on the shape of waterfront protection and the water levels in the open water. Because drainage due to evaporation, transpiration, and infiltration are on a larger timescale than relevant for flooding events these components are not included in the water balance. The contribution of (sub)surface runoff and groundwater runoff is not included, since it is not in the scope of the research. In section 3.3 the inflow and outflow components in the water balance equation are explained more in detail.
In general cities have a certain *storage* capacity in which water can be stored. This capacity may include surface storage (over the ground, including storage in channels, pipeline systems and reservoirs), subsurface storage (within the rootzone), groundwater storage (within the aquifers), and interception (over vegetation, buildings, etc.). In the model all elements are included in one expression (*S*). Basically the sum of these elements is schematized as one reservoir with storage area A_s, so there is no spatial dependence. When the storage volume has reached its maximum capacity, and inflow is still higher than outflow, volumes will start accumulating outside the storage area. In practice this means for cities that water will come into the streets, i.e. pounding starts. Once the amount of water in the streets exceeds a certain alarm level and causes damage, people speak of a flood. The volume of water above storage level is represented as *F*. The storage area A_c is dependent on the geography of the city and varies with the water depth. The total volume of water in the system *V* is the sum of *S* and *F*. Consequently the water balance equation may be written as:

$$\underset{(Inflow,\ I)}{P + R} \qquad \underset{(Outflow,\ O)}{- Q_s - Q_v - Q_p} \qquad = \qquad \underset{(Change\ in\ Volume,\ \Delta V)}{\Delta S + \Delta F}$$

of which the dimensions are in cubic meters or mean water depth in meter, when the volume is divided by the storage area.
When the inflow and outflow components are integrated in the water balance equation, this results in the following form the equation:

$$\frac{dV(t)}{dt} = \frac{dh}{dt}\,(A(t) + h(t)C) = \mathrm{P(t)} + \mathrm{R(t)} - \mathrm{Qs(t)} - \mathrm{Qv(t)} - \mathrm{Qp(t)}$$

in which the incoming and outgoing fluxes are summarized as the resulting flux (Q_{res}):

$$\mathrm{P(t)} + \mathrm{R(t)} - \mathrm{Qs(t)} - \mathrm{Qv(t)} - \mathrm{Qp(t)} = Qres(t)$$

Q_{res} was presented in the equations of section 3.1, in which the inland water level for each time step can be calculated.
The model maintains a certain sequence in the inflow and outflow components, based on the typical water management system of the city. In the model *h* represents the inland water level, starting from zero in the storage area of the reservoir. Once the storage level is exceeded, water will accumulate in the city streets.
When the inflow due to precipitation (*P*) and/or river flow (*F*) exceeds the discharge capacity of the sewer system (Q_s), the storage area, schematized as one reservoir, is filling (ΔS). When the storage area is at its maximum and if the inland water level is higher than the outside water level, valves (Q_v) will discharge the water on open waters by gravity. When the river is below the exit level of the valves, water will discharge the water as free flow. If outside water levels are higher than inland water level, the valves will close, so river water is prevented to flow into the city through the valves. If there is a lack of discharge capacity, water starts accumulating on the streets, which is called ponding (ΔF). Dependent on the water depth and the geographic variation, the water is spreading throughout the city. Consequently pumps are turned on in order to discharge the surplus of water (Q_p). When the discharge capacities of the pumps are also too low for incoming water, exceedance of the alarm water level for streets may occur. In this final case a flood is occurring. At a certain moment the flood level in the city gets higher than the flood defence at the waterfront and when the water level in the river is lower than the flood level, water flows out over the structure.

The sequence of the model is illustrated in following scenarios. In the scenarios a distinction is made between dry or moderate weather without flood and humid or extreme weather with flood. The scenarios are tested in section 2.5.

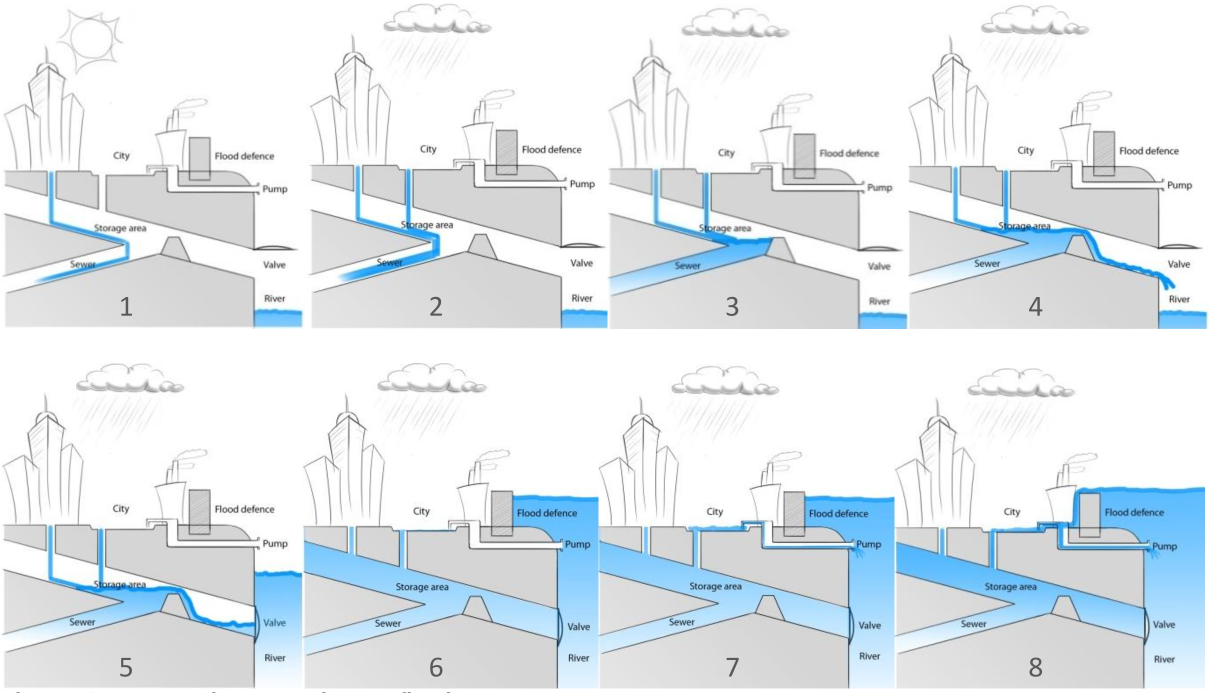


Figure 19 Dry or moderate weather; no flood

In the first scenario (Figure 19) different cases for dry or moderate weather without a flood are possible. The first case is dry weather in which only wastewater is discharged. In the second case inflow does not exceed sewer outflow. In the third case the maximum capacity of the sewer system is reached, but the storage area has enough capacity. In the fourth case the storage capacity has reached its maximum, and valves may discharge excessive water on open waters when the water levels in the river are low enough. In the fifth case outside water levels are higher than inside water levels, so the valves close and the water starts accumulating on the streets. As shown in the sixth case water levels are higher than the river so they can discharge again. In the seventh case the pump is also put into operation because water is on the streets. In the eighth case there is a very small amount of overflow, which is not larger than the water housing system of the city.

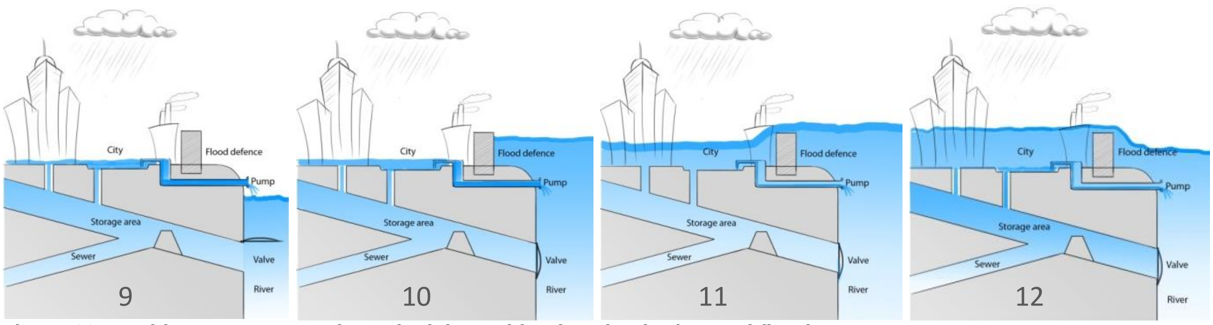


Figure 20 Humid or extreme weather; pluvial, combined or riverine/coastal flood

In the second scenario (Figure 20) humid or extreme weather events with flood are presented. When the discharge system is exceeded by precipitation inflow and there is not sufficient storage capacity, there can be spoken of a pluvial flood (9). When drainage is restricted because of high water levels, this is called a combined flood (10). The other extreme case is caused by water levels, often caused by storm surge, that are higher than the flood defence. Because the amount of water that comes in is much higher than the discharge and storage capacity of the water housing system, it is exceeded quickly and a riverine or coastal flood occurs (11). In the model also the case of river outflow is included when inland water levels are higher than the flood defence and outside water levels (12).

3.3 Model inflow and outflow components

In this section the inflow and outflow components are described. It is explained how the components are calculated and integrated within the model. First of all the two components which represent the inflow values or loads within the system are described. After that the strengths of the system are defined.

3.3.1 River inflow (load)

High water levels in coastal and riverine waters may result in inundation of large parts of land. Sea or river water will flow into the region when the water level exceeds the elevation level of the waterfront and the height of a possible flood defence. For the water balance this is modelled as weir overflow. It is assumed that the flood defence will not fail because of other failure mechanisms than overwash. Weirs are a common structure to control flow. The simulation of overflow is based on the standard weir equation, with a foundation in Bernoulli's equation. In general two situations of flow can be considered: free flow and submerged flow. Submerged flow is the case when downstream water influences the discharge over the weir and in free flow conditions this is not the case. In Figure 21 the principle of flow over a weir is illustrated and the formulas to calculate the discharge are given. These formulas are used to calculate overflow in two directions, water flowing into the city and water flow out the city, representing $\pm R$ in the model.

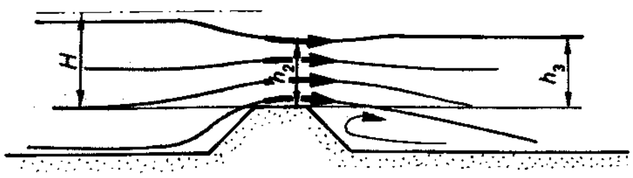


Figure 21 Flow over weir (Nortier, et al., 1994)

For submerged flow $h_3 > \frac{2}{3}H$ and the discharge in m^3/s is:

$$R = c_{ok} * b * h_3 * \sqrt{2g * (H - h_3)}$$

For free flow $h_3 \leq \frac{2}{3}H$ and the discharge in m^3/s is:

$$R = c_{vk} * b * H^{\frac{3}{2}}$$

In the case of river *inflow*, H is the water level variation in the open water and h_3 the inland water level. In case of river *outflow*, this is the other way around. b is the length of the flood defence. For both submergence and free flow, correction factors are defined. The shape of the crest determines the coefficients. This can be varied for the required flood defence type. The streamlines of sharp-crested weirs actually are curved in opposite to broad-crested weirs. Therefore the pressure is not hydrostatic and the flow from point 1 to 2 is higher than in board-crested cases. In practice same formulas are used for both crests, but this is translated with a higher correction factor (Nortier, et al., 1994).
The model is developed for cities, which generally have a high density of buildings and space is lacked. For these situations a sharp-crested weir as flood defence is recommended. Correction values for these structures will be c_{ok}=1 and c_{vk} = 1.75 (Nortier, et al., 1994). The factors may vary for different cases.

3.3.2 Precipitation (load)

Floods in vulnerable urban regions may be the result of extreme weather events when heavy rainfall takes place. Precipitation is modelled as inflow that is uniformly spread over the area of the given city, representing inflow component P in the water balance. Precipitation is often recorded as mean inland water levels in a certain period of time (e.g. mm/day, inches/hour) at a specific measurement station. In the model the amount of water coming in at the measured period of time, is uniformly distributed over the time step for model computations.

3.3.3 Sewer discharge and storage capacity (strength)

The first outflow component in the model is the drainage of the sewer system (Q_s). Sewer systems of cities commonly may be divided into separate and combined sewer systems. In case of combined systems, wastewater and stormwater are collected into the same pipe system; in separate systems different pipes are used for discharge of these waters. In the model wastewater discharge is not computed. In the model incoming stormwater is discharged first to a water treatment plant via the sewer system. This amount of discharge is restricted by a maximum capacity. When the maximum value is reached, the pipes of the sewer system will fill with water. When the pipes are filled, the sewer storage capacity is reached and the sewer system may get overwhelmed. For numerical stability of the system the discharge volume of the sewers in one time interval may never exceed the available inland water volume.

3.3.4 Valve discharge capacity by gravity (strength)

Once the capacity of the sewer system is exceeded, and water inflow does not stop, additional drainage will be necessary. At that point valves are allowed to drain on open water. In combined sewer systems this means wastewater is also discharged into open waters, which is an environmental weakness of these types of sewer systems. Valves can only discharge water out by gravity when the water level in open waters is lower than water levels inside the system. This is the principle of Bernoulli and is in the modelled integrated by the formulas below. It represents the issue that water cannot be discharged on open waters when tide is high and/or storm surges increased the water level.

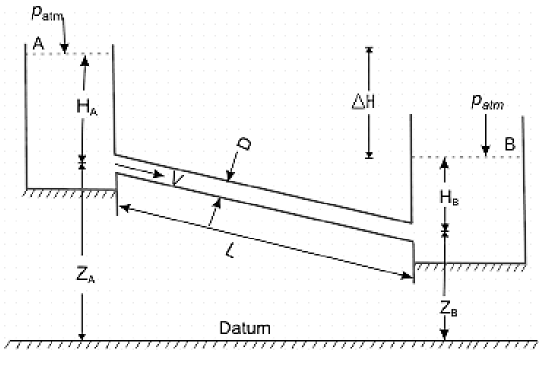


Figure 22 Flow of water from reservoir A to B (NPTEL)

Two reservoirs A and B, as shown in Figure 22, are used to illustrate the inland water levels (A) and outside water levels (B) and the concept of flow potential and flow resistance. Consider the flow of water from one reservoir to another. For a specific situation the reservoirs are maintained with constant water levels. The difference between these two levels is ΔH. In this situation water flows from reservoir A to reservoir B. The equation of Bernoulli is applied between two points A and B at the free surfaces in the two reservoirs. Under steady state conditions the head ΔH causing flow becomes equal to the total loss of head due to the flow.

Three main hydrodynamic losses are present in this situation: the loss of heat at entry to the pipe from reservoir A (ξ_i); the friction loss in pipe over its length L (ξ_w); and the exit loss to the reservoir B (ξ_u).

Therefore the equation for the total loss of head can be written as:

$$\Delta H = \xi_i \frac{U^2}{2g} + \xi_w \frac{U^2}{2g} + \xi_u \frac{U^2}{2g}$$

in which:

$$\xi_i = \left(\frac{1}{\mu} - 1\right)^2 ; \qquad \xi_w = \frac{\lambda\, L}{4\, R} ; \qquad \xi_u = 1$$

U is the average velocity of flow in the pipe in m^2/s. R is the hydraulic radius. μ is the contraction coefficient and λ is the resistance coefficient dependent on the material of the pipes. ξ_u = 1 because as water abruptly exits the reservoir kinetic energy is loss almost completely (Battjes, 2012).
The coefficients that determine the hydrodynamic losses may be summarized as:

$$m = \frac{1}{\xi_i + \xi_w + \xi_u}$$

such that the averaged discharge of flow through the valves (Q_v) in m^3/s may be calculated by:

$$Qv = n * A_{pipe} * \sqrt{m * 2g * \Delta H}$$

in which A_{pipe} is the cross sectional area of the pipe and n is the number of pipes. When the water levels outside remain below the opening of the valves, the head ΔH is the difference between the inland water level and the outfall level of the valves.
The flow is restricted by the maximum capacity of the pipes, depending on their shape and length. Furthermore, to maintain numerical stability of the model, the discharge volume of the valves in one time step may never exceed the available inland water volume.

3.3.5 Pumping discharge capacity (strength)

When the total discharge capacity of the sewer system and the valves is not sufficient for draining the incoming water, additional pumps may have to be put into operation as final drainage possibility. These pumps are called wet weather pumps as they serve as a solution for wet weather events. Discharge by pumps is restricted by their maximum discharge capacities. Similar like the sewer system and the valves, the discharge volume of the pumps may never exceed the available inland water volume in one time interval to maintain numerical stability.
Pumps have to put into process by an automatic or manual operation system. It is assumed that forecasting systems of wet weather work properly in the given city, such that operational delay can be minimized. When the maximum capacity of the pumps is exceeded and water inflow does not stop, excessive water will remain on the streets. In this scenario all drainage possibilities are in service, but the total capacity is not sufficient.

3.3.6 Computed flood levels

The output values of the model are the computed flood levels in Hoboken as function of time. The flood levels can be related and compared to the input of precipitation and water levels, such that it can be found which weather event (or combination of events) is the cause of the flood. Furthermore it can be found which strength components (flood defence, storage, sewer, discharge, valve) lack in capacity.

3.4 Model tests and validation for Hoboken

The model has been tested for Hoboken, using historical data and hydrological and climatological characteristics in Hoboken for different events. First of all two extreme historical situations are chosen to test the model and illustrate the development of the water budget in the city in time. The events that are chosen cover all unique scenarios within the model. After that the model is validated by historical flood events of Hoboken to the model results. As it is aimed to get insight in the contribution of different weather events to floods in Hoboken, the model is applied for this case.

3.4.1 Input

In chapter 2 the main characteristics of Hoboken were discussed. These values are summarized in Table 1, representing the input values of the model. The strength of the City, mainly represented as waterfront protection, storage and outflow components, are also included in the table. Furthermore the maximum time step is included, for which model computations are numerically stable.

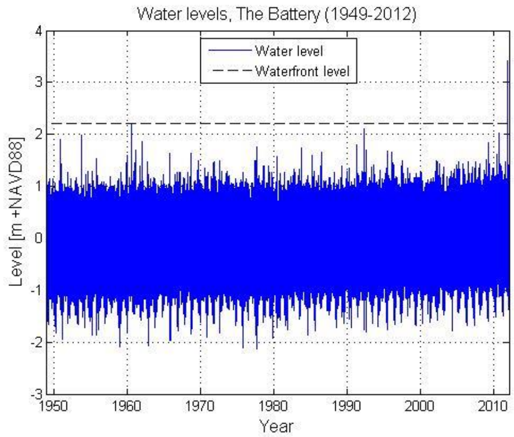
Table 1 Characteristics Hoboken

General	
Population	50,005 (2010)
Adjacent river	Hudson River
Alarm level streets	0.025 m*
Hydrological	
Average annual precipitation (Hoboken)	1,235 mm
Mean tidal range (The Battery)	1.38 m
Topography	
Total area land	3.3 km^2
Mean elevation level of the area	2.0 m + NAVD88
Mean waterfront elevation between 0-2000 m and 3200-2700 m	2.2 m + NAVD88
Mean waterfront elevation 2,000-3,200 m	17 m + NAVD88
Strength	
Water defence protection: height; length; c_{ok}; c_{vk}	d=0.2 m; b=3500 m; c_{ok}=1; c_{vk}=1.75 m$^{0.5}$/s
Storage sewer capacity	420,000 m^3
Maximum sewer capacity	17,185 m^3/hour
Storage capacity of parks	121,406 m^2 (x 1 cm) =1,214 m^3
Valve pipes: length; diameter; μ; λ, number	l=50 m; D=0.5 m; μ =0.6; λ =0.22; n=7
Valves outfall level	0.52 m – NAVD88 (estimated)
Maximum pump capacity**	7,900 m^3/hour
Time step for model calculation	120 s

* uniform over areal extent of city
** completed in 2011

Input components, which represent the loads of the model, are the time series of precipitation and water levels, which determine the inflow of water to the city. Sixty-four years of hourly rainfall and water levels measurements, from 1949 to 2012, were analyzed. The rain is measured at Newark and the water levels are measured at the Battery, lower Manhattan. In Figure 3 the locations of the measurement stations are indicated. From the study of (Blumberg, et al., 2006) it can be concluded that the water levels in Hoboken are comparable with the water levels in the Battery and waves are negligible. Water levels near Hoboken are mostly determined by coastal events (i.e. surge, tide) and not by riverine influences. Therefore flooding in Hoboken due to increasing river water levels, will be called coastal flooding further in this report.

As Newark lies within 10 kilometers from Hoboken it is assumed that the precipitation measurements are representative for Hoboken. The water level and precipitation variations are illustrated in Figure 23. All levels are relative to NAVD88 (North American Vertical Datum of 1988), which is close to Mean Sea Level. The mean values of the inflow components are also included in the table. As Hoboken's wet weather pump was built in 2011, the computations of the historical time series before that time had no pump capacity. The alarm level of Hoboken is 2.5 cm uniformly spread over the city: from this level water in the streets are expected to have consequences for the city. Flood levels are illustrated starting at ground level (flood level = 0). Below this level water is in the storage area. However, a flood in this study is considered when the flood level is higher than 2.5 cm.



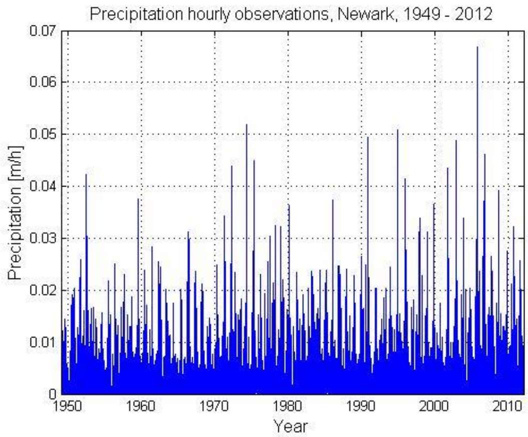


Figure 23 Water levels, The Battery 1949-2012 (left); Precipitation, Newark 1949-2012 (right)

The historical events were used to compute the flood levels by the model and sixty-six years were simulated. The computed flood levels are used to test and verify the model. For this purpose typical flood events were compared to historical data of the city of Hoboken.

3.4.2 Model tests

To test the model, first the situation of 12 hours during the storm surge of Hurricane Sandy is evaluated. During this event also rainfall took place. The step size was set on $\Delta t=1$ s. In Figure 24 the elements that determine the inflow components, water levels and precipitation, are respectively illustrated in the first and second plot. The total inflow is the sum of these two components, shown in the third plot as the red line. In this plot the outflow is visualized as the green line and the resulting flux as the blue line. The inflow and outflow components are illustrated more in detail in Figure 25. In Figure 26 the inland water levels that are calculated from the water balance are presented. In this plot also the water levels outside and several important levels are illustrated, such as the alarm level which is the maximum allowed inland water level. Above this level the city considers the excessive water in the system as a flood event.

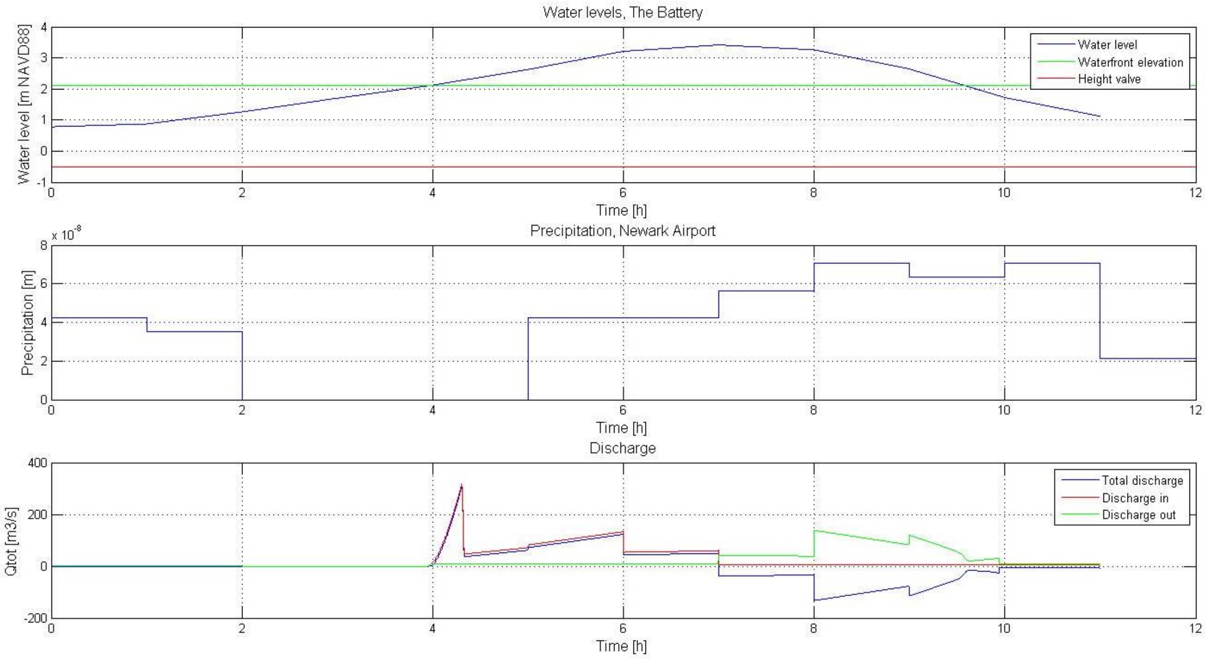


Figure 24 Model results during overflow (Hurricane Sandy Hoboken): Water levels (plot 1); Precipitation (plot 2); Inflow and outflow fluxes (plot 3)

In the second plot of Figure 24 inflow due to the precipitation component is visible from hour 0 to 2. As water starts flowing in, output components start working, as shown in Figure 25. First the sewers (d) start discharging water. As the inflow capacity does not exceed the maximum value of the sewer system, the sewer outflow is equal to the inflow and discharge by valves and pumps are not necessary.

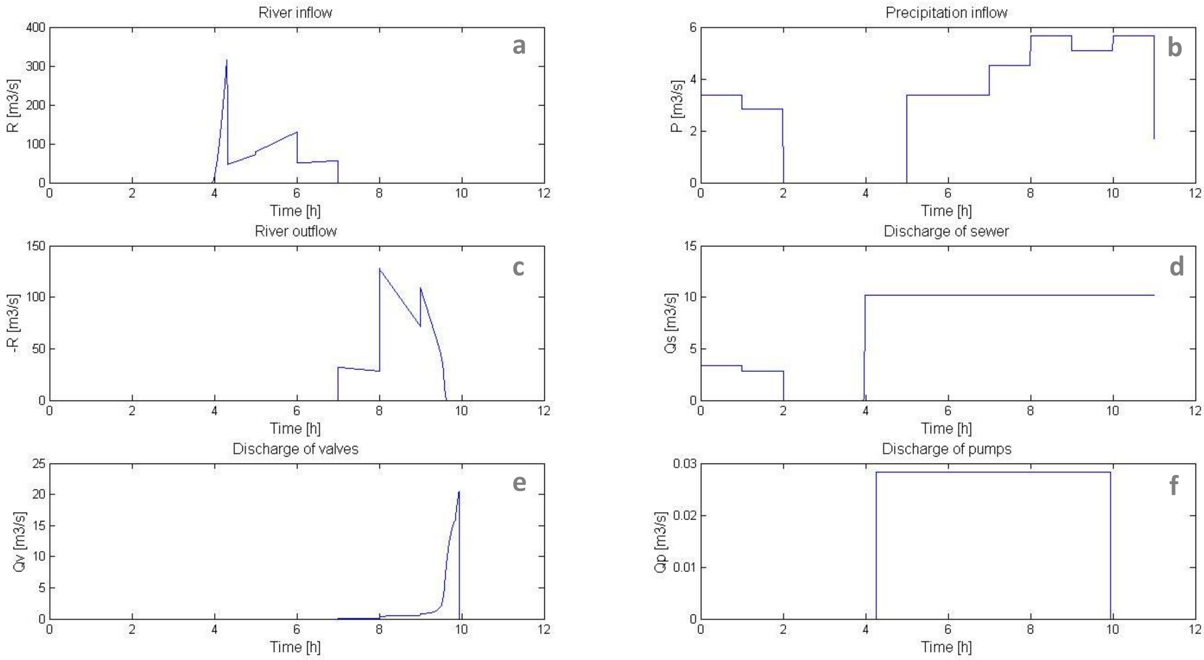


Figure 25 Model results during overflow (Hurricane Sandy Hoboken): River inflow (plot a); Precipitation inflow (plot b); River outflow (plot c); Sewer discharge (plot d); Valve discharge (plot e); Pump discharge (plot f)

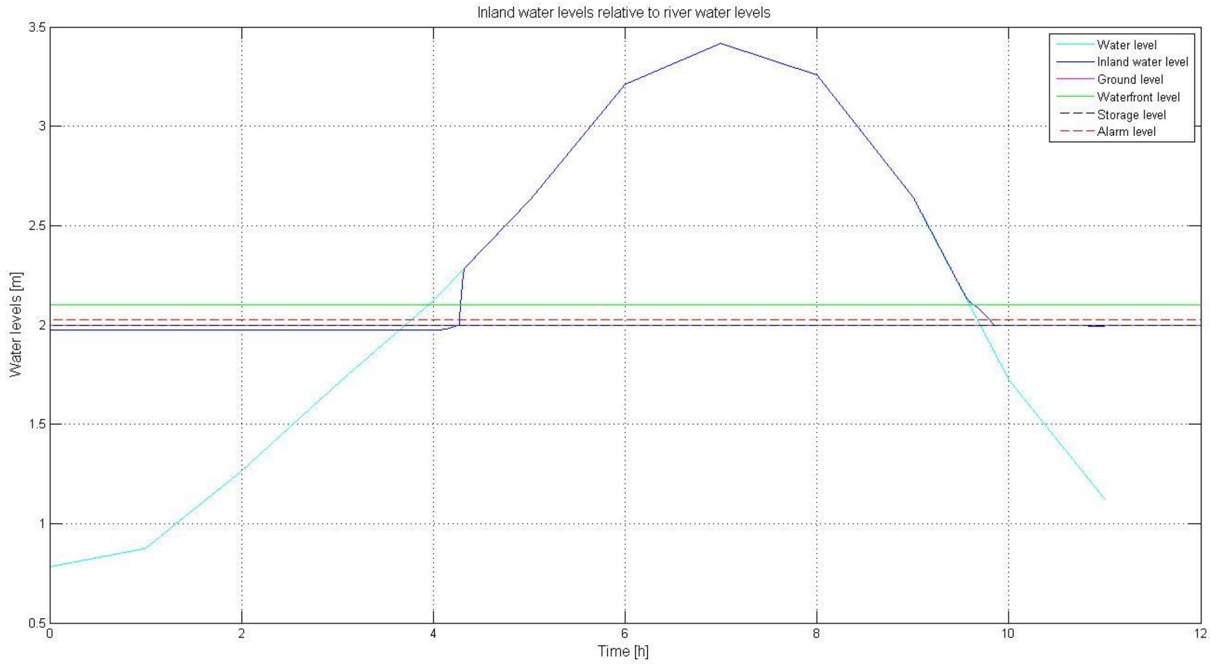


Figure 26 Model results during overflow (Hurricane Sandy Hoboken): Outside water level; inland water level; important limit levels

Furthermore in the first plot of Figure 24 it is illustrated that the water level exceeds the elevation level of the waterfront (including the flood defence) at hour 4. In Figure 25a it is shown that river inflow F starts at this moment. At hour 5 precipitation starts again, but from Figure 25b it follows that the amount of precipitation inflow is almost 100 times smaller than the river inflow. Therefore the river inflow is dominating. In Figure 26 it is visible that the water levels outside are followed by the increase of inland water levels in the city. They increase until the highest point of the water level at hour 7. At this point the water level decreases and river outflow starts, as shown in Figure 25c, again following the water levels outside. When the inland water level has reduced to a value below the flood defence (waterfront level), the river outflow is zero again (just before hour 10). When the river inflow started it was visible that the capacity of the sewer system was exceeded almost immediately.
Furthermore it is shown that valves do not drain until hour 7, because (as shown in Figure 26) the inland water levels are not higher than the outside water levels. The pump is put into operation quickly because the inland water level increases immediately and reaches the maximum storage level. At that moment the water level outside decreases and is slightly lower than the inland water level, and therefore the inland water can drain out. Just before hour 10 a sudden increase of valve discharge is seen, because the water level becomes below the flood defence and river outflow stops. The remaining water is discharged quickly, forced by gravity.
In Figure 27 to Figure 29 a situation of six hours during an extreme rainfall event (21st of July, 2006) is visualized. Again the step size was set on $\Delta t=1$ s and the reference level at NAVD88. In the figures, the discharging procedures of water are presented, similar as was shown for Hurricane Sandy. However, during this event no coastal flooding took place, but the pluvial event was the cause of the flood. Additionally in plot 1 of Figure 27 it is shown that during hour 1 to 3, the water level remained below the valve outfalls. In Figure 28e it can be found that during this time interval the outflow was constant when there was inflow and a constant inland water level.

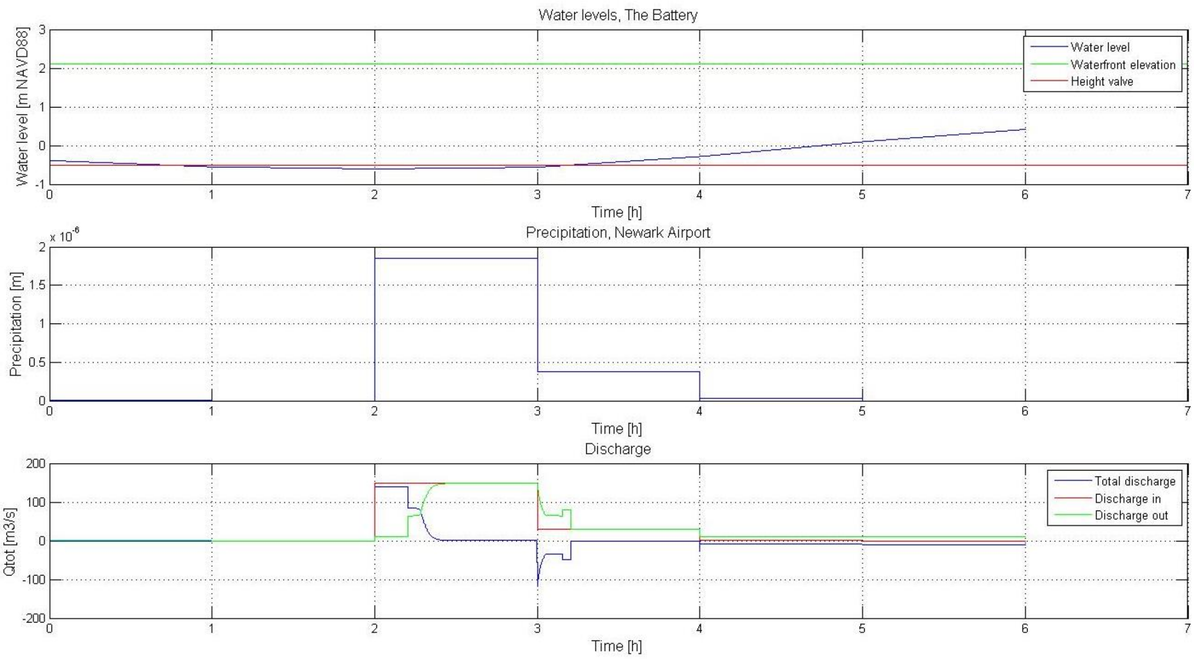


Figure 27 Model results of an extreme rainfall event Hoboken: Water levels (plot 1); Precipitation (plot 2); Inflow and outflow fluxes (plot 3)

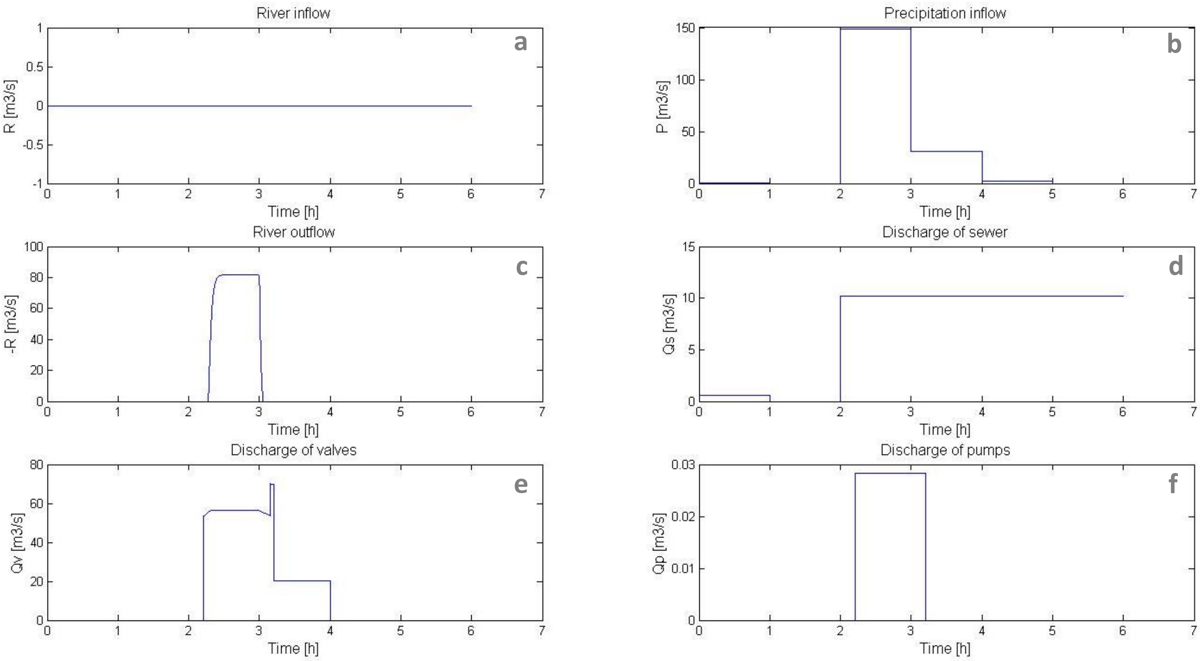


Figure 28 Model results of an extreme rainfall event Hoboken: River inflow (plot a); Precipitation inflow (plot b); River outflow (plot c); Sewer discharge (plot d); Valve discharge (plot e); Pump discharge (plot f)

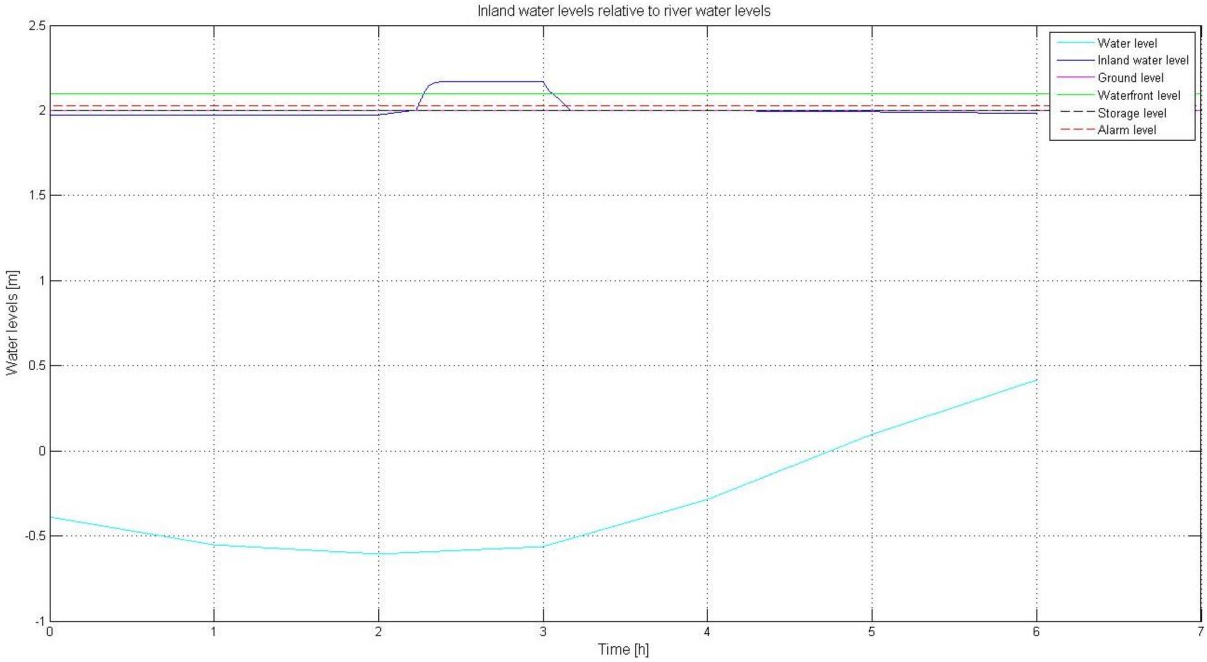


Figure 29 Model results of an extreme rainfall event Hoboken: Outside water level; inland water level; important limit levels

3.4.3 Model verification

In chapter 2 some storms which affected Hoboken in history were described. Different events were chosen and tested in the model. The model results are verified with historical data and information about the amount of flooding during these events in Hoboken. In Table 2 the main values during these events are summarized. Two events of street flooding due to rainfall, and one event of coastal flooding were studied.

Table 2 Historical flood events (EmNet, 2011)

Date	Total Rainfall	Duration (hours)	Notes
August 14-15, 2011	5.81” = 0.148 m	23	Larger than a 10 year storm event with street flooding*
August 27-29, 2011	6.87” = 0.174 m	26	Tropical Storm Irene (50 year storm event) with street flooding*

Date	Maximum water level (m + NAVD88)	Notes
October 28-29, 2012	3.8 m	Hurricane Sandy

In Figure 30 and Figure 31 first two events of pluvial flooding are illustrated. Of each event the precipitation values are illustrated in the first plots. In every second plot in the figures the calculated inland water levels, starting in the storage area (dark blue), are illustrated and plotted in the same figure as the water levels in the river (light blue). In each third plot the flood levels in Hoboken are plotted. The red dotted line indicates the alarm level in Hoboken, at which the city experiences consequences due to excessive water in the streets.

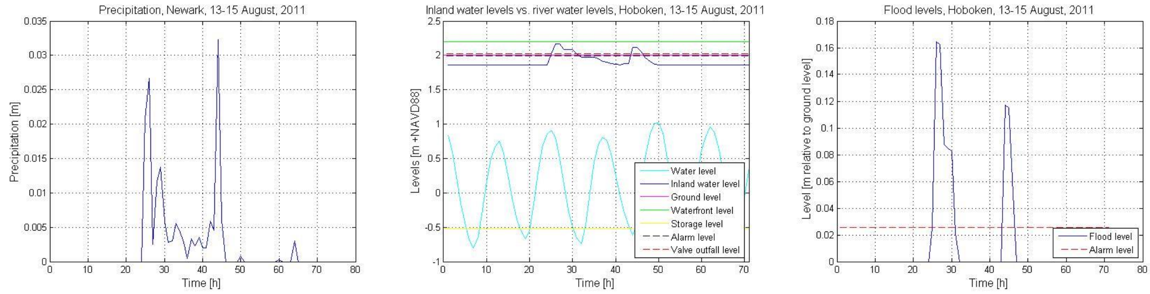


Figure 30 Model results August 14-15, 2011

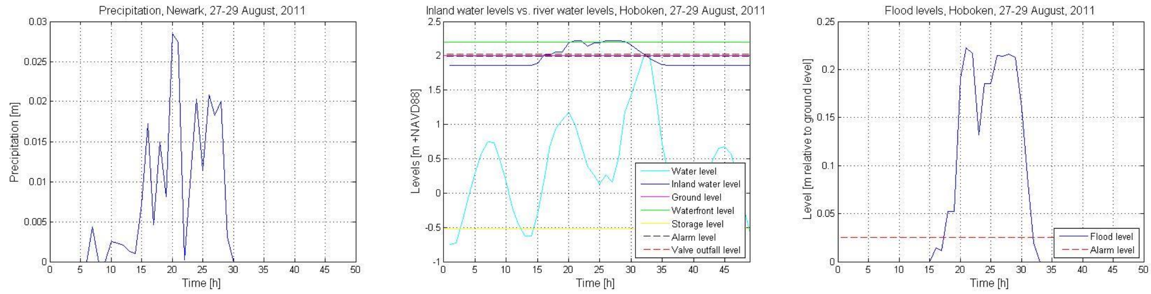


Figure 31 Model results August 27-29, 2011 (Tropical Storm Irene)

At last one situation of a coastal flood is taken into account. In the flood levels, shown in Figure 33, only one extreme flood event due to surge was found: Hurricane Sandy. This event was already illustrated in the plots for model test and will be verified in this section. In Figure 32 the precipitation values, inland and river water levels, and flood levels are illustrated. During Sandy high flood levels were measured. It was estimated that Hoboken was flooded for almost 80%. In the plots a maximum flood depth of almost 1.5 m is shown.

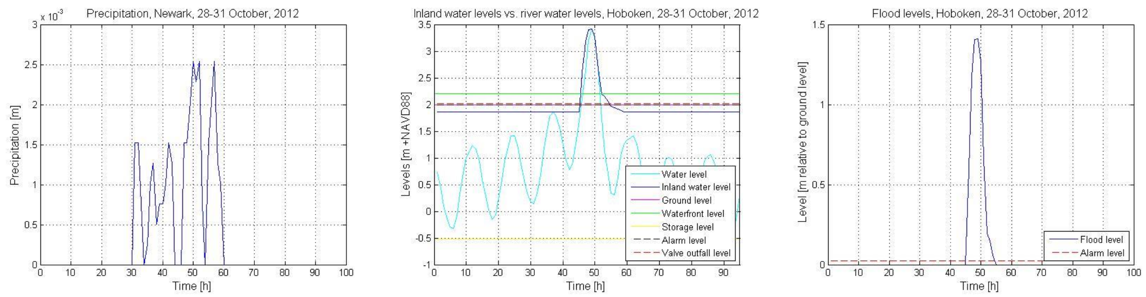


Figure 32 Model results October 28-31, 2012 (Hurricane Sandy)

The computed flood depths are not fully realistic, as assumptions about the routing of the water were made and urbanization was neglected. The amount of flood depths that follow from the model are some lower than locally measured during historical floods in Hoboken. A part can be contributed to the routing effects and high urbanization of the city. The maximum flood level is not higher than 0.27 meter because the dike height in the city is 0.2 meter (7 cm is contributed to overflow height). The pluvial flood levels do not get higher than the height of the dike when water levels are lower in the river.

It is recommended that for improvements of the model, this matter is further investigated. When it is aimed that the model simulates more realistic flood levels, further research is recommended. However, the scale of coastal flood depths, compared to pluvial flood depths, is realistic. This is an important objective in identifying the main contributing weather events to floods in areas.

3.4.4 Evaluation of computed flood levels due to historical events

In Figure 33 in the left figure the inland water levels over sixty-four years are plotted. These values represent the amount of water in the system, starting from zero in the storage area of the sewer system of Hoboken. In the right plot the water levels, starting from ground level in Hoboken, and the alarm level (2.5 cm) are illustrated.

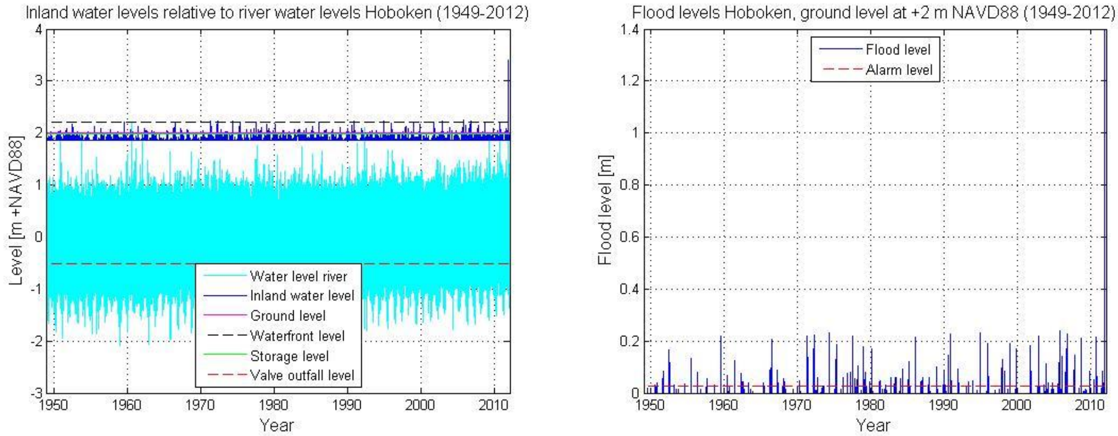


Figure 33 Hoboken 1948-2012: Inland water levels relative to river levels; flood levels

In the simulation of sixty-four years, the model flooded one time because of overflow, which was during Hurricane Sandy in 2012, and several times due to pluvial events. The flood depth during pluvial floods varied up to 0.27 meter, and during the coastal flood it reached a level of 1.4 meter. The flood depths are a function of the areal extent: they represent the mean water depths for a constricted area, as a relation of the elevation levels of Hoboken. When the flood depth becomes higher, this means that the areal extent of water in the city becomes larger and more surface in Hoboken is flooded. From the results it follows that pluvial floods occur more often, but the coastal flood has a higher flood depth and extent.
It can be concluded that for the extreme case of river water overflowing the flood defence (Hurricane Sandy), the system capacities are exceeded immediately. Rainfall in a small amount does not necessarily exceed the system, but during events of high water (when outfall discharge is restricted) flooding may occur.

3.5 Assumptions and limitations

In this section main assumptions and limitations of the model are summarized. Their effects on the final outcome of the model are discussed at the end of this report.

- Data from the Battery and Newark were assumed to be equal to events in Hoboken.
- The model that was developed to calculate flood levels in a delta city is a schematization of reality. The city was schematized as a reservoir with varying areal sections dependent on the elevation level. Several aspects were excluded from the model (e.g. groundwater, routing).
- Constant values were selected for several model parameters for Hoboken (e.g. mean height city, mean waterfront level).
- In the schematization of the model assumptions were made about the positions of different elements and their relations in the flood protection system of a city. A study to dependency of the loads and strengths is beyond the scope of the research. Further investigation to this matter is recommended.
- Spatial influences were not included (e.g. inflow locations sewer).
- Failure mechanisms: the only failure mechanism in the flood protection system is exceedance of flood defence height and storage and discharge capacities.

- Perfect functioning system components were assumed (e.g. no delays in functioning, no technical interruptions).
- The alarm level is based on 1 inch over the entire area of Hoboken. In reality local alarm levels will lie higher.

3.6 Conclusion

Hoboken is vulnerable to pluvial and coastal flooding because of low-lying areas, an impermeable surface and a lack of drainage. Floods can occur during high rainfall events, especially when the excess water cannot be drained into the river, or during storm surges. The consequences of a flood can be very large because of Hoboken's economic valuable character and central location.
The flood computations prove that the model gives a first realistic quantification of the contribution, frequency and scale of historical flood events in Hoboken. Floods due to pluvial events were observed more often than coastal flood events. However, flood extents due to coastal events were much larger. The idealized hydrologic model gives quick insight in the contributing weather events to flooding in a delta city and identifies the weakest elements in the flood protection system. With these results the model forms a good basis for a flood risk assessments, in which an optimal safety level of flood protection can be derived for Hoboken.

4. Economic flood risk analysis

As Hoboken flooded frequently in the past and *Hobokenites* want to be protected against extreme floods like Hurricane Sandy, a solution against flooding is aimed. In this chapter expected flooding in Hoboken is further investigated. Different combinations of pluvial and coastal flood risk reduction measures are studied and assessed.
The central question, from an economic point of view, in this chapter is: how safe is safe enough? In other words: how much safety is desired by society at which costs and how much flood risk is tolerated? Even though this question is a political one, risk management may help with this decision (Jonkman, et al., 2008). First of all the concept of economic optimization is introduced and the steps which have been taken are explained. In the sections that follow it is explained how the optimal safety level in Hoboken has been derived by means of economic optimization.

4.1 Concept of comprehensive flood safety optimization

Flood risk may be defined as the probability of a flood times the consequences. Investments in a higher flood safety level may be balanced with the reduction of the risk, to find an optimal level of protection (Mai, et al., 2008). The results will give insight into the order of magnitude of the protection level that could be chosen based on this analysis.
The investigation of the flood risk in Hoboken is an application of the principles used in the Netherlands for risk-based design of flood protection. The approach was first used for the Delta Works (van Danzig, 1956), and was later also applied for areas such as New Orleans, Japan or Vietnam (Jonkman, et al., 2008). In a former study in this way the flood safety level of the waterfront defence level of Hoboken was determined. The optimal safety level was determined to be 500 years (Hillen, et al., 2014).

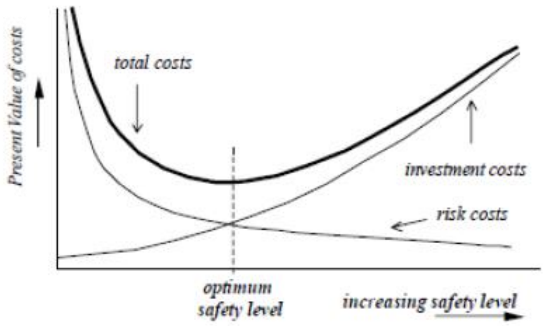


Figure 34 Concept of economic risk optimization (van Danzig, 1956).

As flooding in Hoboken is not only caused by high water levels due to storm surges, but also due to heavy rainfall or a combination of those two, in this study the flood risk analysis of Hoboken is further elaborated and the focus will be on the combination of different floods. In the economic optimization the protection against pluvial, riverine and coastal flooding are studied. For that reason different combinations of pluvial, riverine and coastal flood measures will be taken into account.
The focus will be on three measures, in this study named *Resist*, *Store* and *Discharge*, following the design approach of Team OMA of Rebuild by Design (OMA, 2014). *Resist* will focus on the waterfront protection. *Store* and *Discharge* will focus on the internal water management system and serve respectively as increase of the storage capacity of the reservoir and discharge capacity of the drainage system. Different combinations of the *Resist*, *Store* and *Discharge* measures are studied.
When the city is protected with strong flood reduction measures, the probability of flooding and therefore the expected damage will be smaller. The three types of measures are integrated in the model and for different values the reduced flood risk, compared to the current situation of Hoboken, can be calculated. For every combination a new flood safety level is determined.

The investments in flood reduction measures consist of the costs to strengthen and raise the river flood defenses, costs to increase storage capacity and costs to increase discharge capacity. It is assumed that flooding could only occur due to overflow of the flood defenses, or exceedance of the storage or discharge capacities of the system. Structural or technical failure mechanisms, such as other dike failure mechanisms (e.g. piping or macro-instability) are not taking into account. The investment costs of each combination will be balanced with its corresponding benefit (i.e. risk reduction). The sum of the investment costs and the expected damage can be seen as the total costs as a function of the (new) safety level in the city. In this study an economic optimal decision is the found for the combination with the lowest costs. The steps taken in this research to come to an economic optimum for Hoboken are:

1. Creation and analysis of synthetic flood levels over 1,000 years in Hoboken;
2. Determination of damage due to flooding;
3. Determination of the current risk level of Hoboken;
4. Investigation of possible flood risk reduction measures;
5. Determination of the investment costs required for improvement of the system;
6. Comparison of risk reduction measures and determination of economic optimum.

The analysis for Hoboken is a simplified one and not fully realistic, but the data used for the damage assessment and investment costs, are based on available sources for first-order estimation. Therefore it will give a first impression of the required flood safety level of Hoboken in terms of economic optimization.

4.2 Flood level analysis over 1,000 years

In this section synthetic time series of precipitation and water levels of 1,000 years are created by means of extreme value analysis, in order to investigate extreme flood levels in Hoboken. By investigating the extreme events per year of the current time series of 64 years, new time series of 1,000 years have been created, which include higher extremes, and fit the extreme value distribution of the current time series.

Flooding in Hoboken is dependent on high water levels and rainfall events. High water levels and rainfall events are often presented as probability distributions or exceedance frequency curves. In this study the extreme loads of high water levels and rainfall are considered, since risks are usually caused by extreme events and flood risk reduction measures are generally designed for the ultimate limit state. Extreme water levels or rainfall are mainly caused by extreme phenomena, such as cyclones and storm depressions. As high water levels in Hoboken are mainly the result of storm surge, the surge levels are estimated by subtracting the tidal variation and the trend from the water level time series. The variations of surge at the Battery and precipitation in Newark from the 1st of January 1942 to the 31st of December 2012 are illustrated in Figure 35. The negative values of surge can be contributed to set-down.

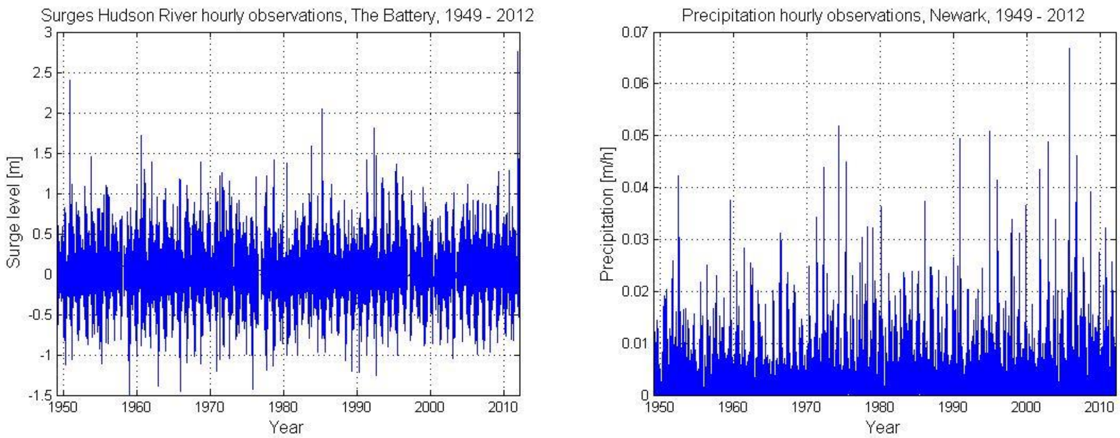


Figure 35 Current time series, complete years from 1949 to 2012

The flood levels during these historical events were studied in chapter 3. In this section it is aimed that larger expected floods are estimated. For that reason the probability distribution of the extreme events of both surge and precipitation are investigated. The probabilities of the extreme events are estimated by the technique of plotting order-ranked data (Makkonen, 2006). For the estimation of the return periods of the extreme values the following steps are taken: 1. ranking; 2. searching for the cumulative probability P_c; 3. fitting; and 4. interpolation & extrapolation.

4.2.1 Estimation of return periods of extreme values

For investigating extreme events, every year's greatest value is considered and statistics of yearly maxima are applied. First of all, all annual extremes of a period of N years are ranked in increasing order of magnitude from the smallest value m=1 to the largest m=N and can be plotted on logarithmic paper. After that the cumulative probability P_c is associated to each value, by applying cumulative frequency analysis. The cumulative probability P_c (probability of non-exceedance) that should be associated with the sample of rank m, can be estimated by dividing the cumulative frequency M by N+1. The cumulative probability may be estimated by: $P_c=m/(N+1)$. The plotting positions used in this analysis follow from the study of (Makkonen, 2006).
The probability of exceedance P_e is found from: $P_e=1-P_c$. The return period RP (in years) of an event is related to the probability P_e of not exceeding this event in one year by $RP=1/(1-P_c)$. In Figure 36 the ranked annual extremes of surge and precipitation near Hoboken and their return periods are illustrated.

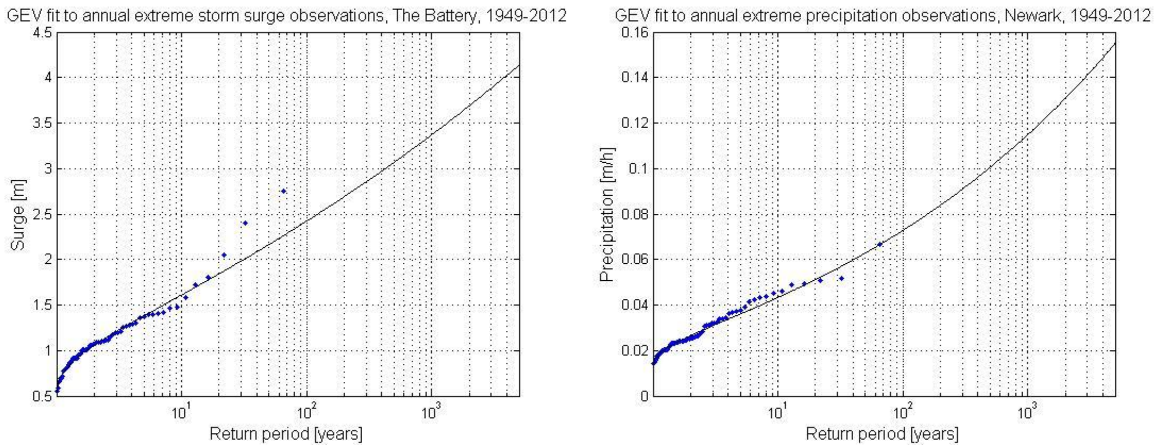


Figure 36 Generalized Extreme Value distribution surges The Battery (left); extreme value distribution precipitation Newark (right)

To present the cumulative frequency distribution as a continuous mathematical equation, instead of a discrete set of data, the cumulative frequency distribution can be fit to a known cumulative probability distribution. This concerns both the type of the distribution and the corresponding parameters.
In this study for both extreme surges as extreme rainfall Generalized Extreme Value Distributions were selected. Parameters that followed from a best fit analysis were found and a line was fit through the ranked data points, as shown in Figure 36. Prove of the validity of this hypothesis is beyond the scope of this study.
In the left plot it is shown that the highest data points of the right-hand tail deviate from the fit. The distribution is assumed to be a discontinuous distribution, which is the case when one type of probability distribution can be fit to the lower part of the data range and another type to the higher part, separated by a breakpoint. This can be contributed to the variety of weather events in the region (nor'easters, hurricanes etc.), which influence the water levels, and all have physically and statistically different characteristics. However, this complexity of events is beyond the scope of this research and the data points are approached as a continuous distribution. The fit that follows is assumed to be representative for this research. It is recommended to further investigate these events and the sensitivity of the distribution to the results.

4.2.2 Generation of synthetic data series

Extrapolation from the graph has been used to estimate the return period of higher extreme values than the observations. These estimations are used in the generation of 1,000 years of synthetic water levels and precipitation in Hoboken. Following steps were taken for the generation of these time series:

1. For the creation of water levels and precipitation data, 1,000 random cumulative probabilities were selected: P_c=m/N+1, in which m=1:N and N=1,000;

2. Return periods (RP) corresponding to these probabilities were calculated: RP=1/(1-P_c);

3. From the fitted Generalized Extreme Value Distribution the 1,000 annual extreme values (H) were obtained that correspond to the 1,000 cumulative probabilities (with return period 1 to 1,000) (Figure 36);

4. 1,000 times a random year (Y) was uniformly drawn from year 1 to year 64 of the historical hourly observations (Figure 35);

5. In this random selected year the annual extreme was found (Y_{max}). As storm events could affect the hydrological or local weather conditions for a couple of days, a section (S) of data points from 3 days before and 3 days were considered;

6. Each section (S) around the extreme value of each historical year, was scaled to the new random drawn extreme value (H);

7. As a result 1,000 new years of surge and precipitation were created with annual extremes (H).

No sample correlation was taken into account between precipitation and surge, as the historical time series have a low correlation. In Figure 37 the correlation of the 64 years that were analyzed is illustrated and the correlation as a function of the timelag is plotted. From the figures it becomes clear that for a timelag of 6 hours the correlation is at its maximum. As at this point the correlation is 0.17 the correlation between surge and precipitation is assumed to be negligible and has not been included in the created time series of 1,000 year.

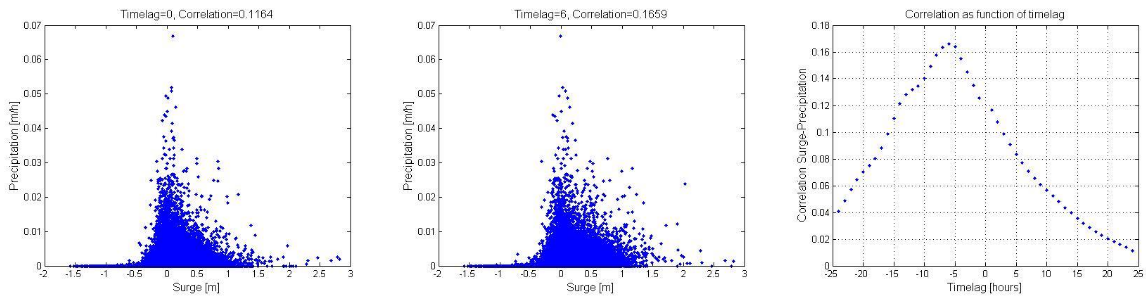


Figure 37 Correlation precipitation and surges

The two time series that have been created are illustrated in Figure 38. The left plot is the sum of the new created surge and the tidal variation, which represents the water level variation over 1,000 years. In this figure also the height of the 3.5 kilometers of the lowest parts of the waterfront in Hoboken are shown. The right plot illustrates the precipitation over 1,000 years. Furthermore the annual extremes are illustrated in Figure 37.

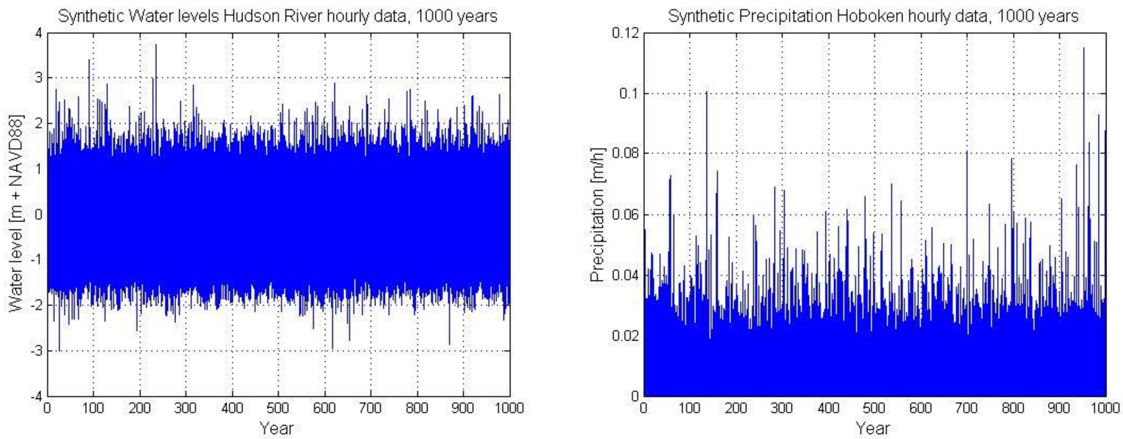


Figure 38 Created 1,000 year of water levels (surge + tide) (left); Created 1,000 year of precipitation (right)

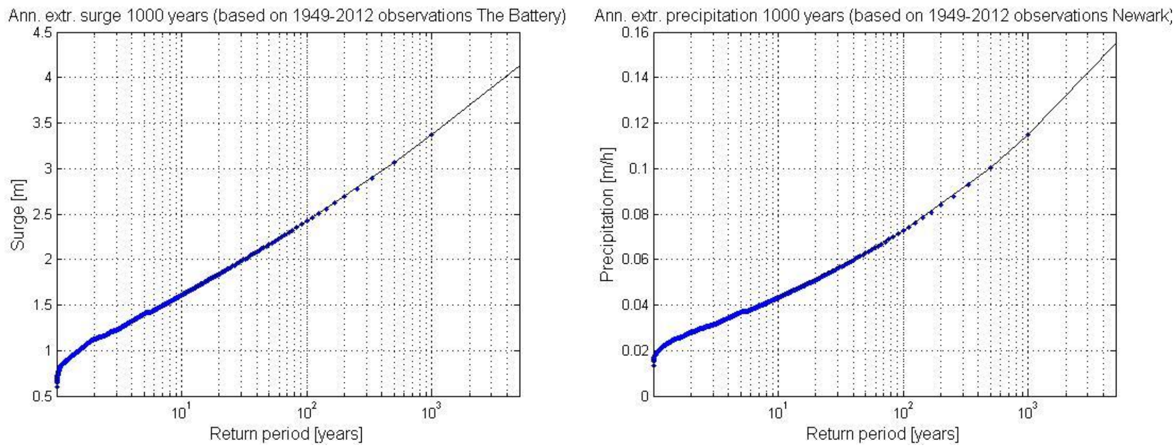


Figure 39 Annual extremes of synthetical time series of 1,000 years: surge (left), precipitation (right)

4.2.3 Results and analysis

The created variations of water levels and precipitation were used as new input in the model and flood levels over 1,000 years were computed. For the current situation of Hoboken (characteristics in Table 1), the expected flood levels (inland water levels above ground level) were calculated for every chosen time step in the model. The hourly maximum flood levels over 1,000 years were saved, of which the results are shown in Figure 40 (left plot). Also the annual maximum flood levels and their return periods are plotted in a ranked order in Figure 40 (right plot).

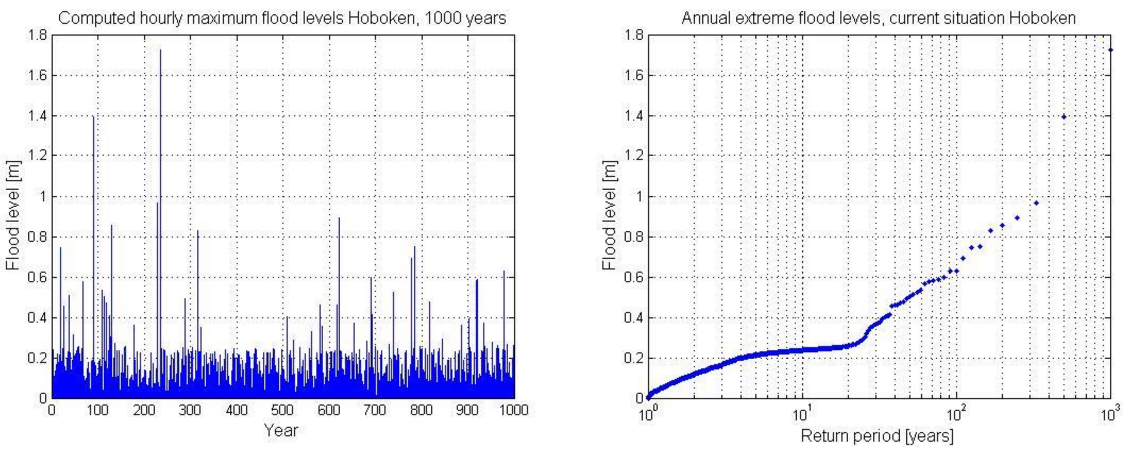


Figure 40 Computed flood levels (left), Right: Computed annual extreme flood levels (Hoboken, 1,000 years)

It can be found that the maximum flood level has a flood level of 1.72 m and a return period of 1,000 years. A flood of 1.5 meter has a return period of 500 years (this value can be compared to a storm as Hurricane Sandy). When a flood hour is defined as exceedance of the alarm level in the streets of Hoboken (0.025 m), almost 5,000 hours were measured as flood hours.
When the flood levels are compared to the 1,000 years of created water levels and precipitation (Figure 38), insight is offered in the contribution of different weather events to flooding in Hoboken. In Figure 41 the flood levels are plotted as a function of water levels (left) and as a function of precipitation (right). On the y-axis of both figures the flood levels are plotted. The flood levels and water levels are relative to NAVD88. Mean ground level in Hoboken was assumed to be +2 m NAVD88.

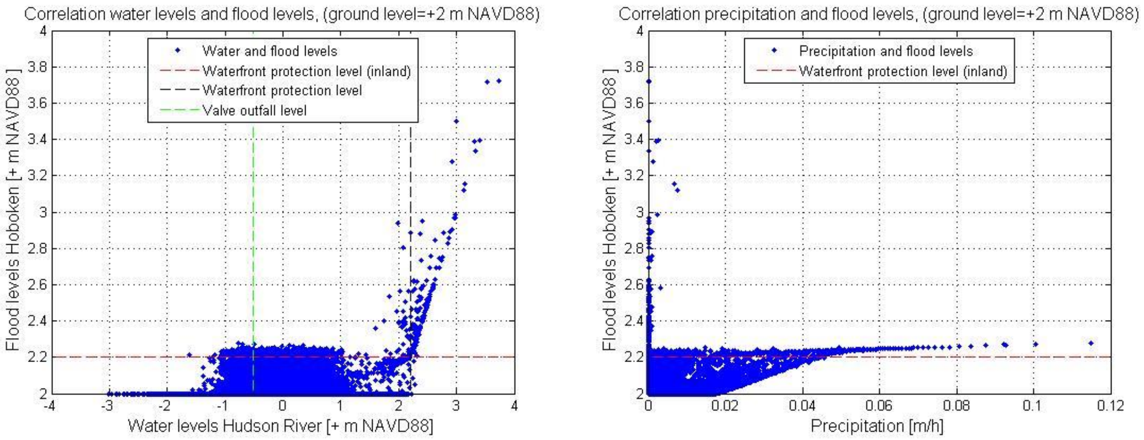


Figure 41 Left: correlation water levels and flood levels; right: correlation precipitation and flood levels 1,000 years

In these figures every computed maximum hourly value is plotted. For the flood levels these are the maximum measures values in an hour. The plots give an impression of the contribution due to different weather events to floods and insight is offered in the main phenomena during flooding.
Overall it can be found that the highest floods occur when the waterfront level is exceeded (WL > 2.2 m +NAVD88). This means that a coastal or riverine flood occurs and river water has flown over the flood defense. The maximum value of 1.72 m can be contributed to a coastal event.
Furthermore it can be found that most floods occur when the water levels are higher than the valve outfall level. When water levels are below this value, the valves can drain into the river with maximum capacity. When the water is higher, the hydraulic head is smaller, so the drainage capacity decreases and can become too low for draining the excess water. When Figure 38 and Figure 40 (left) are compared, it can be found that most flood levels due to pluvial events only, belong to these smaller flood levels and have maximum flood levels of 0.27 meter. As the pluvial flood levels are related to the drainage capacity and therefore to the water levels in the river, most pluvial floods are the result of compounding events (a combination of two non-extreme events, which do lead to an extreme consequence).
It is recalled that flood levels in the city during low waters cannot be higher than 0.27 m as the water flows out of the city when the flood defence height is reached. The flood levels that are found below the flood defence, but are higher than 0.27 meter (for example FL=0.35 m & WL=1.6 m and FL =0.9 m & WL = 2.0 m), are values after a coastal flood during lowering of the water levels.
Concluding from these results, pluvial floods are categorized as floods with flood levels lower than 0.27 m. Coastal floods are categorized as floods higher than 0.27 meter. Following these categorizations and when flooding is defined as flood levels higher than 0.025 m, it was found that 44 annual maxima are higher than 0.27 meter. This means that 4.4 % of the annual extreme flood events are due to coastal events and 95.6 % of the annual maximum flooding due to rainfall events. In the right plot of Figure 40 the distinction of the pluvial and coastal floods is clearly visible in the discontinuity of the plotted computed values.
As 95.6 % of the flood events in 1,000 years occurred due to rainfall, pluvial flooding in Hoboken can statistically occur every year. This means that the current safety level of the water management system

is approximately 1 year. This confirms historical observations for pluvial events in the current situation of Hoboken. For example, two years after Hurricane Sandy, Hoboken experienced flash flooding for four times (OMA, 2014). As 4.4 % of the flood events in 1,000 years are contributed to coastal events, coastal flooding in Hoboken has a return period of approximately 23 years. This means that the current safety level of the waterfront protection is 23 years. It can be concluded that pluvial flooding occurs much more frequent than coastal or riverine flooding, but the flood levels are lower. These events do not lead to extreme flooding, but could have consequences for Hoboken. The effect of flood levels to damage in the area is investigated in section 4.3.

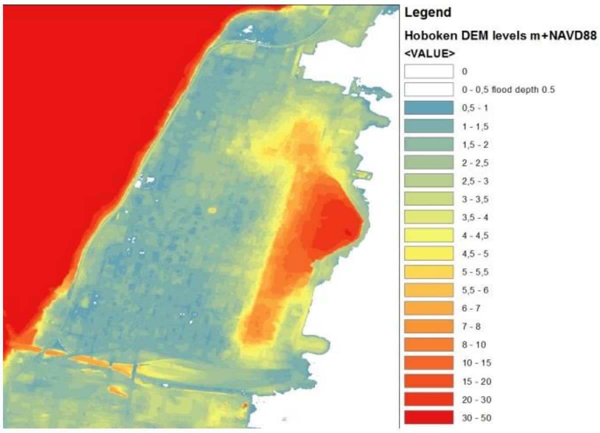
4.3 Damage due to flooding

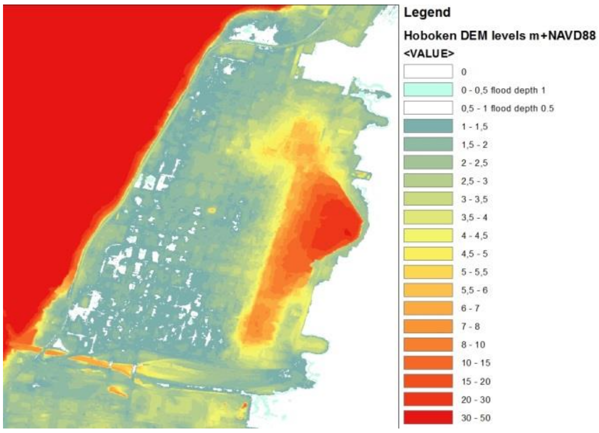
In this section the damage due to flooding in Hoboken is investigated. Often consequences of an event are divided in economical, individual, societal and ecological consequences. The economic consequence is the total material damage expressed in monetary terms, consisting of direct and indirect damage. Individual consequence can be described as the loss of life of an average, unprotected person that is constantly present at a certain location (Jongejan, et al., 2008). Societal risk is the consequence for a society when for example a disaster occurs and more people are involved. The ecological consequence is about the harm to ecological values.
A short study to individual consequences in Hoboken was done and it followed that the individual risk in Hoboken is relatively low. The main reason is that a large part of Hoboken is at very high elevation level and people can evacuate to these areas easily. This was also concluded during Hurricane Sandy when in Hoboken nobody became a victim during the flood. For that reason individual risk is not further investigated and neglected in this study.
Economic consequences are expected to be high in Hoboken as it is a densely populated, urbanized and industrialized region. Therefore in this study the focus is on economic damages. In the different dimensions of flood damages a distinction can be made between *direct* damages inside the flooded area and *indirect* damages outside the flooded area. Indirect damages such as disruption of social life or indirect business interruptions are not included in this study.
For the damage assessment the steps described in the paper of (Jonkman, et al., 2008) were followed. In this approach flood characteristics and direct physical damages are combined. The estimation of direct physical damages is split into two steps. First the structural damages to objects such as buildings are estimated and secondly the physical damages are priced with so-called stage-damage functions. The steps that are followed are:

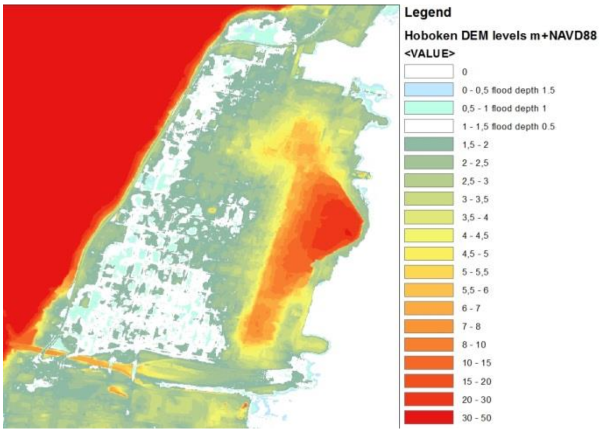
1. Determination of flood characteristics
2. Collecting information on land use and economic data
3. Application stage-damage functions

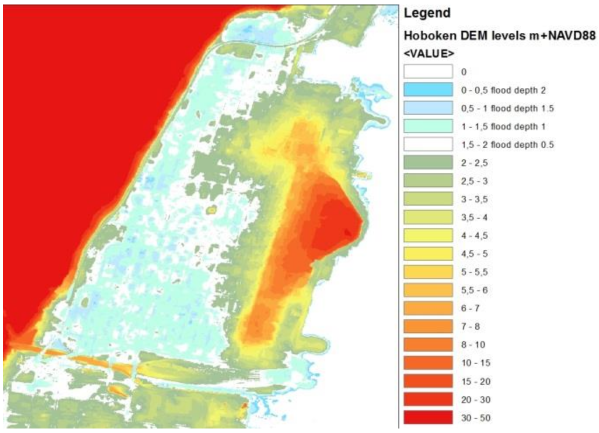
4.3.1 Determination of flood characteristics

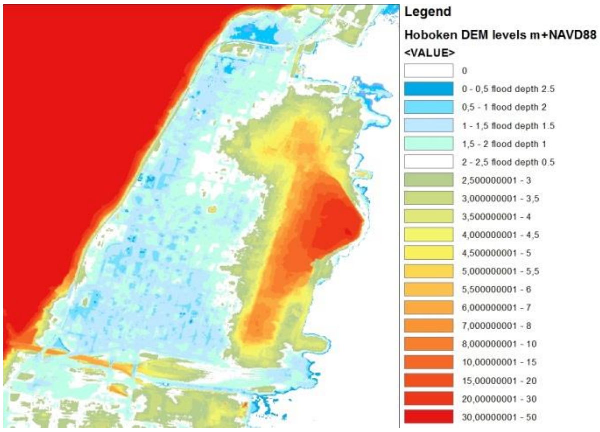
The first step further elaborates on the outcome of the model, namely the flood characteristics maintained in this research. They include the development of flood depth (in *m*) over time as a function of rainfall and water levels in the river. In the model it was assumed that the area is filled as a function of its elevation levels, following the hypsometric curve, so the flooded area (in m^2) is the second flood characteristic. The economic damage is related to the flood depth and the extent of the area that is flooded. The geographical dimension of the outcome of the model is visualized in flood maps in ArcGIS (Figure 42). The estimated spatial developments of these flood levels are studied in steps of half a meter. It has been investigated which areas are flooded with every added half a meter. In the flood maps of Figure 42 the different flood zones and their corresponding flood depths are visualized. In this approach flood duration is not taken into account, but it was assumed that the flood occurred for a period in which the area could fully flood. Routing is not included in this research. In reality water will develop in a different way, dependent on the source of the flood (i.e. flash flood or dike breaches at different locations), and may result in higher damages. The internal topography and the presence of internal boundaries, such as the ridges and buildings, could affect or stop the flood flow (Jonkman, et al., 2008). Further investigation to this subject is recommended.

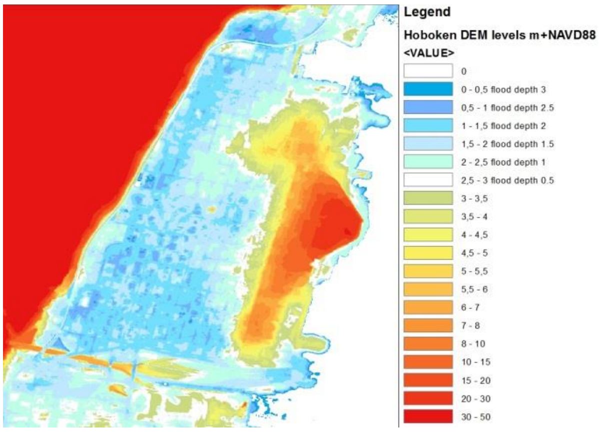












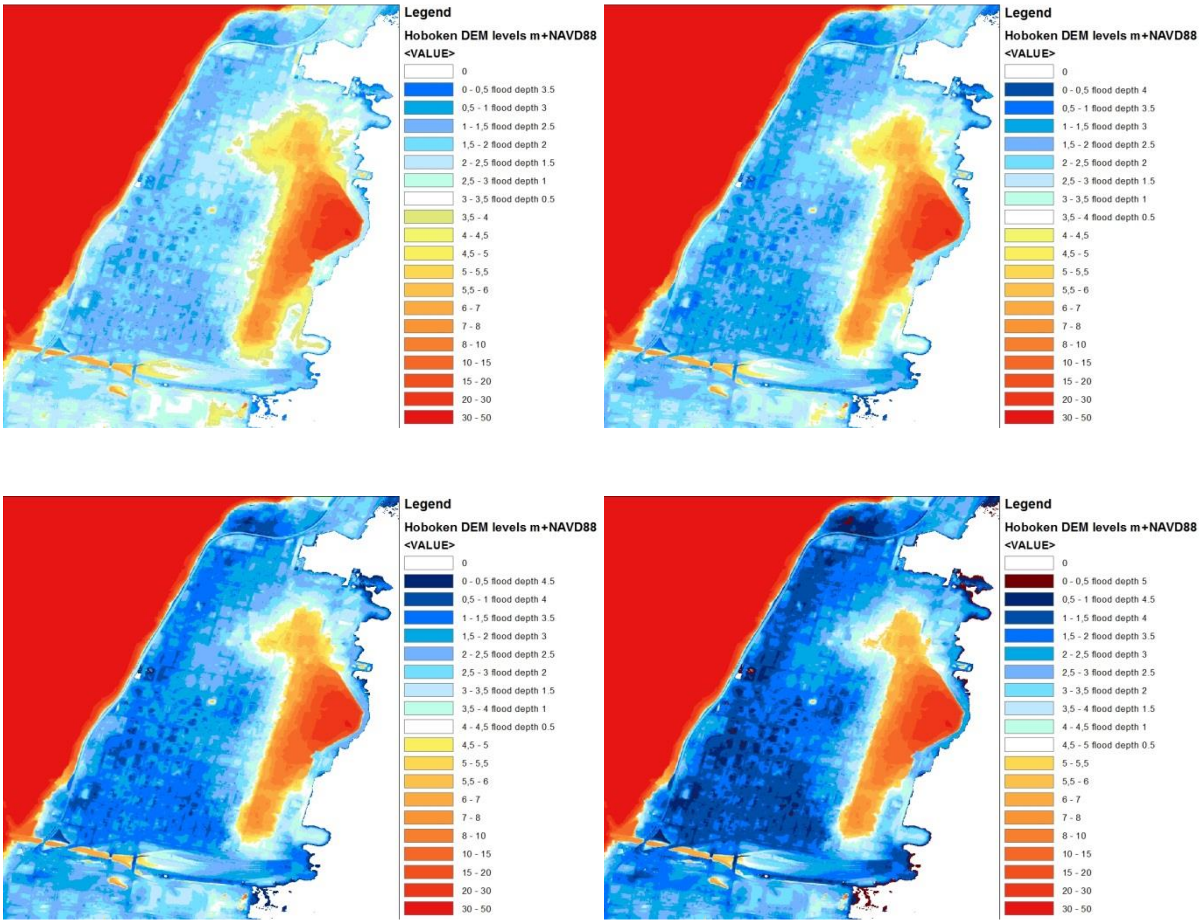


Figure 42 Flood maps Hoboken, varying from 0 to 5 m flood depth (ArgGIS)

4.3.2 Land use data and maximum damage amounts

Secondly the economic values of objects and zones in Hoboken have been investigated. For modelling flood damage in the Netherlands a distinction was made between five main categories and subcategories (Jonkman, et al., 2008). The classification of damage categories in Hoboken is based on these values. For the amount of maximum direct physical damage in the Netherlands different values were used from different sources. In Table 3 the following items are shown: the maximum damage amount per damage object and damages due to direct business interruption (economic loss when people are not able to continue their work) in terms of value per added working space. A damage object is for example a building or a meter road. The most suitable categories for Hoboken are included in the table.

In chapter 2 the surroundings of the City of Hoboken were described. In order to investigate the damage categories shown in Table 3, the City is first of all divided in several subareas to study the vulnerability of the region. The two main distinctions used in this study are a division in census tracts and a division in land use zones. A census tract is a geographic area used for the census defined by the United States Census Bureau. A census tract normally covers a smaller area than a city or zip code and is uniformly distributed in terms of the number of residents, on average 4,200 residents (based on the U.S. 2010 Data). Census tracts are often used to compare and study smaller scale locations inside and across multiple states.

For each census tract the main land uses are determined and an investigation is done about the amount of objects of the damage categories in the census tract. In Figure 43 the different census tracts, are divided in letters A to N. In these figures land uses in Hoboken were projected on the census tracts. This way for each census tract, the main land uses can be filled in more in detail.

Table 3 Maximum damage amounts (based on (Jonkman, et al., 2008))

Damage Category	**Damage sub-category**	**Unit**	**Maximum damage ($)**	**Value (unit)**
Land use	Urban area	Square meter	$67	3315185
Infrastructure	Major roads	Meter	$1.343	4100
	Other roads	Meter	$370	50000
	Railways	Meter	$34.250	5200
Households	Houses (low/middle/high rise)	Object	$235.640	26855
Companies	Industrial District (industry)	Value added per work space	$382.230	11496
	Electric substations	Value added per work space	$849.400	3
	Trading, catering, commercial, retail	Value added per work space	$27.400	2590
	Banking and insurance	Value added per work space	$123.300	4
	Transport (Transit)	Value added per work space	$102.750	2
Other	Pumping stations	Object	$1.027.500	1
	Water purification installations (sewer)	Object	$15.070.000	1

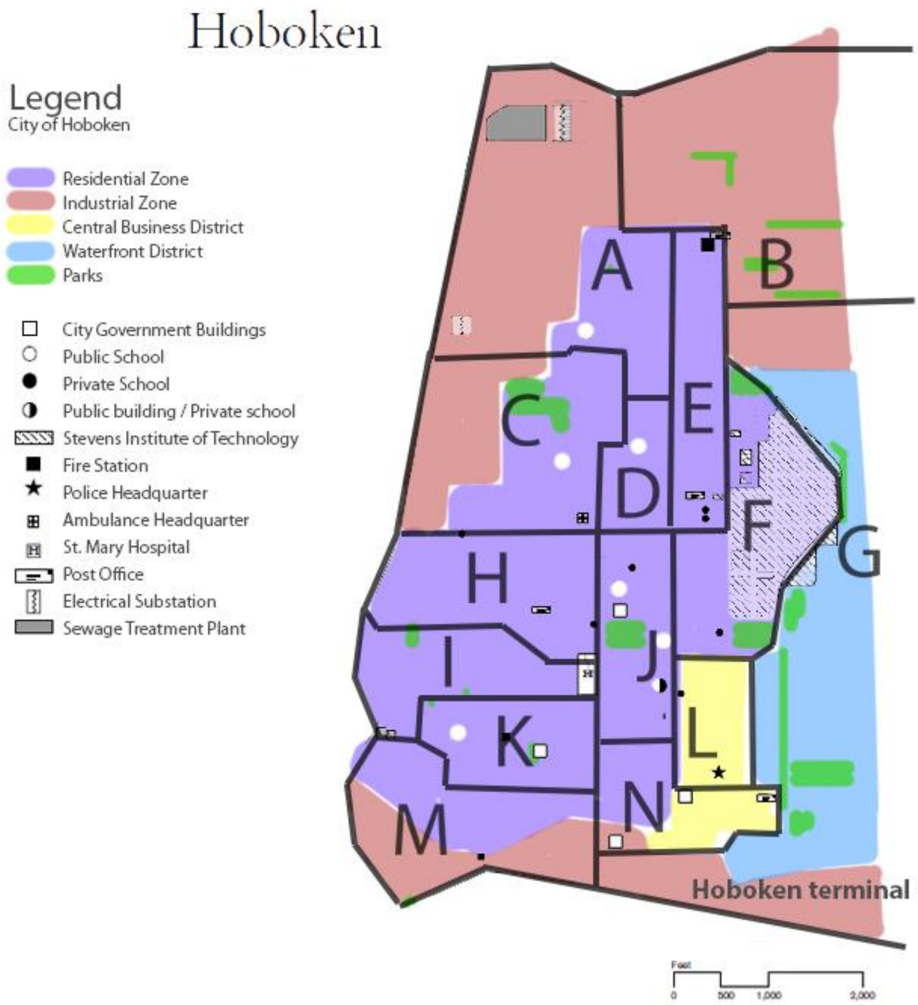


Figure 43 Land use Hoboken (based on maps and information in (Hoboken Planning Board Master Plan, 2003))

The zones, categorized in main land uses in the City of Hoboken, are also illustrated in Figure 43 in different colors. Hoboken can be divided in the following zones: the residential districts, the industrial districts and the review districts (Hoboken Planning Board Master Plan, 2003). The buildings in Hoboken are generally low-rise to mid-rise, from two to five stories. Some recently constructed buildings contain over ten stories. It was estimated that approximately 4,100 m of major roads, 5,200 m of railways and 50,000 m of other roads can be found in Hoboken. Parks in Hoboken are shown in green in the figure.
The three residential districts in the City are illustrated in purple in the figure. Residential buildings and retail businesses and services are permitted uses in all three residential districts. Additional uses such as schools or restaurants are permitted in these zones. One residential subdistrict covers the campus of Stevens Institute of Technology.
The industrial zone, in red in the figure, consists of the northwest corner of Hoboken, which takes a large portion, the entire southern border, which is smaller, and the entire northeast waterfront area. The industrial uses contain office buildings, research laboratories, warehouses, food processing, storage and distribution, manufacturing, retail businesses and services and public buildings and uses. A mix of residential, commercial, industrial, public, or quasi-public uses can be found in the industrial area.
The City's two review districts are the Central Business District in yellow and the Waterfront Zone in blue. In the Central Business District a wide variety of commercial and residential uses can be found. The Waterfront District includes the Hoboken Terminal, Sinatra Drive along the western edge, and the South Waterfront Redevelopment Area.
In Table A of Appendix I, for each census tract the main damage categories were included. Per census area the maximum damage amount has been calculated. These values are summarized in Table B of Appendix I. A main distinction has been made between roads, houses, businesses and other.
It has been investigated which census zones are affected, with the help of the flood maps and the land use map. In section D Appendix I some examples of the projection of the ArcGis maps on the land use maps are illustrated. From this information it has been estimated how much percent each census tract is additionally flooded per flood depth. These values are included in Table F of Appendix I.

4.3.3 Application stage-damage functions

At last the damage per flood depth has been calculated based on the maximum flood depth of an object. The fraction of maximum damage as a function of the water depth flood characteristic to objects can be estimated by the stage-damage functions for the different types of land use and objects. The values are based on stage damage curves from (CUR, et al., 1990). In Table 4 the stage-damage values for Hoboken are listed.

Table 4 Stage-damage values for Hoboken as a function of flood depth

Stage-damage values for Hoboken	**0.5 m**	**1 m**	**1.5 m**	**2 m**	**2.5 m**	**3 m**	**3.5 m**	**4 m**	**4.5 m**	**5 m**
Roads	0.2	0.4	0.6	0.8	1	1	1	1	1	1
Houses	0.125	0.25	0.375	0.5	0.625	0.75	0.875	1	1	1
Businesses	0.2	0.4	0.6	0.8	1	1	1	1	1	1
Other	0.2	0.4	0.6	0.8	1	1	1	1	1	1

4.3.4 Resulting damage curve

The total estimated direct damage follows from the combination of flood characteristics (water depth and location), land use data, maximum damage values and stage-damage functions. Therefore these values are related and the damage at different flood levels has been determined. In Table G in Appendix I these damages are summarized for the total area. The values for each census tract as a function of flood depth and flood extent are added for this purpose. The results are the estimated damage for a calculated model flood depth as a function of flood extent. This result is illustrated in Figure 44 and Table 5.

From the damage assessment the damage flood function can be concluded, as shown in Figure 44. The damage curve is expressed per meter of flood depth.

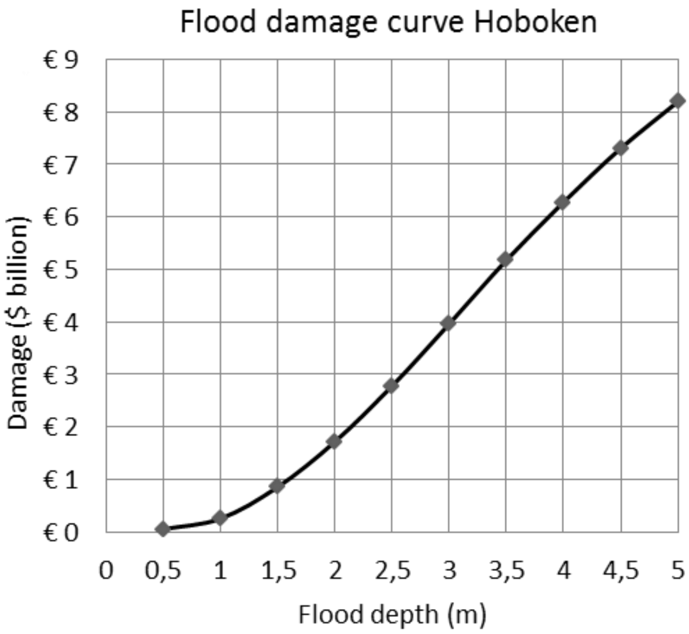


Figure 44 Damage curve Hoboken

In Table 5 the estimated flood damages for the flood characteristics in Hoboken are summarized. The damage curve has been compared to the damage that was estimated after Hurricane Sandy. The damage was estimated between $300 million and $750 million (OMA, 2014). From the hydrologic model computations, it followed that the maximum flood depth during Hurricane Sandy was 1.5 meter. The amount of $850 million from the modeled damage amount comes relatively close to this amount. It can be concluded that the damage function gives a realistic first-order estimate of direct economic flood consequences in Hoboken. For detailed verification of the damage function, further research is recommended.

Table 5 Flood damage Hoboken

Damage	Max flood level	h	A (m^2)	% flooded
$M 54	0,5	0-0.5	15.175	0.47
$M 252	1	0-1	167.025	5.2
$M 853	1,5	0-1.5	926.350	29
$B 1.7	2	0-2	1.602.175	50
$B 2.8	2,5	0-2.5	2.011.225	62
$B 4.0	3	0-3	2.240.625	69
$B 5.1	3,5	0-3.5	2.431.125	75
$B 6.3	4	0-4	2.568.975	79
$B 7.3	4,5	0-4.5	2.658.000	82
$B 8.2	5	0-5	2.722.625	84

4.4 Determination current flood risk

The current safety level of the flood protection system is approximately 23 years for the waterfront protection and approximately 1 year for the water management system (section 4.2). In this section the flood risk of the current situation in Hoboken is determined and expressed in terms of expected value of loss.

In section 4.2, computed hourly and annual maximum flood levels over 1,000 years were discussed. In this section the highest expected losses per year have been determined, based on the annual maximum flood levels. Flood events that are smaller than the maximum annual flood levels are neglected.

4.4.1 Theory

For the determination of the safety level, the risk is capitalized (Civil Engineering Lecture Notes, 1997) and written as:

$$P_{f_i} \cdot S \quad [\$/\text{year}]$$

In which P_{fi} = failure probability of the system concerning activity i [1/ year] and S = total damage.
This is the expected value of the amount of loss every year.
When the consequences are insured, the risk can be seen as the insurance contribution that has to be paid every year. When inflation is included, this contribution will increase:

$$P_{f_i} \cdot S \cdot (1+i)^n$$

In which i = inflation.
The present value of the risk (C), which is the capitalized sum of the insurance contribution that has to be paid during the lifespan (N) of the measures, is:

$$C = \sum_{n=1}^{N} \frac{P_{f_i} \cdot S \cdot (1+i)^n}{(1+r)^n}$$

In which r = rate of interest.
For small values of the inflation and the rate of interest the present value may also be written as:

$$C = \sum_{n=1}^{N} \frac{P_{f_i} \cdot S}{(1+r-i)^n} = \sum_{n=1}^{N} \frac{P_{f_i} \cdot S}{(1+r')^n}$$

In which r' = actual rate of interest = r-i.
Economic growth also influences the value. It increases the value of the objects that are involved with failure of the system. The risk grows in real terms:

$$P_{f_i} \cdot S \cdot (1+g)^n$$

In which g = growth rate.
The present value of the increasing risk becomes now:

$$C = \sum_{n=1}^{N} \frac{P_{f_i} \cdot S}{(1+r'-g)^n}$$

Over the entire future (N = ∞) the present value of the risk (expected value of loss) converges to:

$$C = \frac{P_{f_i} \cdot S}{r'-g}$$

4.4.2 Calculation expected value of loss (present value of risk)

The probability of occurrence of a flood equals the probability of failure of the flood protection system. The probability of occurrence of each annual maximum value is investigated to calculate the expected highest value per year. For this reason the sample size is reduced from an hourly basis to a yearly basis.
The expected value of the annual maxima of the flood level represents the highest expected flood level per year. The highest expected loss per year can be calculated by multiplying the annual maximum flood levels by their damage factor (damage curve). Expected loss is the value of a possible loss times the probability of that loss occurring.
The expected value of a function $f(x)$ (flood level $F(x)$ or damage $S(x)$) in a variable x (sample of 1000 years) can be denoted or $E\{f(x)\}$. It can be defined by:

$$E\{f(x)\} = \sum_{j=1}^{M} f(x_j) \, / \, M$$

where M is the number of observation in sample size x. Within a sample size of 1,000, the highest expected flood level $E\{F(x)\}$ per year is 0.14 m and the total expected loss $E\{S(x)\}$ per year is $\$ \, 16.3 \, million$.
For the calculation of the present value of the yearly expected damage, a number of pragmatic assumptions has to be taken to estimate the future development of the expected damage. These assumptions follow from the study of (Jonkman, et al., 2008). The discount rate in this study is adjusted for economic growth and the yearly probability and is concluded with a net discount factor of $r' - g$ = 2% per year. These assumptions include: an infinite time horizon for investments in flood defences for at least 50-100 years; a real discount rate of 4% (long-term historical interest rate (6%) minus inflation (2%)); yearly increase in damage of 1% due to economic growth; increase of flooding probability of 1% per year due to sea level rise; ‘risk neutral’ policy makers and citizens.
The present value of risk for the current situation in Hoboken over the entire future converges to:

$$C = \frac{P_{f_i} \cdot S}{0.02} = \$ \, 817 \, million$$

In section 4.2 pluvial events were characterized in flood levels up to 0.27 meter and it was estimated that in 1,000 years 95.6 % of the annual maximum flooding occurred due to rainfall events. 4.4 % of the annual extreme flood events were contributed to coastal flooding. The question arises which flood events (pluvial or coastal) contribute more to the expected value of loss (C).
In Figure 45 for the current situation the extreme flood levels, damages and their return periods are illustrated. It was found that between return periods of 0 and 23 years pluvial floods occur, with flood levels up to 0.27 meter. Between 23 and 1,000 year return periods flooding can be contributed to coastal events.

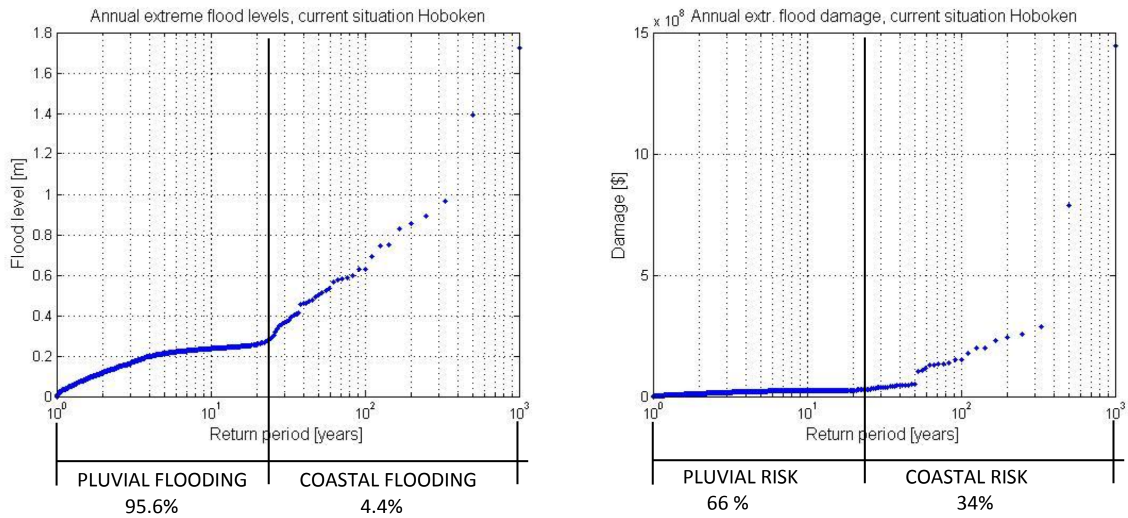


Figure 45 Current situation return periods flood levels and damage in Hoboken

As clearly visible, in the left-hand tail most flood points are registered (95.6% pluvial floods). The right-hand tail consists of 4.4% of coastal flood events. It has been calculated what the expected loss is due to pluvial and coastal events:

$$C_{PLUVIAL} = \frac{\sum S_{PLUVIAL}/1000}{0.02} = \$\,538\,million$$

and

$$C_{COASTAL} = \frac{\sum S_{COASTAL}/1000}{0.02} = \$\,279\,million$$

$$C_{COASTAL} + C_{PLUVIAL} = \$\,817\,million$$

It can be concluded that 66% of the flood damage in the current situation is caused by pluvial events and 34% of the damage by coastal events. As only 4.4 % of the floods are coastal floods it can be concluded that the consequences of coastal floods are much larger, but still the higher frequency of the pluvial – much smaller – floods results in more expected flood damage for the future:

pluvial flood risk = probability x **consequence**

coastal flood risk = probability x consequence

When combinations of flood risk reduction measures are investigated, it becomes clear which risk reduction measures (pluvial versus coastal) will have most impact on reducing the risk of Hoboken.

4.5 Possible flood reduction measures

To cope with the flood challenges, both flood risks due to storm surge and extreme rainfall events, are addressed comprehensively. The strategy to search for optimal flood protection in Hoboken includes coastal flood defences, reducing the risk of storm surge flooding, and green infrastructure and drainage possibilities, reducing the stormwater flood risk. The latter is in line with the already scheduled Hoboken Green Infrastructure Strategic Plan (Together North Jersey, 2013). The comprehensive urban water strategy deploys programmed hard infrastructure and soft landscape for coastal defence (*Resist*);

a circuit of interconnected green infrastructure to *store* and direct excess rainwater (*Store*); and water pumps and alternative routes to support drainage (*Discharge*) (OMA, 2014). This study focuses on a coastal defense at Hoboken Terminal and surroundings, a coastal defense at Weehawken Cove, water pumping stations, a greenbelt and green infrastructure.
In section 4.7, different combinations of *Resist*, *Store* and *Discharge* measures have been evaluated for Hoboken. In this section the possibilities for these risk reduction measures are discussed.

4.5.1 Resist

The current waterfront elevations at Hoboken were shown in the elevation map in Chapter 2. As the lowest waterfront elevation levels can be found around Hoboken Terminal and the Weehawken Cove area, the two development sites are here. In (OMA, 2014) possible flood defences in the area were investigated. For Hoboken Terminal and surroundings hard infrastructure that do not require a lot of space were addressed, because it is a highly developed area and Hoboken Terminal is located here
The chosen location is, in longitudinal direction from the waterfront elevation map, between 0-2,000 m. For Weehawken Cove a soft landscape coastal defence was selected (OMA, 2014).

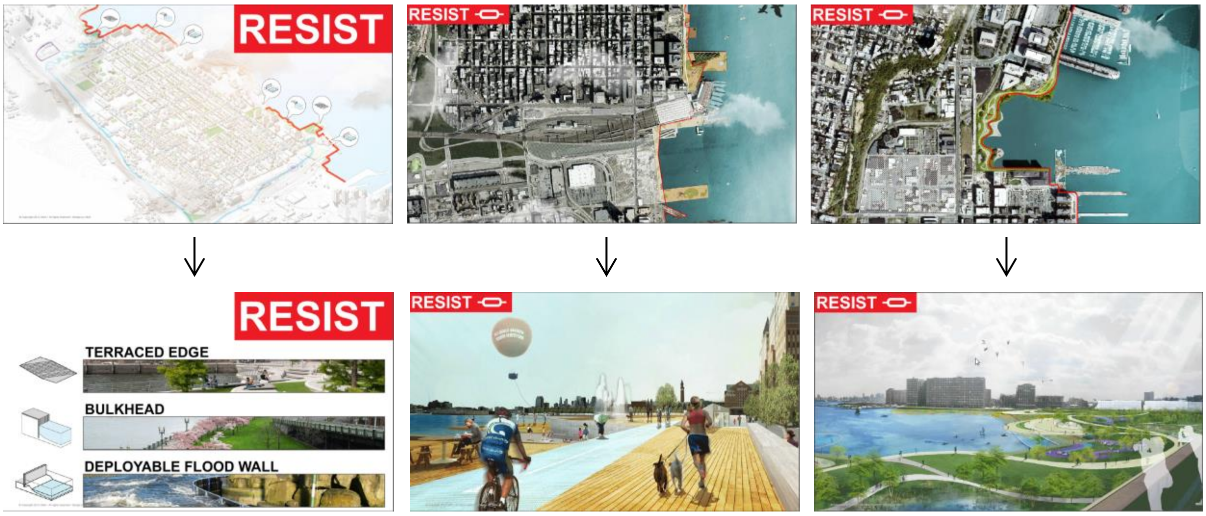


Figure 46 OMA – Resist (Rebuild by Design), flood risk reduction measures location and impression: left: overview, middle: Hoboken terminal, right: Weehawken cove (OMA, 2014)

The location at Weehawken Cove, is between 3,200 m – 4,700 m in the longitudinal waterfront section. This means that this waterfront section covers on estimate 3.5 kilometers (section 2.2). In Figure 46 the two development sites are illustrated and impressions of possible flood protection are shown, designed by (OMA, 2014).
The flood defence in this study is schematized and expressed in terms of additional flood defence height. Three values for *Resist* have been selected: do nothing; increase the flood defence with 0.8 m; and with 1.8 m. These were selected by testing different values of flood defence in the model for the scenario of Hurricane Sandy (model plots in Appendix II). When the flood defence is heightened with 0.8 m, it is exceeded 2 times by water levels in 1,000 years. When it is heightened with 1.8 m, it will not be exceeded in 1,000 years.

4.5.2 Discharge

Hoboken's current discharging system consists of the combined sewer system and one wet weather pump. It has been concluded that the capacity of discharging in Hoboken is too low to reduce flooding. One of the measures that fit the Green Infrastructure Plan of Hoboken is increasing the discharge capacity in the city. Water pumps and alternative routes to support drainage can be built (OMA, 2014). In Figure 47 the proposed drainage plans from team OMA of Rebuild by Design and Hoboken Green Infrastructure Plan are illustrated.

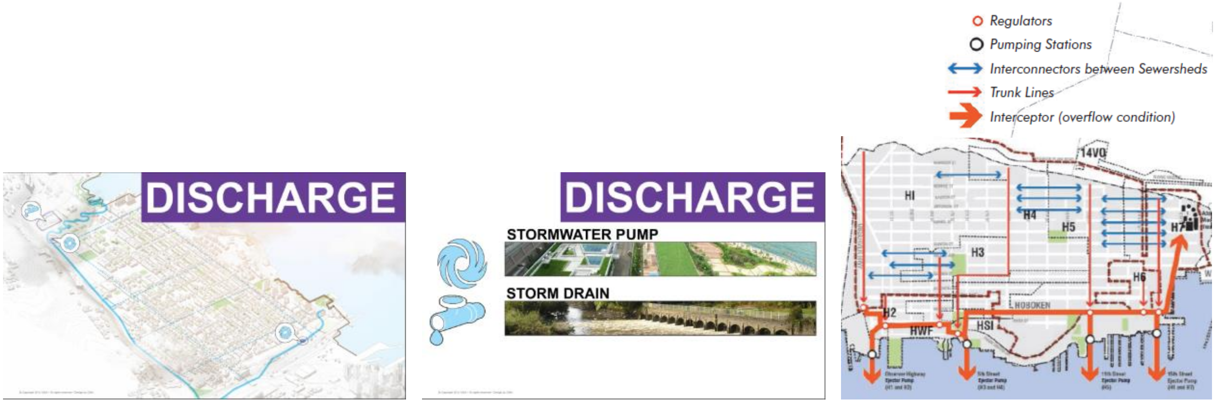


Figure 47 OMA – Discharge (Rebuild by Design) (OMA, 2014); Green Infrastructure Strategy Plan Hoboken Discharge (Together North Jersey, 2013)

For the schematization of extra discharge capacity additional pumps are considered. It has been investigated what the relevant starting point of risk reduction is. This was done by testing discharging measures for the flood scenarios of Hurricane Sandy, Tropical Storm Irene and a street flooding event. The testing plots are illustrated in Appendix II. Four options were selected: do nothing, increase the capacity with a small pump of 2,100 m^3/h; increase the capacity with 92,100 m^3/h; and increase the capacity with 992,100 m^3/h.

4.5.3 Store

For increasing the storage capacity several different possibilities may be constructed, such as underground water reservoirs or building green infrastructure at several places in the city to store and direct excess rainwater. In Hoboken Green Infrastructure Strategic Plan (Together North Jersey, 2013) practical measures and optional alternatives were discussed. They include green infrastructure, such as a green belt, and create numerous alternative options for solving our storage design problem. They can help to reduce the overall volume of stormwater generated on the streets. The possibilities that were considered for use in Hoboken are: Constructed wetlands, Permeable pavements, Stormwater street trees, Vegetated swales, Rainwater harvest and reuse, Basins or ponds, Rain gardens, Stormwater infiltration planters, Subsurface storage or Green roofs (Together North Jersey, 2013).

Figure 48 OMA – Store (Rebuild by Design) (OMA, 2014); Hoboken Green Infrastructure Strategic Plan (Together North Jersey, 2013)

In this study storage is expressed as a total volume of extra storage. The three values that were selected are: do nothing; increase storage area by 5 ha; increase storage area by 50 ha. For these areas half a meter of storage height is selected. The values have been selected by testing storage measures for the flood scenarios of Hurricane Sandy, Tropical Storm Irene and a street flooding event. The testing plots are illustrated in Appendix II.

4.6 Investment costs

In this section the required investments in the flood protection system of each measure are investigated. The physical measures in this case consider flood defence heightening; increasing discharge capacity by building water pumps; and increasing storage capacity. As failure only occurs due to overflow or exceeding capacities, it is assumed that the elements in the flood protection system are constructed in such a robust way that they are functioning well for different safety levels.
Five cost factors mainly determine the unit costs of a design: planning and engineering costs, material costs, labour costs, implementation costs and management and maintenance costs (Jonkman, et al., 2012). For a preliminary estimation the first four factors are combined and defined as construction costs. Maintenance costs are additional costs that have to be paid every year over the lifetime of a structure.

4.6.1 Construction costs

The construction costs include several aspects that determine the value. First of all planning and engineering costs concern the design and planning of the coastal defence. In residential areas with nonuniform and complex conditions, such as Hoboken, these unit costs are relatively high. The costs of materials depend on local and regional market prices. In deltaic regions, there is sometimes a scarcity of construction materials and material costs could influence the unit price of different measures. The implementation costs are mostly dependent on two factors: land use by flood defences and the difference between rural or urban implementation. The land width required for flood defence increases with height. Obtaining this land is financially and legally challenging, and can be a costly and time-consuming task. This can be a problem when space is scarce in urban environments (Jonkman, et al., 2012).
The required waterfront section that has to be covered is estimated on 3.5 kilometers (section 2.2).
When both flood walls as levees are considered, the construction costs can be estimated on:

$$I_{c,RESIST} = \$\ 20{,}000\ /\ m/m$$

for Hoboken (OMA, 2014). In this study the estimated construction costs are assumed to cover most of the discussed matters for construction costs in Hoboken and are a first estimation of the cost aspects for urban area in which complex situations in residential area and higher implementation costs play an important role, as is the case for Hoboken. For the 3.5 kilometers covering the waterfront near Weehawken Cove and Hoboken Terminal area, this means $ 70 million/m. For increasing dike height, a larger footprint is required. This concerns nonlinear growth and it corrected with a factor (OMA, 2014).
Several components play a role in the determination of the costs of a pumping station. From this study first estimates for several pumping station investment costs are concluded.
The estimated price of a pump station is based on the current pump of Hoboken and a large pump in New Orleans (Western Closure Complex New Orleans). The price of the existing wet weather pump in Hoboken, with a capacity of 7,900 m^3 /h, was 18 million dollars in 2011 (Royal HaskoningDHV). The Western Closure Complex in New Orleans has a much higher capacity of almost 2 million m^3 per hour and cost $ 1,000 million, including a flood gate of 150 ft. The costs of the pumping station are estimated on $ 800 million (expert judgement). The price per unit of m^3/h is estimated by considering a linear relation between the pump in Hoboken and the one in New Orleans. This relation is:

$$I_{c,DISCHARGE} = 497 \cdot D + 14.9\ \cdot 10^6$$

in which investment costs I_c is in US $ and the pumping discharge capacity D is in m^3/h. In this relation the investment costs of one pump with the required capacity are taken into account. The electricity costs, which will play a role anytime the pump has to be put into operation, are not included.
For increasing the storage discharge capacity several different possibilities may be constructed, such as underground water reservoirs or building green infrastructure at several places in the city. For these storage areas half a meter of storage height was selected. The investment costs follow from the Hoboken Green Infrastructure Strategic Plan (Together North Jersey, 2013), in which cost estimations for green infrastructure at most suitable locations in Hoboken were made. The mean value of these costs is taken into account. The table is included in Appendix IV. The value can be approximated by:

$$I_{c,STORE} = \$ 3 \text{ million / ha} * 0.5\text{m}$$

4.6.2 Maintenance costs

Proper management and maintenance of defences is essential and represents an ongoing annual cost: poor management and maintenance increases the risk of defence failures (Jonkman, et al., 2012). Therefore the investments costs have to include the costs of additional expected costs of management and maintenance M over the lifespan T. The costs of maintenance will include small operations and reparations on the coastal flood defences, pumps and green infrastructure, such as maintenance of the structures, replacement and regular inspection. Additionally, an organization is needed for the management and maintenance of flood defences, requiring additional annual costs to maintain. The maintenance costs are calculated by:

$$PV(M) = E(M) \cdot \sum_{i=0}^{i=T} \frac{1}{(1+r)^i}$$

In which $PV(M)$ is the present value of the expected maintenance and $E(M)$ is the yearly expected maintenance cost and r is the real effective rate of interest (Mai, et al., 2008). The management and maintenance costs depend on the character of the variant (low versus high maintenance and management). In this project these costs vary from 1% to 2% of the upgrade costs per year for Resist (Jonkman, et al., 2012), 7% for Storage (Together North Jersey, 2013) (Appendix III, Q), and 5% for Discharge (expert judgement). It is calculated over 50 years.

4.6.3 Conclusion

When all costs for the variants are summarized, the following values follow (Table 6). A detailed overview is included in Appendix III. The sum of the construction costs and maintenance costs is the total value of the investment costs:

$$I = I_c + PV(M)$$

The cost estimates are first order and indicative. For a realistic calculation of investment costs, more detailed designs have to be used. On the other hand there will be benefits of the future urban water system and enhanced (green) living environment, like: increase of value area due to green, saving drainage costs when storage covers discharge capacity, and such. These values are not included.

Table 6 Investment costs

Measure	Change in flood protection	Price per unit	Total flood protection	Ic (10^6)	PV(M) (10^6)	I (10^6)
Resist 0	-		0.2 m (2.2 m +NAVD88)	0	0	0
Resist 1	0.8 m heightening	$ 20,000/m/m * 1.2	1 m (3 m +NAVD88)	$ 67	$ 32	$ 99
Resist 2	1.8 m heightening	$ 20,000/m/m * 1.45	2 m (4 m +NAVD88)	$ 182.7	$ 33.4	$ 216
Store 0	-		421,214 m^3	0	0	0
Store 1	5 ha * 0.5 m added storage	$ 3 x10^6 /ha/0.5m	446,214 m^3	$ 15.7	€ 31.8	$ 48
Store 2	50 ha * 0.5 m added storage	$ 3 x10^6 /ha/0.5m	671,214 m^3	$ 157.5	€ 41.7	$ 199
Discharge 0	-		7,900 m^3/h	0	0	0
Discharge 1	2,100 m^3/h extra cap	497*C + M14.9	10,000 m^3/h	€ 14.4	€ 31.4	$ 46
Discharge 2	92,100 m^3/h extra capacity	497*C + 14.9 x10^6	100,000 m^3/h	€ 59.2	€ 33.6	$ 93
Discharge 3	992,100 m^3/h extra capacity	497*C + 14.9 x10^6	1,000,000 m^3/h	€ 506.5	€ 56.0	$ 562

4.7 Results for finding the economic optimal decision

In this section the economic optimal flood protection system in Hoboken is determined. The probability of flooding can be reduced by applying the measures in the system, so the different combinations of flood risk reduction measures (*Resist*, *Store* and *Discharge*) have been tested. This implies a reduction in the present value of risk, but on the other hand an increase of the total investment I (Civil Engineering Lecture Notes, 1997). This means that for the analysis of safety of different combinations of measures the new safety level (and risk reduction) and the investment costs will be determined for every combination. The current level of safety will be compared to the new results. The total costs C_t are defined as the sum of the present value of the expected loss and the investment costs:

$$C_t = C + I$$

In which

$$C = \frac{P_{f_i} \cdot S}{r' - g}$$

And

$$I = I_c + PV(M)$$

When the three flood risk reduction activities are combined, a total of thirty-six activities is the result. For each combination of measures, the new flood levels for the synthetic 1,000 years of precipitation and water levels were calculated by the model. For every combination the annual maximum flood levels and consequently the annual maximum damages were determined. From these results the expected value of loss per year, the net present value of risk and the amount of risk reduction can be calculated. The total investment costs for each combination can be determined by:

$$I = I_{RESIST} + I_{DISCHARGE} + I_{STORAGE}$$

When the investment costs are lower than the risk reduction (ΔC_t / ΔI > 1), the combination is interesting, as it results in a benefit. The decision for the most economical optimal combination is in this study found for the activity of which the sum of the total costs is lowest:

$$\text{Economic optimal decision} = \text{activity} (\min (C_t))$$

4.7.1 Input: loads and strengths

The decision making strategy of finding an economic optimum was applied for Hoboken. The created synthetic 1,000 years of water levels and precipitation were used to calculate the flood levels for the several combinations of flood protection measures (Figure 49). In the left plot the three possible values of Resist are illustrated: current situation; heightening of the dike with 0.8 m; and heightening with 1.8 m. The storage possibilities that were considered are creating: no additional storage; 5 ha x 0.5 m of storage; and 50 ha x 0.5 m of storage. For discharge this was: do nothing; building a pump with a capacity of 2,100 m^3/h; 92,100 m^3/h (10 times the current one); and 992,000 m^3/h (100 times current) (Table 7). The choice for these measures was explained in section 4.5. When all possible combinations of these risk reduction measures are considered, 36 activities are the result.

Table 7 Flood risk reduction measures

Resist (m)	Store (ha 0.5m)	Discharge (m^3/h)
0	0	0
0.8	5	2,100
1.8	50	92,100
		992,100

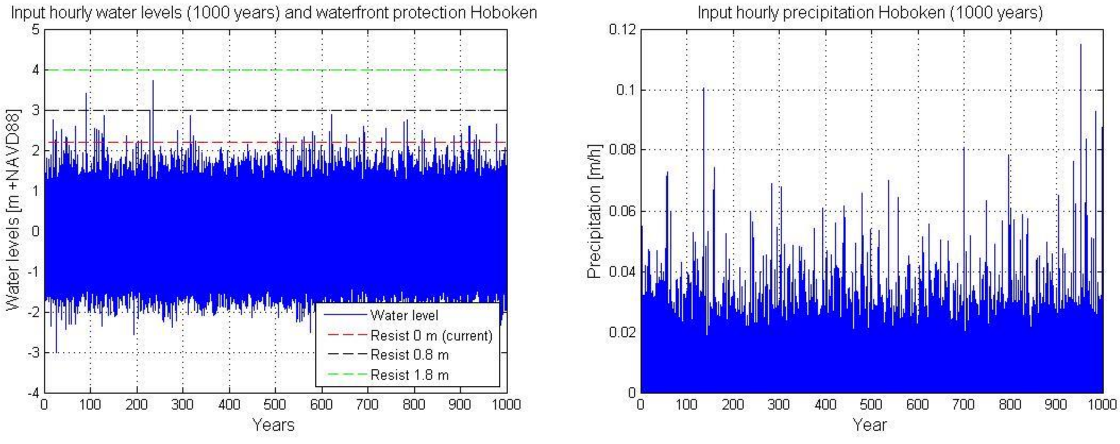


Figure 49 Input for determining optimal combination

4.7.2 Output: investment costs, flood risk and total costs

For each of the 36 activities the annual maximum flood levels and damage levels were determined and the Investment costs (*I*), present value of risk (*C*), total costs (C_t), risk reduction (ΔC) and return rate ($\Delta C_t / \Delta I$) were calculated. All combinations are listed in the table of Appendix VIII, in increasing order of total costs (C_t). The first activity in the list (activity 23) is the optimal combination in terms of total costs and the last activity (activity 34) is the most unattractive activity. The top 10 of total lowest costs are illustrated in Table 8.

Table 8 Top 10 lowest costs combinations economic optimization

#	*Activity*	Resist (m)	Store (ha0.5m)	Discharge (m^3/h)	I (10^6)	C (10^6)	C_t (10^6)	ΔC (10^6)	ΔC /ΔI
1	*23*	0.8	5	92,100	$232	$131	$363	$686	3.0
2	*39*	1.8	5	92,100	$349	$20.2	$369	$797	2.3
3	*19*	0.8	0	92,100	$184	$225	$409	$592	3.2
4	*35*	1.8	0	92,100	$301	$114	$415	$703	2.3
5	*25*	0.8	50	0	$298	$126	$424	$691	2.3
6	*41*	1.8	50	0	$415	$14.0	$429	$803	1.9
7	*7*	0	5	92,100	$133	$316	$448	$502	3.8
8	*26*	0.8	50	2,100	$345	$125	$470	$692	2.0
9	*42*	1.8	50	2,100	$462	$13.0	$475	$804	1.7
10	*3*	0	0	92,100	$84.6	$399	$484	$418	4.9

** Activity numbers higher than 36 were found in the table as originally 64 combinations were tested. Only 36 activities were further elaborated in this study.*

The first outcome of the model is an economic optimal combination of:
- 0.8 m of flood defence heightening;
- 5 ha x 0.5 m of storage volume;
- A water pump capacity of 92,100 m^3/h.

For the optimal combination, the present value of the risk is $ 363 million and the investment costs are $ 232 million. The combination results in a flood risk reduction of $ 686 million compared to the current situation, which gives a value of $\Delta C_t / \Delta I$ = 3.0. This means that the return time is acceptable. In the United States commonly flood infrastructure with values higher than 2 or 3 are constructed (expert judgement). In the following sections the top 10 combinations are evaluated.

4.7.3 Safety levels

The current safety level of Hoboken is approximately 1 year for pluvial flooding and approximately 23 years for coastal flooding. In this section the safety levels for different combinations of coastal and pluvial flood risk reduction measures are discussed.
For the variety of combinations, the ranked annual maximum flood and damage levels and their corresponding return periods are illustrated in Appendix V. In these figures the lowering of pluvial floods (dense left-hand tails) for implementing *Store* and *Discharge* capacities, and the reduction of the coastal floods (right-hand tails) for *Resist* measures, are clearly visible. The safety level of each combination has been estimated from these figures. The safety levels of the top 10 combinations with the lowest costs are summarized in Table 9.

Table 9 Safety levels of combinations (SL P = safety level pluvial, SL C= safety level coastal, SL T= safety level total, all in years)

Store [ha0.5m]	Discharge [m^3/h]	Resist =0 m		Resist =0.8 m		Resist =1.8 m	
		SL P	SL C	SL P	SL C	SL P	SL C
0	0	1	23	1	500	1	1,000+
	2,100	1	25	1	500	1	1,000+
	92,100	8	25	10	500	10	1,000+
	992,100	10	35	10	500	15	1,000+
5	0	1,5	25	2	500	1,5	1,000+
	2,100	2	25	2	500	2	1,000+
	92,100	10	25	**25**	**500**	20	1,000+
	992,100	1,000+	45	1,000+	500	1,000+	1,000+
50	0	15	25	40	500	45	1,000+
	2,100	15	25	50	500	55	1,000+
	92,100	25	30	300	500	1,000+	1,000+
	992,100	1,000+	45	1,000+	500	1,000+	1,000+

The safety level of a flood defence of *0.8 m* is 500 years, as it is exceeded by high water levels 2 times in 1,000 years (Figure 49). The flood defence of *1.8 m* is not exceeded in 1,000 years, so it has a safety level higher than 1,000 years. From Table 9 it follows that the safety levels of combinations with *Resist = 0 m*, become higher with increasing values of *Store* and/or *Discharge*. This is contributed to the fact that storing and discharging flood measures are able to reduce a certain amount of coastal flood water.

Furthermore it can be found that the safety level for the same combination of *Store* and *Discharge* can vary for another value of *Resist*. This can also be seen in the figures in Appendix V: the lower flood levels in the left-hand tails are eliminated. When a higher flood defence is built, the income of coastal flood water is decreased. This means that the *Store* and *Discharge* measures, are less often exceeded by coastal floods and more capacities of *Store* and *Discharge* are available for reducing pluvial floods, when they would occur at the same time.

Another reason of this reduction in lower floods levels with increasing *Resist*, is that some part of the lower floods are caused by small coastal floods. However, in this study flood levels lower than 0.27 m were contributed to pluvial floods. Further investigation to this matter is recommended.

At last it can be seen that – for a combination of *Storage=5 ha* & *Discharge=0 ha*) the pluvial safety level of implementing a flood defence of *1.8 m*, decreasing a little, compared the flood defence of 0.8 m. This small reduce in the pluvial safety level for a higher coastal defence, can be contributed to the fact that water can stay longer in the basis, for a higher flood defence.

It can be concluded that for the optimal combination of *Resist = 0.8 m*; *Store = 5 ha* 0.5 m*; and *Discharge = 92,100* m^3/h, the coastal flood defence in the system has been upgraded towards a safety level of 500 years and the pluvial system towards a safety level of 25 years. In Figure 50 for this combination, the ranked annual maximum flood and damage levels with their corresponding return periods are illustrated.

4.7.4 Optimal flood protection in Hoboken

From the top 10 combinations with lowest costs (Table 8), it can be found that these 10 combinations of flood risk reduction measures all include *Resist*, *Store*, and/or *Discharge* measures. This means that a combination of pluvial and coastal measures is more interesting for Hoboken than only implementing one type of flood risk reduction measures. Both coastal flooding as pluvial flooding, play significant roles in the matter of flood risk reduction.

The two combinations, which are highest in the list, include *5 ha* & *92,100* m^3/h, combined with *0.8 m* or *1.8 m* of flood defence. Other combinations with *0.8 m* and *1.8 m* in the list, include mixtures of *0* *ha*, *50 h*a, *2,100 m^3/h* and *92,100 m^3/h*. However, these combinations have higher investment costs or lower risk reduction, and therefore a higher sum of total costs than the optimal combination of *5 ha* & *92,100 m^3/h*. The risk reductions for the combinations of *50 ha* & *0 m^3/h* and *50 ha* & *2,100 m^3/h* are higher than the optimal combination. These combinations could become interesting for the City of Hoboken, if there are possibilities of lowering the investment costs of storage area. From Table 9, it follows that in this case the pluvial safety level would be increased to approximately 40-55 years.

In Table 8, two combinations with *0 m* of increased flood defence are found: combinations of *0 ha* & *92,100 m^3/h* (activity 3) and *5 ha* & *92,100 m^3/h* (activity 7). These combinations are found in the list of top 10 combinations with the lowest costs, due to their low investment costs. However, from Table 9 it can be found that the pluvial safety levels are 8-10 years and the coastal safety levels 25 years. Compared to the safety levels of the optimal combination –coastal safety level of 500 years and pluvial safety level of 25 years – this is a large difference. For only little more investment ($100 million), the safety levels increase tremendously. Besides, the benefit will be higher in the future ($184 million).

When the two highest combinations (*5 ha* & *92,100 m^3/h* with *0.8 m* or *1.8 m*) in the top 10 list are compared, it can be concluded that an increased flood defence of 0.8 m is most interesting. A flood defence of *1.8 m* is $117 million higher in costs, but compared to the risk, it reduces only $110 million more than the optimal combination. From the results it follows that for all combinations with *Resist =1.8 m*, the investment costs are higher than the risk reduction, compared to the optimal combination.

It can be concluded that for Hoboken a flood defence of *0.8 m* is the most attractive solution for Hoboken from an economical and safety point of view. The combination with *5 ha* of storage area & *92,100 m^3/h* of discharging capacity, is most beneficial. In Figure 50 the plots with ranked order extreme flood and damage levels for the optimal combination are illustrated.

When values in between storage areas of *5 ha* and *50 ha* would have been considered, the combination of *0.8 m* of flood defence heightening with a larger storage area (for example *10 ha*) and lower pumping capacity could become very interesting. It is recommended that these possibilities are further investigated.

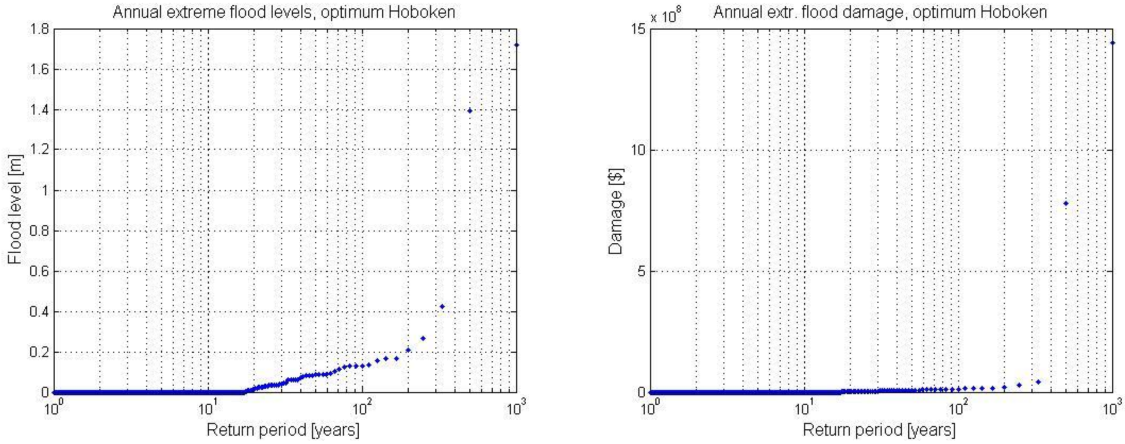


Figure 50 Ranked annual maximum flood and damage levels optimal combination (0.8 m; 5 ha; 92,100 m^3/h)

4.7.5 Effects of Resist, Store, Discharge and combinations

The flood levels and the flood risk in the city are dependent on the model input parameters for *Resist*, *Store* and *Discharge*. Each of these single measures has been varied and compared to the current situation. It was found that *Store* has most effect on risk reduction compared to the current situation, followed respectively by *Discharge* and *Resist*: in Table 10 it can be seen that the risk reduction is much higher for single activities of *Store* and *Discharge* than for *Resist*. As *Resist* measures serve for coastal flood protection and *Discharge* and *Storage* serve mainly for pluvial flood protection, the higher initial effectivity of *Storage* and *Discharge* on the total risk can be contributed to the fact that pluvial risk is highest in Hoboken.

Table 10 Single measures effectivity on risk reduction

Activity	R (m)	S (ha0.5m)	D (m^3/h)	I (10^6)	C (10^6)	Ct (10^6)	ΔC (10^6)
1 (current)	0	0	0	$0	$817	$817	$0
2	0	0	2,100	$47	$799	$846	$18.6
5	0	5	0	$48	$499	$547	$318
17	0.8	0	0	$99	$803	$902	$14.5
3	0	0	92,100	$84.6	$399	$484	$418
9	0	50	0	$199	$306	$505	$511
33	1.8	0	0	$216	$692	$908	$125

The effect of *Discharge* becomes higher when *Store* measures are included. In terms of model sequence, incoming water is first stored in the system, and once the water exceeds the storage level, pumping (*Discharge*) can start. This means that if a part of the incoming water is stored, less discharge will be needed.

The effect of *Resist* on risk reduction, also changes when a combination of measures is implemented. This effect is for example higher for *0.8 m* than for *0 m* when it is combined with *Store* or *Discharge* measures (Appendix VI). It is possible that when *Resist=0.8 m* is combined with *Store* and *Discharge* measures, some incoming water due to coastal floods is caught by *Store* and *Discharge* measures.

Between 0.8 m and 1.8 m, the effect of *Resist* on risk reduction is equal with or without *Discharge* and *Storage* measures, as in this case the two highest surge extreme events are reduced. As these events have much higher volumes, they cannot be reduced by *Store* or *Discharge* measures.

As pluvial floods will determine the largest amount of floods in Hoboken, the effect of *Resist* on the total flood risk is relatively low. When *Discharge* and *Store* measures are implemented, the pluvial flood risk reduces, the difference between coastal and pluvial flood risk becomes less, and the effect of *Resist* on the total flood risk in the city becomes higher.

From these results it can be concluded that when both pluvial and coastal floods occur in a given city, a combination of pluvial and coastal measures is recommended when pluvial risk is higher than coastal risk. Smaller, more frequent floods will be covered by *Discharge* and *Storage* and they will eliminate a lot of pluvial flood risk. *Store* measures are more effective, and for lower investment costs, *Store* would become most interesting in terms of cost optimization for reducing pluvial floods. *Resist* measures serve for reducing the risk of a certain amount of higher coastal floods.

When the frequency of coastal surge becomes higher, it is expected that the effect of *Resist* on risk reduction will increase. At a certain rate of magnitude and frequency, it can be expected that the effect of coastal measures on risk reduction, will dominate pluvial flood risk reduction measures, and only coastal flood risk reduction measures will be recommended. Further investigation to this rate is recommended.

4.7.6 Separate risk optimization *Resist* for water levels; *Store* & *Discharge* for rainfall

In this section it has been estimated whether the outcome of the comprehensive model would give another result if the elements in the flood protection system would be optimized for their own expected largest threat only. For *Resist* this means that water levels would be the only load; and for *Discharge* and *Store* this means precipitation would be the only load.

Every variant of *Resist* (*0 m*, *0.8 m* and *1.8 m*) has 12 possible combinations. From the first three tables of 0 it follows that the optimal combination for every variant includes *Store=5 ha* and *Discharge = 92,100 m^3/h*. This means that for each dike height, the same value for optimal combination of *Store* and *Discharge* was found. In the case of *1.8 m* flood protection, rainfall is the only cause of a flood, as coastal floods do not occur with this value of *Resist*. Due to these results it can be concluded that if *Store* & *Discharge* would be optimized for only rainfall, the optimal combination would be *Store=5 ha* & *92,100 m^3/h*.

When different variants of *Store* (*0 ha*; *5 ha*; *50 ha*) and *Discharge* (*0 m^3/h*; *2,100 m^3/h*; *92,100 m^3/h*) are compared, for both *Store* as *Discharge*, an optimal value of *Resist* of *0.8 m* is found. It is expected

that the *Store* and *Discharge* measures do not have a high effect on the optimization of the coastal flood defence and therefore it results in the same optimum for every combination. For this reason it is expected that if the measure for the variants of *Resist* (*0 m*, *0.8 m* and *1.8 m*) would be optimized for only water levels, it would result in an optimum value of *0.8 m*.
In this separate approach the optimal safety level for *Resist* is 500 year and the safety level for *Store* & *Discharge* is 25 years. It can be concluded that when the elements are optimized for their main threats only (*Resist* for water levels; *Store* $ *Discharge* for rain), the results are the same as the comprehensive model results.
It is expected that pluvial and coastal risk reduction measures served mainly for their own purposes, because precipitation and surges were not correlated and extreme events of both did scarcely occur at the same time in the 1,000 years of generated data. When surges and precipitation have a higher correlation, the interactions of the loads and strengths in the system can play a larger role as more elements in the system would operate at the same time. Therefore a combined approach might result in another optimal combination than the separate approach. Further research is to this subject recommended.

4.8 Conclusion

From the results of the economic risk analysis, it can be concluded that the optimal combination of measures includes an upgrade of the coastal system towards a safety level of 500 years and an upgrade of the pluvial system towards a safety level of 25 years.
In practice for *Resist* this means that flood defences at the Weehawken Cove and Hoboken Station waterfront is constructed, with a total of 3.5 km in length and increased elevation levels to 3 m + NAVD88. For the internal water management system it means 25,000 m^3 of added green infrastructure in the City for *Store* and a total pumping capacity of 100,000 m^3/h for *Discharge*, which equals a capacity of building 12 more pumps like the current water pump in Hoboken. For the optimal combination, the present value of the risk is $363 million and the investment costs are $232 million. This corresponds to a flood risk reduction of $686 million compared to the current situation. The cost-benefit ratio of this solution is reasonable in terms of constructing flood infrastructure in the United States. A schematization of the optimal combination of flood risk reduction measures in the City of Hoboken, compared to the current situation, is illustrated in Figure 51, on the next page.

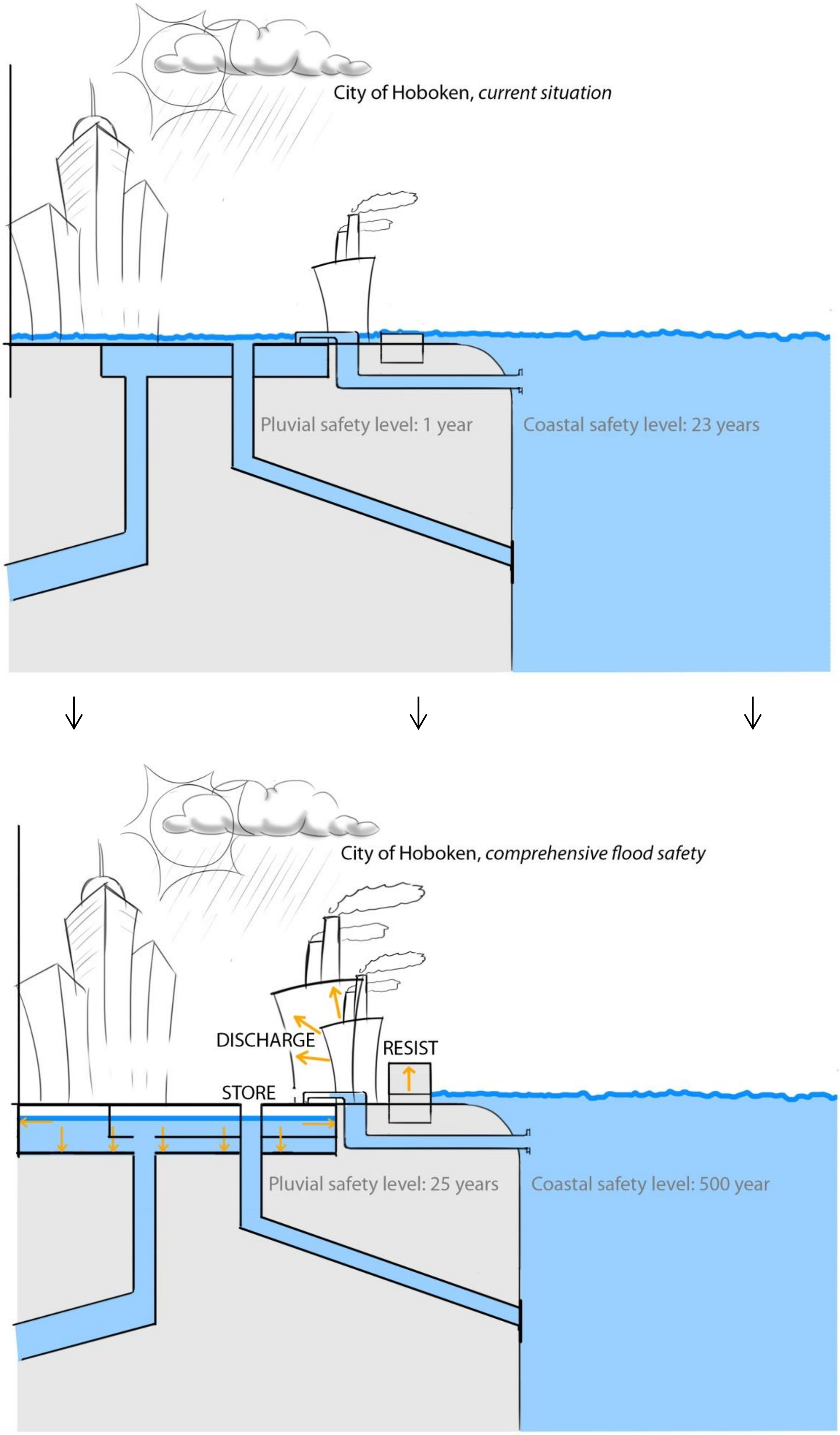


Figure 51 Optimal combination of flood risk reduction measures in Hoboken (before and after)

4.9 Assumptions and limitations

In this section main assumptions and limitations are summarized.

- The flood levels are related to annual extreme values of historical time series of precipitation and water levels. The synthetic time series that were based on historical observations of water levels and precipitation and created by a statistical method for creating longer time series by upscaling extremes values to higher extremes.
- The synthetic time series of water levels were only based on surge and tide, other effects were excluded.
- The extreme value distribution of surges was approached as a continuous distribution.
- The years in the new time series were scaled 3 days before and 3 days after an annual peak.
- Climate changes were not included.
- The alarm level influences the value from which a flood level is defined. When the alarm level is higher, the pluvial flood risk would decrease and might influence the outcome of the model.
- It was assumed that the storm surges and precipitation are not correlated. It is expected that the results of the separate and comprehensive approaches lie close to each other due to this matter.
- Only direct economic damages were taken into account.
- The flood characteristics in the damage assessment were only based on the flood levels and flood extent (geography of the area). Different effects such as flood duration, routing and urbanization of the area were excluded.
- Economic data based on other cities was related to the area.
- Smaller flood events (i.e. lower than annual extremes) were not included.
- A number of assumptions were taken to estimate the future development of the expected damage, dependent on inflation, economic growth, and increasing probability of sea level rise. The present value of risk changes for the net real discount rate.
- For Hoboken first-order estimates were done for construction and maintenance costs (investment costs).

4.10 Discussion

4.10.1 Added value of this modeling approach

Floods in vulnerable delta cities are often caused by precipitation, river flow, high sea levels, or combinations. In this study a model has been developed for assessing flood risk due to combined pluvial, riverine and coastal events. The first part of the model consists of an idealized hydrologic schematization of a delta city from which insight can be offered in the scales and frequencies of different types of floods. The second part of the model focusses on monetizing the flood levels in terms of economic risk and searching for an optimal mixture of pluvial, riverine and coastal flood protection elements.

The main objective of the model is serving as a decision tool in which flood risk reduction measures due to pluvial, riverine and coastal flooding are addressed. The outcome is dependent on the investment costs of these measures and the present value of risk for the city, dependent on the adapted flood protection system. The results show that – as economical optimal risk measures are dependent on the present value of the flood risk – the optimal combination for *Discharge*, *Store* and *Resist* measures can vary when changes in flood probabilities and damage functions take place.

Despite assumptions and limitations, the model functions as a convenient tool which gives first-order insight in flood extent and optimal mixture of flood risk reduction measures in a delta city. It can recognize the cause(s) of floods and it can quantify their frequencies and scales quickly. For this matter it offers realistic insight in the rates between pluvial, riverine and coastal flooding.

It can be concluded that the recommended types of flood risk measures give a good impression of the frequency and scale of flood issues and required flood protection elements (pluvial, riverine, coastal

and/or combinations) within the city. In this way, with the assumed input parameters, for Hoboken it was found that pluvial flooding gives highest expected flood risk in the future.
The comprehensive approach was compared to a separate risk optimization of the flood protection elements. *Resist* was optimized for water levels only, and *Store* & *Discharge* were optimized for rainfall. In the study for Hoboken the results of the three optimal flood risk reduction measures were the same in both approaches. It is expected that because of the uncorrelated surges and precipitation in Hoboken, risk reduction measures served mainly for their own purpose in the comprehensive approach: *Resist* for resisting high river water levels; *Store* for storing rainfall; and *Discharge* for draining the excess water. The impact of the measures to other floods (e.g. restriction rainfall water outflow due to dike restriction) does barely influence the individual optimization. However, it is expected that when high water levels and rainfall have a higher correlation, the dependencies of the loads and strength can play a significant role. It is expected that a combined approach could then result in another optimal combination than the separate approach. For studies in which the systems are correlated, it is highly recommended that these issues are further studied and the relations are included in the model.
For the uncorrelated system, it can be concluded that when the risk reduction elements (*Resist*, *Store*, and *Discharge*) are optimized for their specific threats only, the results are the same as the comprehensive model results. This means that the model for these systems gives a realistic identification of a combined flood risk protection system. Instead of assessing three different studies, for *Resist*, *Discharge* and *Store* risk reduction measures, this model offers an outcome of the three measures, in one flood risk assessment. It means that the model can be used as a quick and effective tool to find the optimal combination of flood risk reduction measures.
The integrated approach provides parties like urban planners, decision makers of delta cities and engineering companies quickly insight in the scale and types of different combinations of flood risk reduction measures from an economical point of view. This allows them to design an optimal comprehensive flood risk reduction strategy, in which both pluvial, riverine as coastal flood measures are included.

4.10.2 Recommendations for further research

Many opportunities lie in future studies to the improvements of the model as several assumptions were made to simplify complex processes in flood issues and to schematize numerous flood protection elements in a delta city. As was discussed in earlier chapters, numerous factors influence the values that are determining in the outcome of the economic optimization, such as the schematization of the city, the selected definition of a flood (alarm level), flood defence failure mechanisms, observed time series of precipitation and water levels, selected extreme value distributions, and the choice for a simplified cost-based approach (e.g. by neglecting individual risk).
The flood levels are determined by the loads and strengths in the system. When the precipitation and water levels change, the flood levels can become different. The surge levels that were observed were higher than the estimated distribution and therefore the fit – and the created synthetic water levels - could be an underestimation. When for instance, other structural failure mechanism of flood defences besides overflow are included, coastal flooding is expected to occur more often, which will eventually result in a shift in recommended flood risk reduction measures and the safety level of the optimal variant of *Resist* will lie higher. Furthermore the alarm level influences the value from which a flood level is defined. When the alarm level is higher, less pluvial floods would be the result. These variations can give a shift in the rate between coastal and pluvial flooding and could influence the outcome of the model.
For the damage assessment different assumptions were made. Only direct economic damages were taken into account and a lot of other consequences were neglected. When for example loss of life is included in the study, the expected risk due to coastal floods is higher, as this risk will be expected to be higher for coastal floods (e.g. higher consequences due to dike breaches, high velocities, and higher water depths). In the damage assessment damage amounts were based on flood levels and flood extent. The latter was related to the geography of the area. However, different effects such as routing and urbanization of the area were excluded. As the present value of risk is dependent on these values, the outcome of the model might change for a changing damage function.

Secondly, when changes in the investment costs of *Discharge*, *Store* and *Resist* take place, the outcome of the model can change and other optimal combinations can be found. When the investment costs of *Store*, *Discharge* and *Resist* measures change, another optimal combination can be the result. For Hoboken first estimations were done for construction and maintenance costs. Other costs can be included easily in the model, dependent on the objective of the risk assessment.
Both risk and investment costs are influenced by the chosen net discount factor, which is very uncertain due to uncertain scenarios in future, such as economic growth. For different future scenarios, other decisions might be more interesting.
Uncertainty and sensitivity analyses can be very useful for determination and identification of the elements that play the largest role in the possible variations of the model outcome. When most sensitive elements are found, it is recommended that improvements in the model start here. When uncertainties within the weakest elements determining the present value of the risk and investment costs are minimalized, the outcome of the model can become more robust.
Furthermore, in the design of the model, several assumptions were made about the relations between different elements in the flood protection system of a city. The city was schematized as a storage basin with varying areal cross sections as a function of the city's elevation levels; incoming and outgoing water fluxes; and different strengths of flood protection elements.
In the schematized flood protection system, the elements and fluxes are dependent. The total value of the incoming flux is dependent on precipitation, water levels and the dike height, and indirectly related to the storage areas and all draining components. The outgoing flux is dependent on the dike height, discharging components, storage areas, water levels, and indirect to the incoming flux. The dependency of all elements may influence the results of the model outcome. For example, in the current schematization, the flood levels cannot become higher than the flood defence height. This correlation results in an increased pluvial flood risk when the value of *Resist* is increased, as flood levels can get higher in the city. Moreover, the *Store* and *Discharge* elements in this model can reduce coastal flood levels. However, as the scale of these flood volumes is very large compared to the capacities of *Store* and *Discharge* measures, these pluvial flood risk reduction measures cannot eliminate pluvial floods anymore, when a coastal flood occurs at the same time as a pluvial flood. It means that this ability of *Store* and *Discharge* to reduce coastal flooding, has a negative impact for pluvial flood reduction.
In the case of Hoboken, the water levels and precipitation were not correlated, so rainfall events did scarcely occur during coastal floods. However, in systems that have a high correlation of surge and precipitation, this issue could influence the outcome for optimal combinations of measures. It has to be further investigated how the incoming fluxes, outgoing fluxes and flood protection elements are related to each other in reality and in what matter this influences the model results.
Further studies to the limitations, dependencies and correlations of the loads and strengths within the model are very important. Model improvements will lead to more realistic and robust results for the outcome of the model, which can serve as an advice for flood risk reduction measures in a delta city.

5. Conclusions and recommendations

In this study the effects of pluvial, riverine and coastal events and different types of flood risk reduction measures on flood safety in urban environments have been investigated. Currently integrated risk tools to define the effects of combined weather events are missing and an instrument to evaluate the effectiveness of a mix of pluvial, riverine and coastal measures in a combined way does not exist. The objective of the study was to develop a risk-based model, which supports decision making in delta cities on measures against pluvial, riverine and coastal floods in a comprehensive way. In this chapter the research questions are concluded and recommendations for further studies are carried out.
In general it can be concluded that the presented comprehensive flood risk model in this study is an effective and efficient tool for urban planners, decision makers of cities and engineering companies as they can estimate pluvial, riverine and coastal types of flood risk reduction measures for a delta city.

5.1 Conclusions

In this section the research questions of the thesis are answered and the results for the case study Hoboken are concluded.

1. **How can flooding and flood risk in urban areas due to pluvial, riverine and coastal events be identified and quantified?**

An idealized model has been developed to assess flood extent and volume due to combination of riverine, pluvial and coastal flooding in urban environments. The model is a practical tool that can be used in the search for an optimal combination for flood risk reduction measures. The model gives insight in the flood hazards and their consequences:

- The model recognizes the contribution of weather events to floods in the city by including precipitation and water level events and quantifies flood levels and damages due to these events. It quantifies flood scale and frequency by calculating flood levels as a function of precipitation and water levels in time. With the results it can be found which elements of the flood protection system (i.e. waterfront resistance, discharge capacity, storage capacity) of the city lack in capacity or magnitude.

- The computed flood levels can be translated into the economic flood consequences of the city. When both the frequency and consequences of pluvial, riverine and coastal floods are identified, the economic flood risk of the city can be calculated and the contribution of different weather events to the flood risk can be quantified. The flood risk is determined by expressing it in terms of expected value of loss. The economic damage is related to the flood depth and the flood extent of the area that is flooded.

From the model results, it follows that flooding in Hoboken occurs every year due to pluvial events and the current safety level of the water management system is 1 approximately year. The current safety level of the waterfront protection which serves for coastal flood protection is approximately 23 years. The flood risk in Hoboken has been determined by expressing it in terms of expected value of loss. It can be concluded that the consequences of coastal floods are much larger, but due to higher frequency, pluvial floods result in higher net flood risk.

2. **What are for a given delta city most effective measures to take to reduce pluvial, riverine and coastal flood risk?**

Cities can decide on flood risk reduction measures by comparing flood risks and investments costs of flood risk reduction measures. Measures that result in benefits over a certain period of time are worth implementation. As in reality causes of floods and a variety of flood protection components in systems are coupled, in this study different flood risk reduction measures are assessed in a combined way.

Three types of flood risk reduction measures were assumed to be most decisive in the flood protection system of a delta city: coastal or riverine flood defences, storage areas and discharging possibilities, which in this study are called *Resist*, *Store* and *Discharge* measures.
The main parameters for the flood risk assessment within the model are the investment costs for risk reduction measures and the net present value of risk. For different combinations of the *Resist*, *Store* and *Discharge* measures, the reduced flood risk – compared to the current situation of the city – has been calculated. The sum of the investment costs and the expected risk, are the total costs for the combination. In this study the economic optimal decision is defined as the combination with the lowest total costs.
In the optimal combination of Hoboken the waterfront flood defence has a new safety level of 500 years. The pluvial safety level was upgraded towards a safety level of 25 years.

3. Will comprehensive modeling of pluvial, riverine and coastal floods lead to more effective decision recommendations for flood risk reduction measures in urban area?

The comprehensive approach was compared to single risk optimization of the flood protection elements. *Resist* was optimized for only water levels, and *Store* & *Discharge* were optimized for rainfall. It was concluded that for Hoboken the same optimal decision for combined flood risk reduction measures was found in a combined and separate approach.
It is expected that because of the uncorrelated surges and precipitation in Hoboken, risk reduction measures served mainly for their own purpose in the comprehensive approach: *Resist* for resisting high river water levels; *Store* for storing rainfall; and *Discharge* for draining the excess water. The interactions of the other measures do not influence the individual optimizations in this case.
However, it is expected that when high water levels and rainfall have a higher correlation, the dependencies of the loads and strength can play a significant role. The combined approach for a correlated system can result in a different optimal combination than the separate approach.
For the uncorrelated system, it can be concluded that when the risk reduction elements (*Resist*, *Store*, and *Discharge*) are optimized for their individual threats only, the results are the same as the comprehensive model results. This means that the model for these systems gives a realistic identification of a combined flood risk protection system.
It can be concluded that the comprehensive risk model is an effective and efficient tool for urban planners, decision makers of cities and engineering companies as they can estimate three types of flood risk reduction measures with one tool. Flood and risk-based parameters for a given delta city can be adapted and varied easily, such that for different scenarios of a case, an economic optimum can be found.

5.2 Recommendations

In this study pluvial flooding and coastal flooding were addressed in a comprehensive way. For Hoboken it followed that the recommended safety level for pluvial flood risk reduction measures has a safety level of 25 years and the coastal protection has a safety level of 500 years.
Several assumptions and limitations were imposed in this model and recommended areas for further improvement are: sensitivity & uncertainty analyses for improving model robustness; a study to the dependency of input variables and system elements; and investigation to the effects of correlated surges and precipitation on the model results.

1. Sensitivity and uncertainty analyses for improving realistic outcome values and robustness of the model.

Future studies to the improvements of the model are recommended as several assumptions and limitations were made to simplify complex processes in flood issues and to schematize numerous flood protection elements in a delta city. It is recommended that uncertainties and sensitivities are investigated for this matter. When uncertainties in the most sensitive elements that determine the present value of risk and investment costs are minimalized, the outcome of the model can become more robust. Areas that need attention are:

- Effect of change in water level and precipitation time series on model outcome (for example by varying selected probability distributions);
- Effect of including other (structural, technical) failure mechanism;
- Effect of neglected elements such as runoff, routing and spatial relations, in the city schematization on detailed and realistic flood calculation;
- Effect of changing the value of the flood alarm level;
- Effect of considering only direct economic risk for the decision: what is the difference in flood risk when for example indirect or individual (loss of life) risks are included?
- Effect of changing economic values for damage functions in Hoboken;
- Effect of change in investment costs, for example due to economic growth;
- Effect of climate changes.

In this preliminary study for varying flood reduction measures, thirty-six combinations of variants were considered in order to get a first order impression in different types of flood risk reduction measures. For a more detailed outcome it is recommended that the number of variants is increased.
Furthermore investigation to the effect of changing the rate between coastal and pluvial flood risk is recommended: at what rate does coastal flooding become dominant and does this eliminate the need for pluvial risk reduction measures, when the decision is made by the comprehensive cost-benefit approach?

2. Analysis to the dependency of the loads and strengths within the model, and the effect of these dependencies on the model outcome.

It is recommended that the dependency of the loads and strengths in the model are studied, such that insight can be offered in the effect of the dependency of these elements on the model outcome. The total value of the incoming flux is dependent on precipitation, water levels and the dike height, and indirectly related to the storage areas and all draining components. The outgoing flux is dependent on the dike height, discharging components, storage areas, water levels, and indirect to the incoming flux. The dependency of all elements may influence the results of the model outcome. It has to be investigated whether when the actual relations of the incoming fluxes, outgoing fluxes and flood protection elements are included, the model will give more realistic and robust results.

3. Application of the model to cases in which surge events and precipitation occur more often at the same time, i.e. have a higher correlation.

It is recommended that a study is done to scenarios in which high water levels and extreme rainfall events are correlated. The focus has to be on the effects of the dependencies between correlated loads and strength in the systems, on the model outcome (i.e. decision for optimal combination). It is recommended that the investigation is done to the question whether in systems, in which surge and precipitation have a high correlation, a comprehensive approach is more realistic and cost-effective for decision making than a separate approach – which is currently most applied in decision making on flood risk reduction measures.

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Figures and Tables

Appendices

Appendix I. Economic Flood Damage Assessment

A. Maximum Flood Damage in Census Tracts Hoboken

				Census	A		B		C	
Category	damage sub-category	unit	Max damage ($)	value (unit)	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]
Zoning	Industrial	% in census			75%		100%		50%	
	Central business district									
	Waterfront									
	Residential				25%				50%	
Land use	Urban area		$67	3315185	569.797	€ 38.250.498	207.199	€ 13.909.272	362.598	€ 24.341.226
Infrastructure	Major roads	meter	$1.343	4100	410	€ 550.466	410	€ 550.466	410	€ 550.466
	Other roads		$370	50000	3.571	€ 1.321.071	3.571	€ 1.321.071	3.571	€ 1.321.071
	Railways		$34.250	5200	867	€ 29.683.333			867	€ 29.683.333
	Total Road Damage					**€ 31.554.871**		**€ 1.871.537**		**€ 31.554.871**
Households	Average house price in census				$603.100		$732.900		$500.400	
	Total Housing Damage	**Object**	**$235.640**	**26855**	**2.477**	**€ 583.680.280**	**1.802**	**€ 424.623.280**	**3.313**	**€ 780.675.320**
Companies		Val.added/workspace	$2.493.400							
	Industrial District (industry)	(spread over census)	$382.230	11496	1.642	€ 627.730.869	1.642	€ 627.730.869	1.642	€ 627.730.869
	Electric companies/substations	Val.added	$849.400		2	€ 1.698.800				
	Trading, catering, commerc, retail	(spread over census)	$27.400	2590	235	€ 6.451.455			235	€ 6.451.455
	Central Business Distr (bank/insur)	Val.added	$123.300							
	Transport (Transit)	Val.added	$102.750		2	€ 205.500				
	Total Direct Business Interuption					**€ 636.086.623**		**€ 627.730.869**		**€ 634.182.323**
Other	Pumping stations	Object	$1.027.500							
	Water purification inst. (Sewer)		$15.070.000		1	€ 15.070.000				
	Total other					**€ 15.070.000**				
Information										
	transit									
	port authority									
	electrical substation				2					
	school				1				1	
	ambulance headquarter								1	
	fire station									
	post office									
	university (stevens)									
	library									
	multi service comm center									
	hospital									
	police									
	city hall									
	city garage									
	public									

				Census	D		E		F	
Category	damage sub-category	unit	Max damage ($)	value (unit)	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]
Zoning	Industrial	% in census								
	Central business district									
	Waterfront									
	Residential				100%		100%		100%	
Land use	Urban area		$67	3315185	103.600	7,0E+06	155.399	€ 10.431.954	284.899	€ 19.125.249
Infrastructure	Major roads	meter	$1.343	4100	410	5,5E+05	410	€ 550.466	410	€ 550.466
	Other roads		$370	50000	3.571	1,3E+06	3.571	€ 1.321.071	3.571	€ 1.321.071
	Railways		$34.250	5200						
	Total Road Damage					**1,9E+06**		**€ 1.871.537**		**€ 1.871.537**
Households	Average house price in census				$720.700		$607.500		$727.300	
	Total Housing Damage	**Object**	**$235.640**	**26855**	**1.307**	**3,1E+08**	**2.312**	**€ 544.799.680**	**843**	**€ 198.644.520**
Companies		Val.added/workspace	$2.493.400							
	Industrial District (industry)	(spread over census)	$382.230	11496						
	Electric companies/substations	Val.added	$849.400							
	Trading, catering, commerc, retail	(spread over census)	$27.400	2590	235	6,5E+06	235	€ 6.451.455	235	€ 6.451.455
	Central Business Distr (bank/insur)	Val.added	$123.300							
	Transport (Transit)	Val.added	$102.750							
	Total Direct Business Interuption					**6,5E+06**		**€ 6.451.455**		**€ 6.451.455**
Other	Pumping stations	Object	$1.027.500							
	Water purification inst. (Sewer)		$15.070.000							
	Total other									
Information										
	transit									
	port authority									
	electrical substation									
	school				1		1		1	
	ambulance headquarter									
	fire station						1			
	post office						1		1	
	university (stevens)								1	
	library									
	multi service comm center									
	hospital									
	police									
	city hall									
	city garage									
	public									

				Census	G		H		I	
Category	damage sub-category	unit	Max damage ($)	value (unit)	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]
Zoning	Industrial	% in census			66%					
	Central business district									
	Waterfront				33%					
	Residential						100%		100%	
Land use	Urban area		$67	3315185	336.698	€ 22.602.567	207.199	€ 13.909.272	233.099	€ 15.647.931
Infrastructure	Major roads	meter	$1.343	4100						
	Other roads		$370	50000	3.571	€ 1.321.071	3.571	€ 1.321.071	3.571	€ 1.321.071
	Railways		$34.250	5200			867	€ 29.683.333	867	€ 29.683.333
	Total Road Damage					**€ 1.321.071**		**€ 31.004.405**		**€ 31.004.405**
Households	Average house price in census				$753.400		$495.500		$524.500	
	Total Housing Damage	**Object**	**$235.640**	**26855**	**1.130**	**€ 266.273.200**	**1.954**	**€ 460.440.560**	**2.354**	**€ 554.696.560**
Companies		Val.added/workspace	$2.493.400							
	Industrial District (industry)	(spread over census)	$382.230	11496	1.642	€ 627.730.869				
	Electric companies/substations	Val.added	$849.400						1	€ 849.400
	Trading, catering, commerc, retail	(spread over census)	$27.400	2590			235	€ 6.451.455	235	€ 6.451.455
	Central Business Distr (bank/insur)	Val.added	$123.300							
	Transport (Transit)	Val.added	$102.750		4	€ 411.000				
	Total Direct Business Interuption					**€ 628.141.869**		**€ 6.451.455**		**€ 7.300.855**
Other	Pumping stations	Object	$1.027.500		1	€ 1.027.500				
	Water purification inst. (Sewer)		$15.070.000							
	Total other					**€ 1.027.500**				
Information										
	transit				1					
	port authority				1					
	electrical substation								1	
	school						1			
	ambulance headquarter									
	fire station									
	post office						1			
	university (stevens)									
	library									
	multi service comm center									
	hospital								1	
	police									
	city hall									
	city garage									
	public									

				Census	J		K		L	
Category	damage sub-category	unit	Max damage ($)	value (unit)	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]
Zoning	Industrial	% in census								
	Central business district								100%	
	Waterfront									
	Residential				100%		100%			
Land use	Urban area		$67	3315185	155.399	€ 10.431.954	155.399	€ 10.431.954	103.600	€ 6.954.636
Infrastructure	Major roads	meter	$1.343	4100	410	€ 550.466			410	€ 550.466
	Other roads		$370	50000	3.571	€ 1.321.071	3.571	€ 1.321.071	3.571	€ 1.321.071
	Railways		$34.250	5200						
	Total Road Damage					**€ 1.871.537**		**€ 1.321.071**		**€ 1.871.537**
Households	Average house price in census				$485.400		$446.000		$566.200	
	Total Housing Damage	**Object**	**$235.640**	**26855**	**1.917**	**€ 451.721.880**	**2.024**	**€ 476.935.360**	**1.680**	**€ 395.875.200**
Companies		Val.added/workspace	$2.493.400							
	Industrial District (industry)	(spread over census)	$382.230	11496						
	Electric companies/substations	Val.added	$849.400							
	Trading, catering, commerc, retail	(spread over census)	$27.400	2590	235	€ 6.451.455	235	€ 6.451.455		
	Central Business Distr (bank/insur)	Val.added	$123.300						1	€ 123.300
	Transport (Transit)	Val.added	$102.750							
	Total Direct Business Interuption					**€ 6.451.455**		**€ 6.451.455**		**€ 123.300**
Other	Pumping stations	Object	$1.027.500							
	Water purification inst. (Sewer)		$15.070.000							
	Total other									
Information										
	transit									
	port authority									
	electrical substation									
	school				2		1		1	
	ambulance headquarter									
	fire station									
	post office									
	university (stevens)									
	library				1					
	multi service comm center						1			
	hospital									
	police								**1**	
	city hall									
	city garage									
	public									

				Census	M		N	
Category	damage sub-category	unit	Max damage ($)	value (unit)	Number / m2	Max Damage [$]	Number / m2	Max Damage [$]
Zoning	Industrial	% in census			50%		40%	
	Central business district							
	Waterfront						50%	
	Residential				50%		10%	
Land use	Urban area		$67	3315185	284.899	€ 19.125.249	155.399	€ 10.431.954
Infrastructure	Major roads	meter	$1.343	4100	410	€ 550.466	410	€ 550.466
	Other roads		$370	50000	3.571	€ 1.321.071	3.571	€ 1.321.071
	Railways		$34.250	5200	867	€ 29.683.333	867	€ 29.683.333
	Total Road Damage					**€ 31.554.871**		**€ 31.554.871**
Households	Average house price in census				$544.400		$475.000	
	Total Housing Damage	**Object**	**$235.640**	**26855**	**2.050**	**€ 483.062.000**	**1.692**	**€ 398.702.880**
Companies		Val.added/workspace	$2.493.400					
	Industrial District (industry)	(spread over census)	$382.230	11496	1642,285714	€ 627.730.869	1642,285714	€ 627.730.869
	Electric companies/substations	Val.added	$849.400					
	Trading, catering, commerc, retail	(spread over census)	$27.400	2590	235,4545455	€ 6.451.455	235,4545455	€ 6.451.455
	Central Business Distr (bank/insur)	Val.added	$123.300					
	Transport (Transit)	Val.added	$102.750					
	Total Direct Business Interuption					**€ 634.182.323**		**€ 634.182.323**
Other	Pumping stations	Object	$1.027.500					
	Water purification inst. (Sewer)		$15.070.000					
	Total other							
Information								
	transit							
	port authority							
	electrical substation							
	school							
	ambulance headquarter							
	fire station				1			
	post office							
	university (stevens)							
	library							
	multi service comm center							
	hospital							
	police							
	city hall						1	
	city garage						1	
	public							

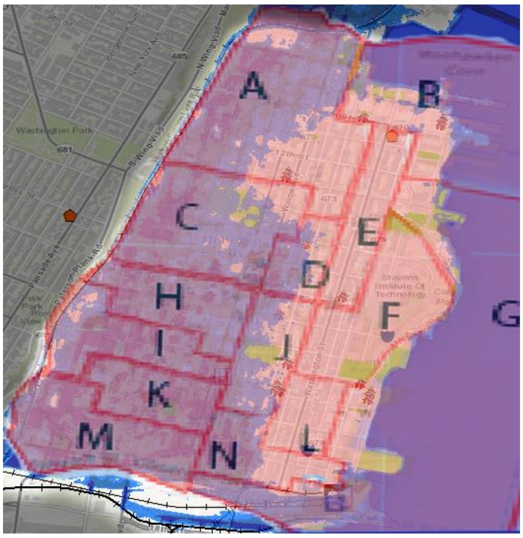
B. Maximum Flood Damage to roads, houses, businesses, and other

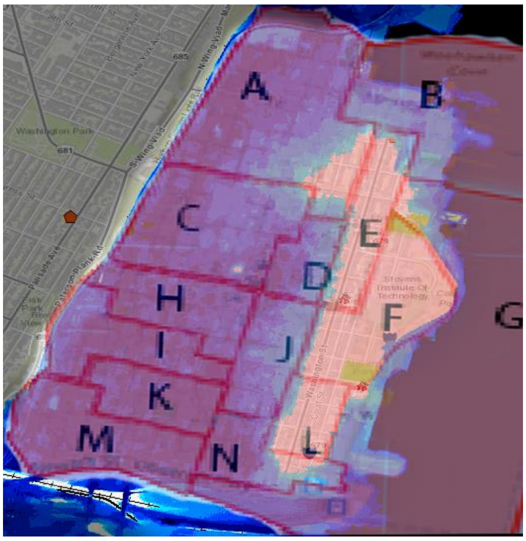
Maximal damage census per category	roads ($)	houses($)	business int($)	other($)
A	3,2E+07	5,8E+08	6,4E+08	1,5E+07
B	1,9E+06	4,2E+08	6,3E+08	
C	3,2E+07	7,8E+08	6,3E+08	
D	1,9E+06	3,1E+08	6,5E+06	
E	1,9E+06	5,4E+08	6,5E+06	
F	1,9E+06	2,0E+08	6,5E+06	
G	1,3E+06	2,7E+08	6,3E+08	1,0E+06
H	3,1E+07	4,6E+08	6,5E+06	
I	3,1E+07	5,5E+08	7,3E+06	
J	1,9E+06	4,5E+08	6,5E+06	
K	1,3E+06	4,8E+08	6,5E+06	
L	1,9E+06	4,0E+08	1,2E+05	
M	3,2E+07	4,8E+08	6,3E+08	
N	3,2E+07	4,0E+08	6,3E+08	

C. Stage-Damage relations Hoboken

Flood depth (m)	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Stage damage values										
Roads	0,2	0,4	0,6	0,8	1	1	1	1	1	1
Houses	0,125	0,25	0,375	0,5	0,625	0,75	0,875	1	1	1
Busines interuption	0,2	0,4	0,6	0,8	1	1	1	1	1	1
Other	0,2	0,4	0,6	0,8	1	1	1	1	1	1

D. Examples of projected floods on census tract map





E. Total damage per flood depth in census tract when the area is fully flooded

Flood depth:	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Flood depth:	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5
Damage (%*tot$)	($)	($)	($)	($)	($)	($)	($)	($)	($)	($)
A	2,1E+08	4,2E+08	6,3E+08	8,4E+08	1,0E+09	1,1E+09	1,2E+09	1,3E+09	1,3E+09	1,3E+09
B	1,8E+08	3,6E+08	5,4E+08	7,2E+08	8,9E+08	9,5E+08	1,0E+09	1,1E+09	1,1E+09	1,1E+09
C	2,3E+08	4,6E+08	6,9E+08	9,2E+08	1,2E+09	1,3E+09	1,3E+09	1,4E+09	1,4E+09	1,4E+09
D	4,0E+07	8,0E+07	1,2E+08	1,6E+08	2,0E+08	2,4E+08	2,8E+08	3,2E+08	3,2E+08	3,2E+08
E	7,0E+07	1,4E+08	2,1E+08	2,8E+08	3,5E+08	4,2E+08	4,9E+08	5,5E+08	5,5E+08	5,5E+08
F	2,6E+07	5,3E+07	7,9E+07	1,1E+08	1,3E+08	1,6E+08	1,8E+08	2,1E+08	2,1E+08	2,1E+08
G	1,6E+08	3,2E+08	4,8E+08	6,4E+08	8,0E+08	8,3E+08	8,6E+08	9,0E+08	9,0E+08	9,0E+08
H	6,5E+07	1,3E+08	2,0E+08	2,6E+08	3,3E+08	3,8E+08	4,4E+08	5,0E+08	5,0E+08	5,0E+08
I	7,7E+07	1,5E+08	2,3E+08	3,1E+08	3,8E+08	4,5E+08	5,2E+08	5,9E+08	5,9E+08	5,9E+08
J	5,8E+07	1,2E+08	1,7E+08	2,3E+08	2,9E+08	3,5E+08	4,0E+08	4,6E+08	4,6E+08	4,6E+08
K	6,1E+07	1,2E+08	1,8E+08	2,4E+08	3,1E+08	3,7E+08	4,3E+08	4,8E+08	4,8E+08	4,8E+08
L	5,0E+07	1,0E+08	1,5E+08	2,0E+08	2,5E+08	3,0E+08	3,5E+08	4,0E+08	4,0E+08	4,0E+08
M	1,9E+08	3,9E+08	5,8E+08	7,7E+08	9,7E+08	1,0E+09	1,1E+09	1,1E+09	1,1E+09	1,1E+09
N	1,8E+08	3,7E+08	5,5E+08	7,3E+08	9,1E+08	9,6E+08	1,0E+09	1,1E+09	1,1E+09	1,1E+09

F. Percentage of census tract area flooded per flood depth

Flood depth	0-0.5	0.5-1	1-1.5	1.5-2	2-2.5	2.5-3	3-3.5	3.5-4	4-4.5	4.5-5
Percentage of census flooded										
A	4%	10%	17%	17%	10%	10%	10%	10%	8%	7%
B	7%	10%	10%	10%	20%	20%	13%	8%	5%	0%
C	5%	10%	25%	25%	20%	10%	7%	5%	5%	0%
D	0%	7%	13%	20%	20%	20%	17%	8%	0%	0%
E	0%	0%	0%	0%	0%	0%	5%	6%	6%	6%
F	0%	0%	0%	0%	0%	0%	0%	0%	5%	5%
G	4%	8%	14%	17%	13%	10%	10%	10%	10%	5%
H	4%	13%	33%	33%	10%	0%	0%	0%	0%	0%
I	4%	17%	50%	17%	13%	8%	0%	0%	0%	0%
J	0%	0%	10%	25%	25%	20%	10%	5%	0%	0%
K	4%	14%	60%	25%	0%	0%	0%	0%	0%	0%
L	0%	0%	0%	0%	0%	0%	0%	10%	8%	8%
M	4%	13%	60%	11%	10%	5%	0%	0%	0%	0%
N	0%	7%	25%	17%	10%	13%	10%	10%	7%	5%

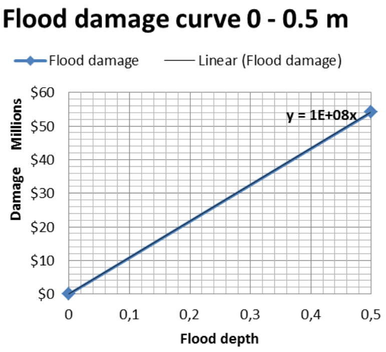
G. Summary of damage in all census tracts per flood extent per flood depth

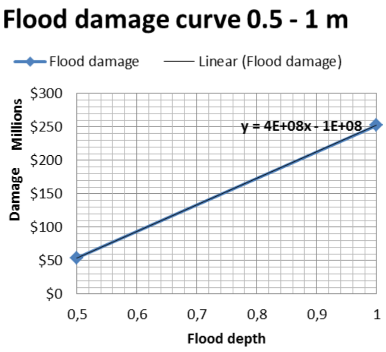
flood extent>	0 - 0.5 m	0.5 -1 m	1 - 1.5 m	1.5 - 2 m	2 - 2.5 m	2.5 - 3 m	3 - 3.5 m	3.5 - 4 m	4 - 4.5 m	4.5 - 5 m	
max depth:	$	$	$	$	$	$	$	$	$	$	**SUM ($)**
0.5 m	5,4E+07										**5,4E+07**
1 m	1,1E+08	1,4E+08									**2,5E+08**
1.5 m	1,6E+08	2,9E+08	4,0E+08								**8,5E+08**
2 m	2,2E+08	4,3E+08	8,1E+08	2,6E+08							**1,7E+09**
2.5 m	2,7E+08	5,8E+08	1,2E+09	5,2E+08	2,0E+08						**2,8E+09**
3 m	2,9E+08	7,2E+08	1,6E+09	7,8E+08	4,0E+08	1,5E+08					**4,0E+09**
3.5 m	3,2E+08	7,9E+08	2,0E+09	1,0E+09	6,0E+08	3,1E+08	1,1E+08				**5,2E+09**
4 m	3,4E+08	8,5E+08	2,2E+09	1,3E+09	8,0E+08	4,6E+08	2,2E+08	9,7E+07			**6,3E+09**
4.5 m	3,4E+08	9,2E+08	2,4E+09	1,4E+09	1,0E+09	6,2E+08	3,3E+08	1,9E+08	7,4E+07		**7,3E+09**
5 m	3,4E+08	9,2E+08	2,6E+09	1,6E+09	1,1E+09	7,7E+08	4,4E+08	2,9E+08	1,5E+08	4,0E+07	**8,2E+09**

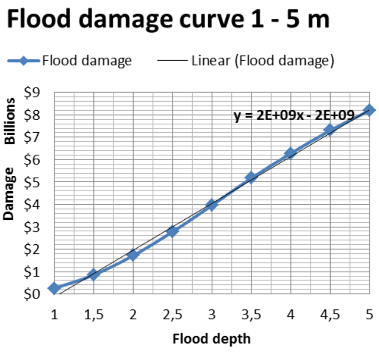
H. Damage per flood characteristics (flood extent and flood depth)

FL [m]	h [extent]	A [m2]	%	Total damage ($)
0,5	0-0.5	15.175	0.47	5,4E+07
1	0-1	167.025	5.2	2,5E+08
1,5	0-1.5	926.350	29	8,5E+08
2	0-2	1.602.175	50	1,7E+09
2,5	0-2.5	2.011.225	62	2,8E+09
3	0-3	2.240.625	69	4,0E+09
3,5	0-3.5	2.431.125	75	5,2E+09
4	0-4	2.568.975	79	6,3E+09
4,5	0-4.5	2.658.000	82	7,3E+09
5	0-5	2.722.625	84	8,2E+09

I. Linear approximations of damage function



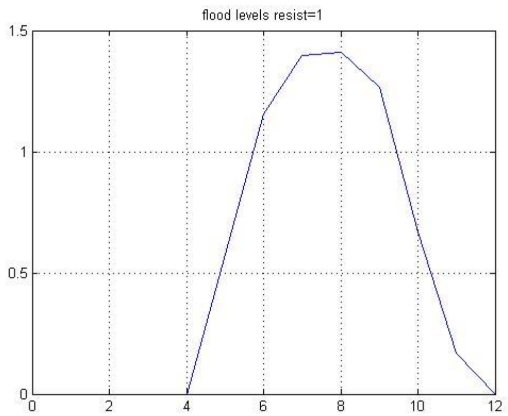


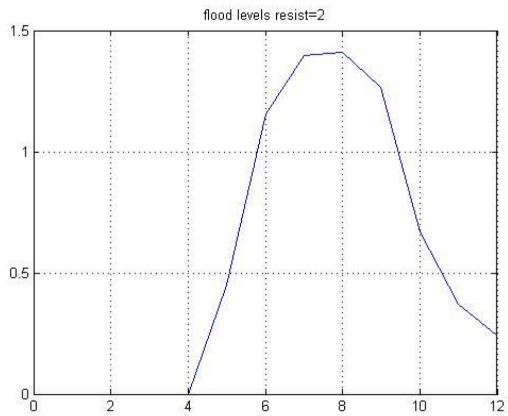


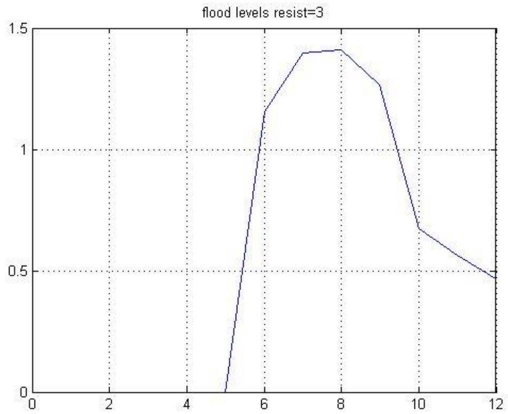
Appendix II. Effect of Resist, Store and Discharge measures (for historical flood events)

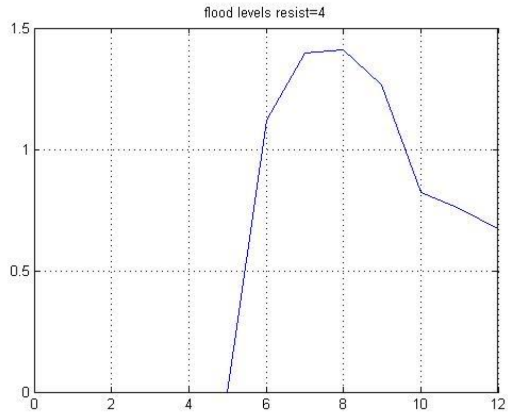
In all plots flood levels on the y-axes are in m relative to ground level (+2m NAVD88). The x-axes are in hours.

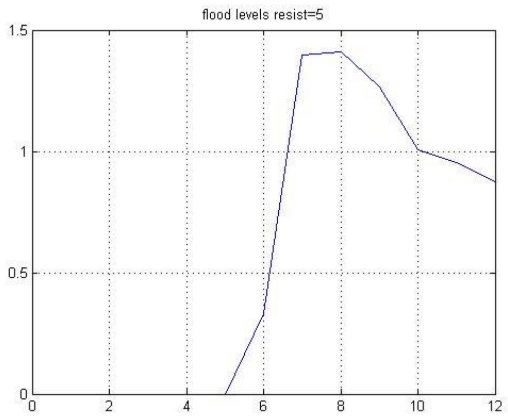
J. Effect of variants for Resist on flood depths during Sandy

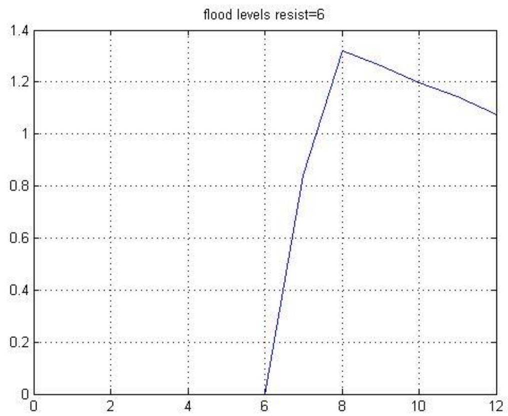


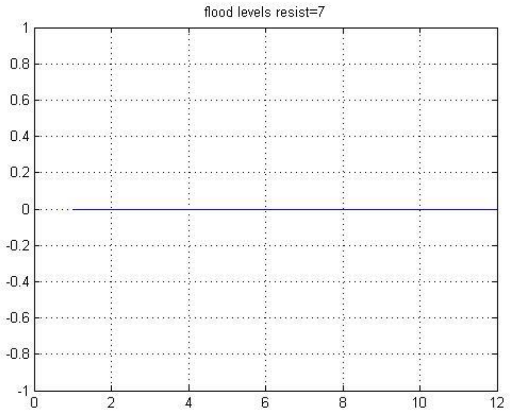




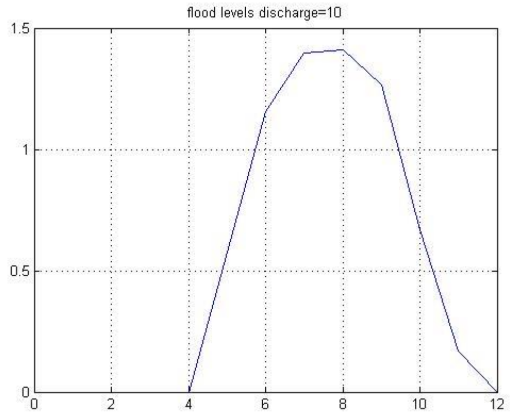


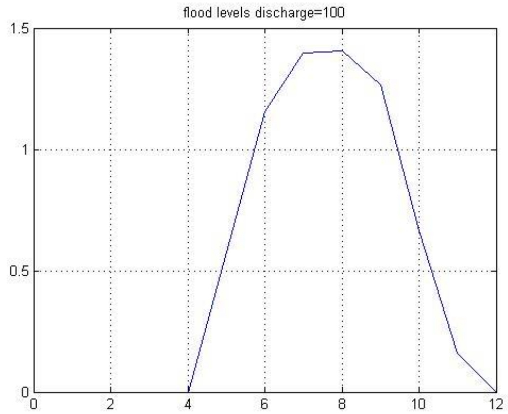


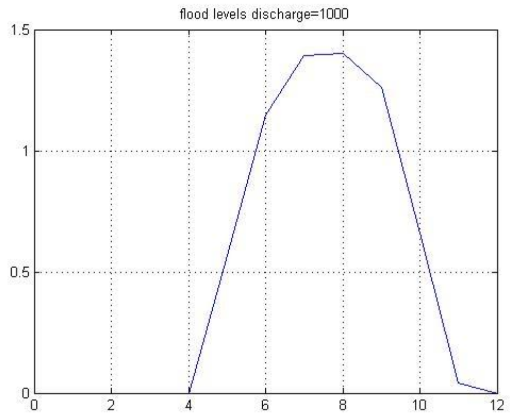


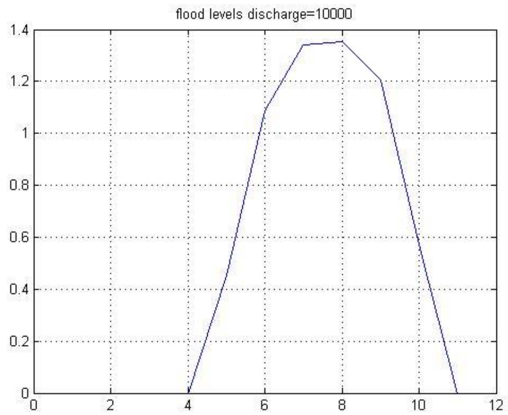


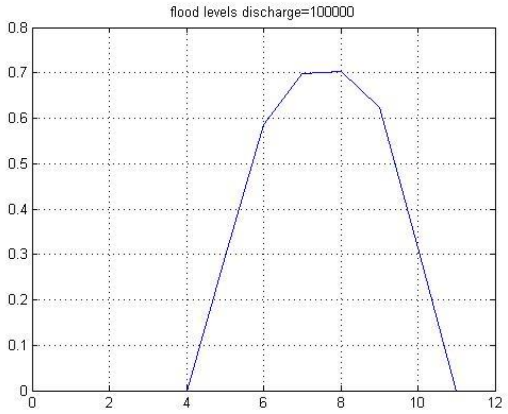
K. Effect of variants for Discharge on flood depths during Sandy



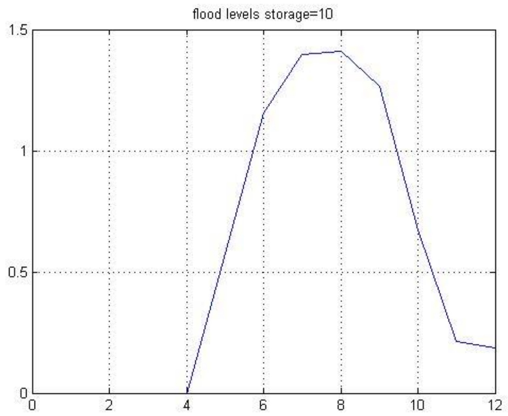


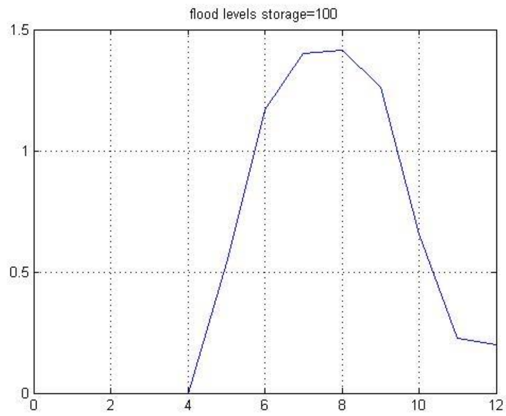


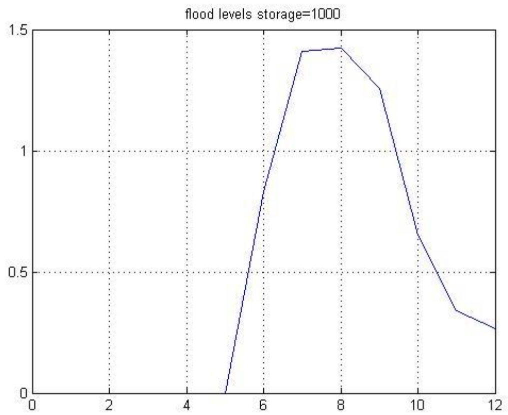


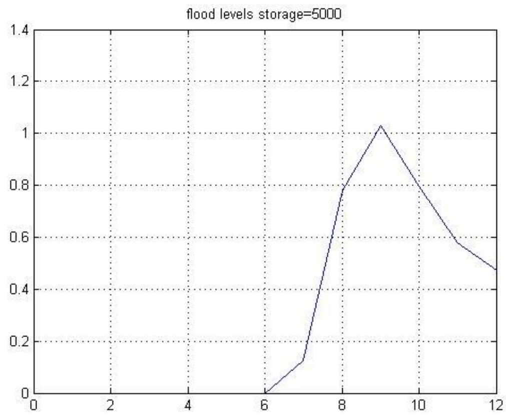


L. Effect of variants for Store on flood depths during Sandy

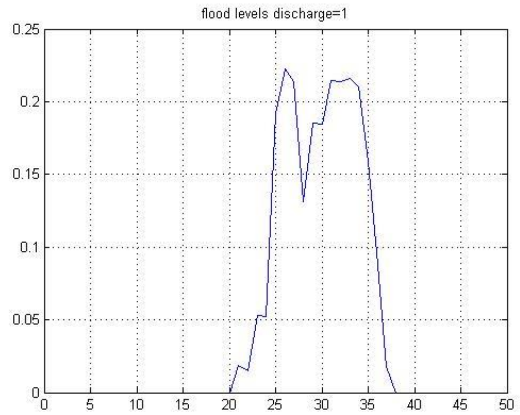


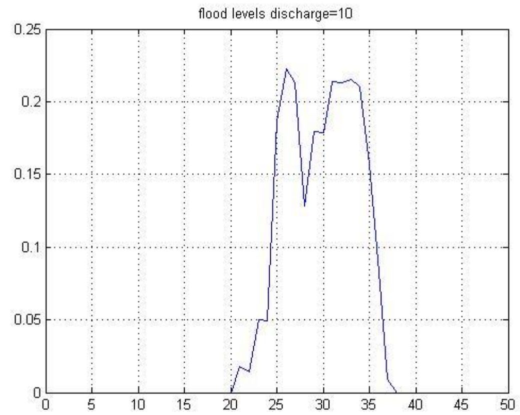


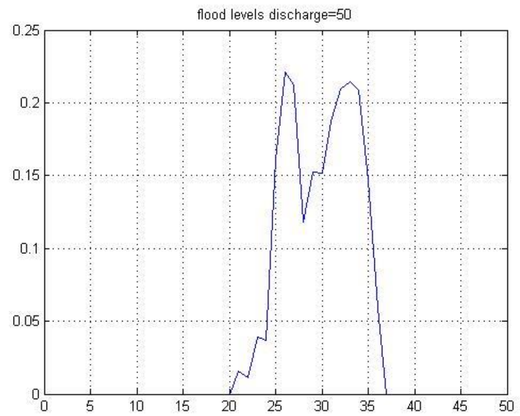


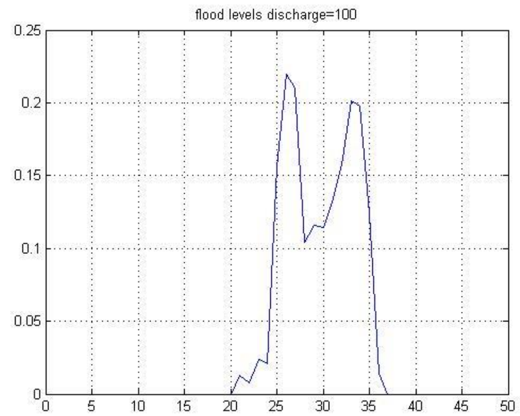


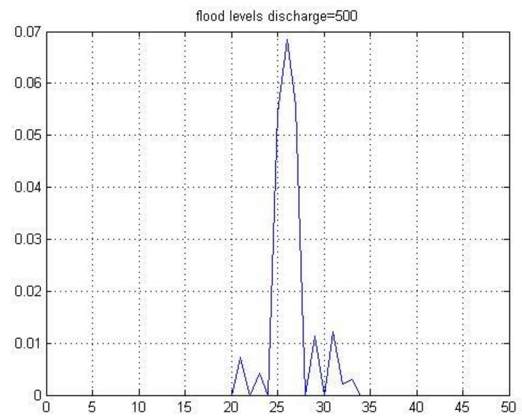
M. Effect of variants for Discharge on flood depths during Irene

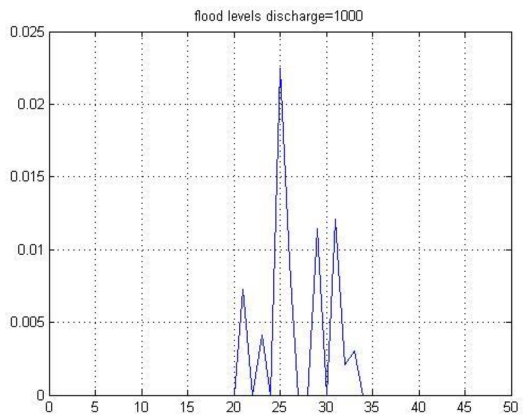




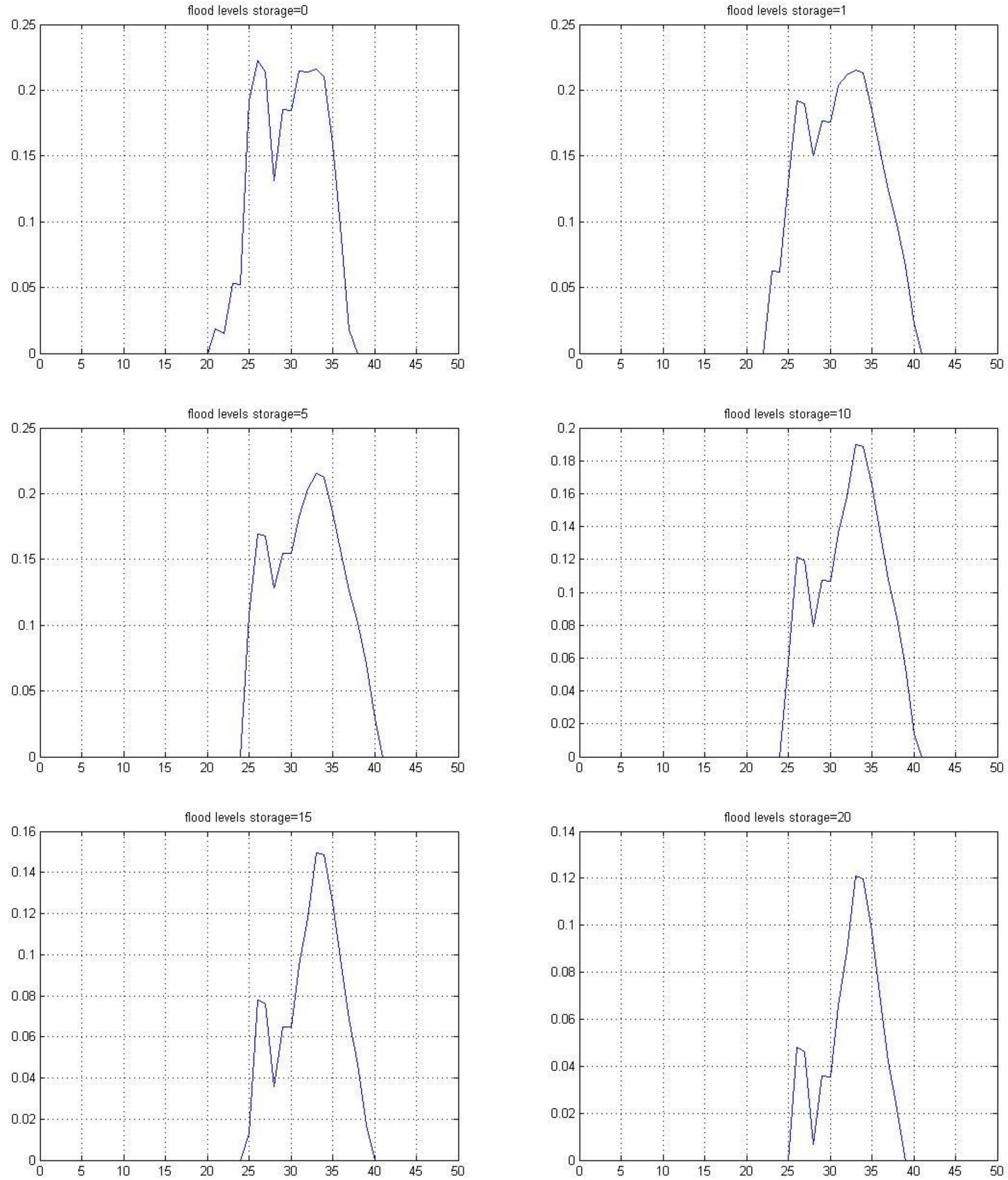


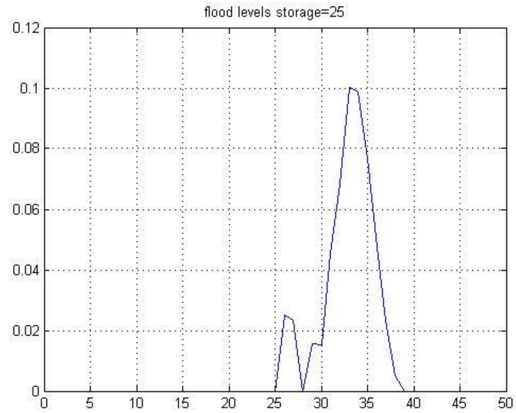


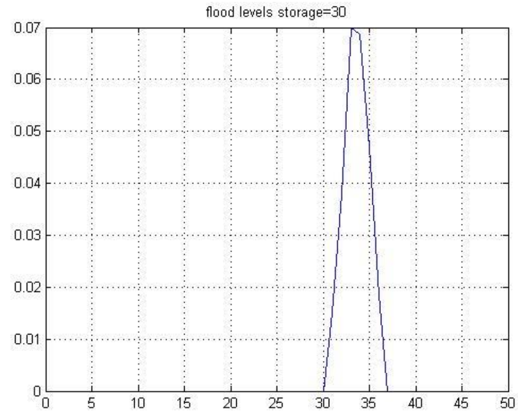


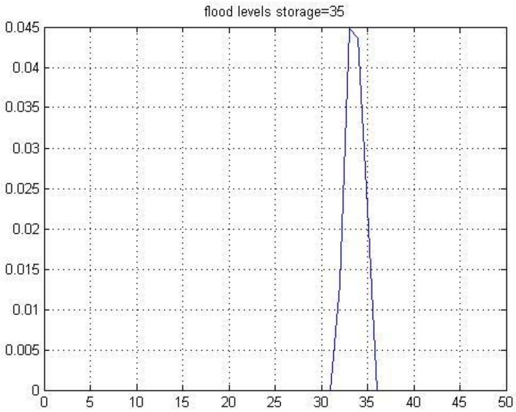


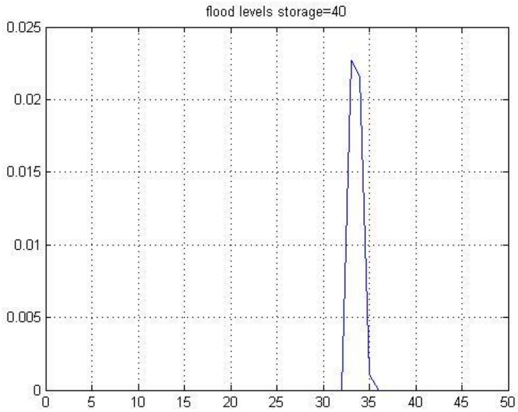
N. Effect of variants for Store on flood depths during Irene

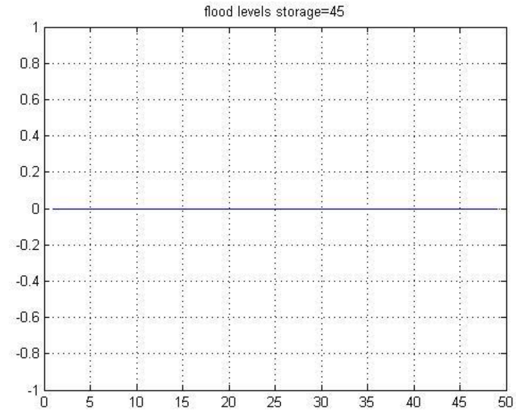



flood levels storage=25
0.12
0.1
0.08
0.06
0.04
0.02
0
0 5 10 15 20 25 30 35 40 45 50

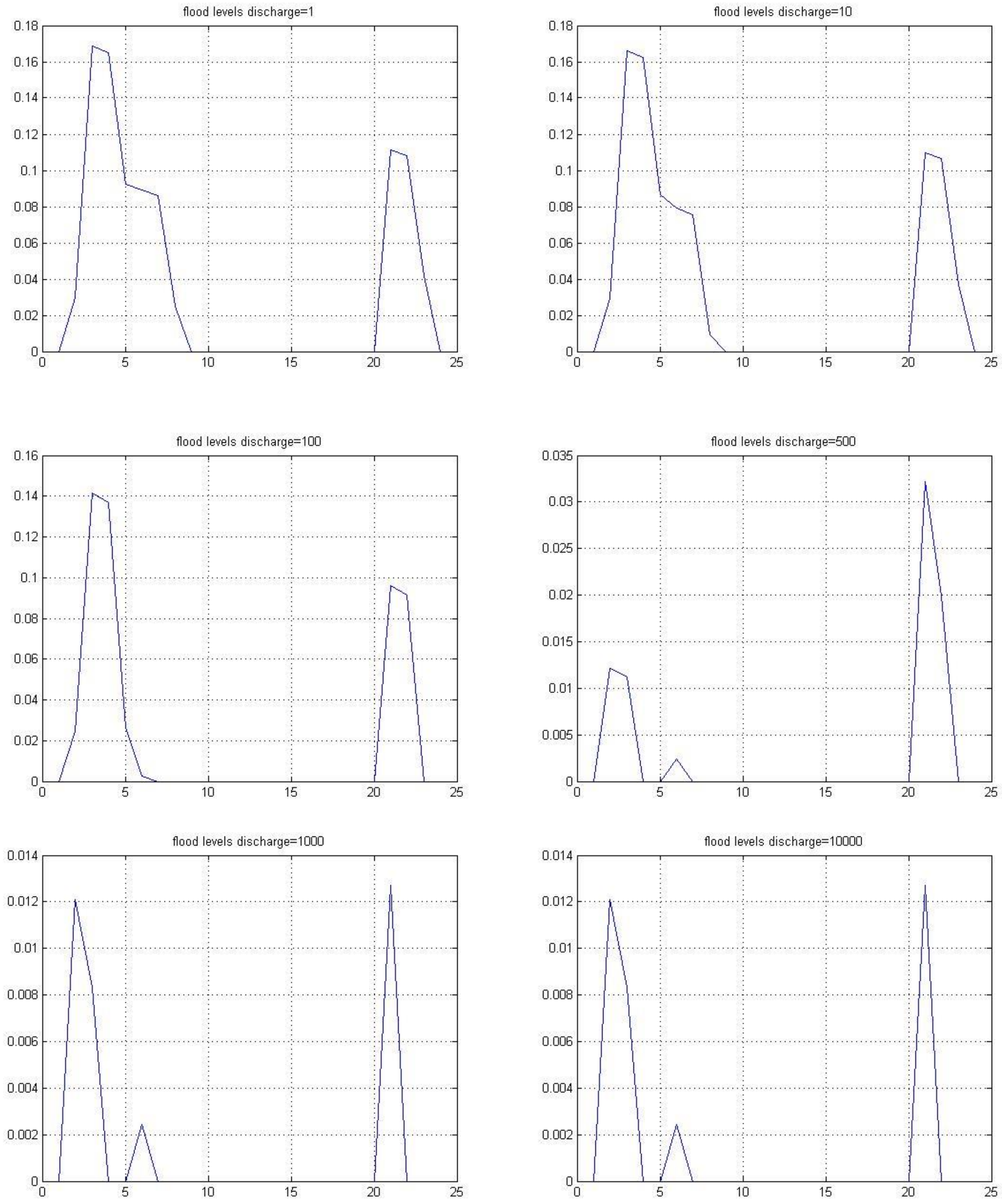

flood levels storage=30
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0 5 10 15 20 25 30 35 40 45 50


flood levels storage=35
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0 5 10 15 20 25 30 35 40 45 50

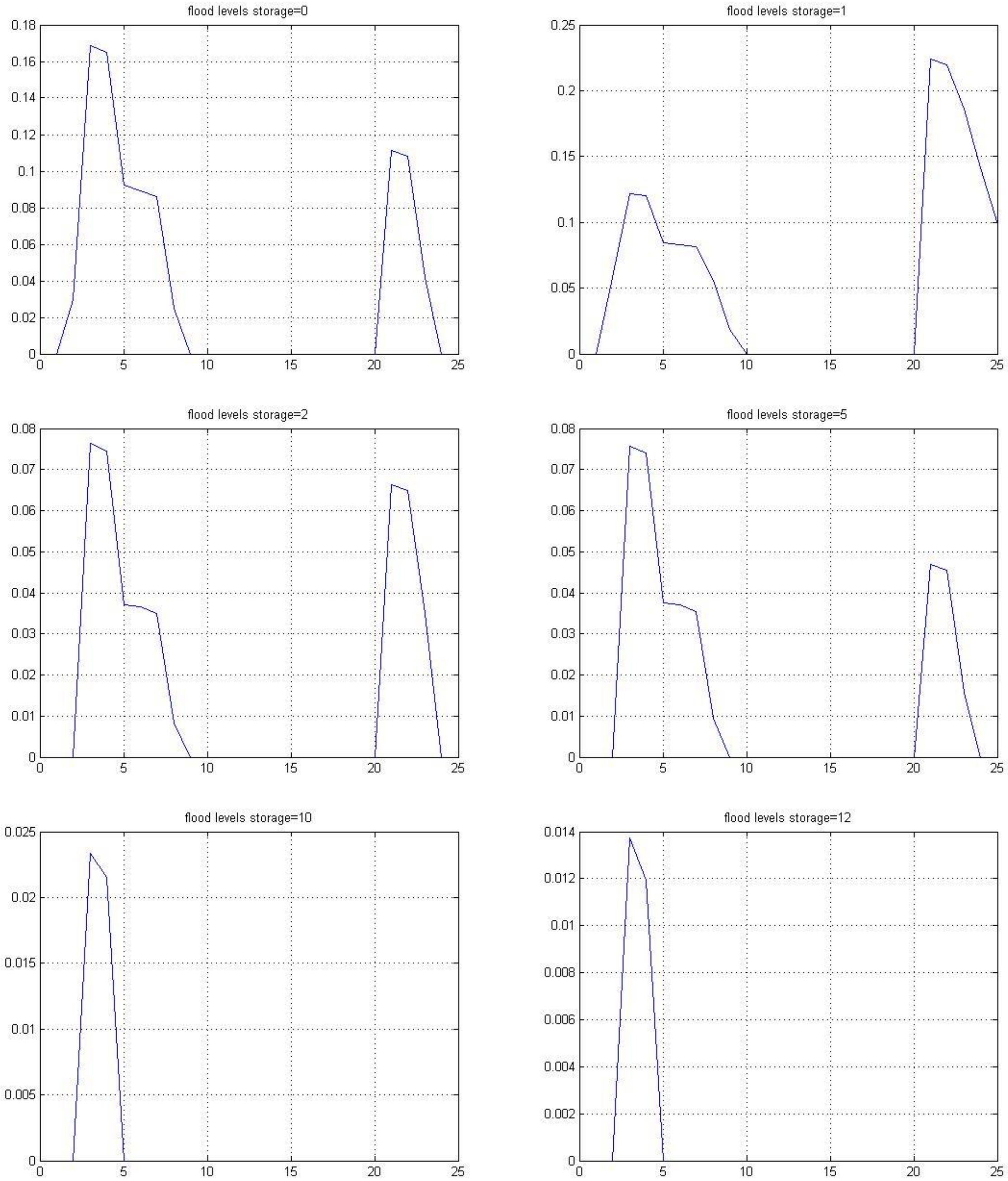

flood levels storage=40
0.025
0.02
0.015
0.01
0.005
0
0 5 10 15 20 25 30 35 40 45 50

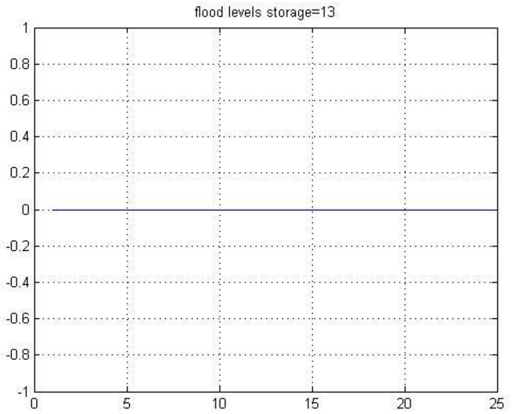

flood levels storage=45
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0 5 10 15 20 25 30 35 40 45 50

O. Effect of variants for Discharge on flood depths during pluvial flood (August, 15, 2011)



P. Effect of variants for Store on flood depths during pluvial flood (August, 15, 2011)




flood levels storage=13
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0
5
10
15
20
25

Appendix III. Investment costs

Q. Construction and Maintenance investment costs of Green Infrastructure in Hoboken, NJ (Together North Jersey, 2013)

Green infrastructure Hoboken	**$ / cu.ft**	**annual maint/oper. (%)**	**$/m^3**	**$/ha*m**	**$/ha*0.5m**
constructed wetland	$0,45	6,00	$15,89	$158.915	$79.458
permeable pavements	$2,62	3,00	$92,52	$925.239	$462.620
stormwater street trees	$5,98	8,00	$211,18	$2.111.806	$1.055.903
vegetated swales	$9,72	6,00	$343,26	$3.432.567	$1.716.284
rainwater harvest and reuse	$11,03	5,00	$389,52	$3.895.187	$1.947.593
basins or ponds	$15,00	12,00	$529,72	$5.297.171	$2.648.586
rain gardens	$28,05	8,00	$990,57	$9.905.710	$4.952.855
stormwater infiltration planters	$29,92	5,00	$1.056,61	$10.566.091	$5.283.046
subsurface storage	$34,52	12,00	$1.219,06	$12.190.557	$6.095.278
green roofs	$41,14	2,00	$1.452,84	$14.528.375	$7.264.188
mean		**7**			**$3.150.581**

R. Determination of investment costs of Resist, Store and Discharge variants

Levee/flood wall	**Resist**	length	height	width	
	0	3500	0,2	-	
Dimensions / capacity		**heightening**	**0**		
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs	$20.000	$/m/m	huidig	m x m	
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use (footprint indicates)					
Urban implementation (space)					
Management and maintenance costs (PV(M))	2%	per year	50	year	
Total costs					
Round					

Levee/flood wall	Resist	length	height	width	unit
	1	3500	1	3	m
Dimensions / capacity		**heightening**	**0,8**		
		factor RBD footprint	1,2		
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs	$20.000	$/m/m	3.5 x1 x 3	m x m	$67.200.000
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use (footprint indicates)					
Urban implementation (space)					
Management and maintenance costs (PV(M))	2%	per year	50	year	$31.694.759
	$1.008.000				
Total costs					**$98.894.759**
Round					**$M 99**

Levee/flood wall	Resist	length	height	width	unit
	2	3500	2	6	m
Dimensions / capacity		**heightening**	**1,8**		
		factor RBD footprint	1,45		
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs	$20.000	$/m/m	3.5 x2 x 6	m x m	$182.700.000
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use (footprint indicates)					
Urban implementation (space)					
Management and maintenance costs (PV(M))	2%	per year	50	year	$33.427.259
	$2.740.500				
Total costs					**$216.127.259**
Round					**$M 216**

Green zones	Store				
	0				
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs (capital costs)	$3.150.581	ha*0.5m	huidig	0	
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Operations and maintenance costs (PV(M))	7%	per year	50	year	
Total costs					
Round					

Green zones	Store				
	1				
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs (capital costs)	$3.150.581	ha*0.5m	5	ha*0.5m	$15.752.905
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Operations and maintenance costs (PV(M))	7%	per year	50	year	€ 31.789.463
	$1.102.703				
Total costs					**$47.542.367**
Round					**$M 48**

Green zones	Store				
	2				
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs (capital costs)	$3.150.581	ha*0.5m	50	ha*0.5m	$157.529.046
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Operations and maintenance costs (PV(M))	7%	per year	50	year	€ 41.713.793
	$11.027.033				
Total costs					**$199.242.839**
Round					**$M 199**

Stormwater pumping station	Discharge		*current*	*50Mgal/d=m3/h*	*7900*
	0	K=497*C+13,4*10^6	C in m3/h *		
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs					
Construction costs		m3/h	huidig=7900		
Planning and engineering costs					
Material costs					
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Management and maintenance costs (PV(M))	5%	per year	50	year	
and operation en verbruik?					
Total costs					
Round					

Stormwater pumping station	Discharge				
	1	K=497*C+13,4*10^6	C in m3/h		
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs			10.000	tot m3/h	
Construction costs	€ 0		2.100	added m3/h	€ 15.704.307
Planning and engineering costs					
Material costs				€ 15.704.307	
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Management and maintenance costs (PV(M))	5%	per year	50	year	€ 31.471.975
and operation en verbruik?	$785.215				
Total costs					**$47.176.282**
Round					**$M 47**

Stormwater pumping station	**Discharge**				
	2	K=497*C+13,4*10^6	C in m3/h		
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs			100.000	tot m3/h	
Construction costs	€ 0		92.100	added m3/h	€ 51.327.125
Planning and engineering costs					
Material costs				€ 51.327.125	
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Management and maintenance costs (PV(M))	5%	per year	50	year	€ 33.253.116
and operation en verbruik?	$2.566.356				
Total costs					**$84.580.240**
Round					**$M 84.6**

Stormwater pumping station	**Discharge**				
	3	K=497*C+13,4*10^6	C in m3/h		
Dimensions / capacity					
	price/unit	unit	value	unit	tot costs
Costs			1.000.000	tot m3/h	
Construction costs	€ 0		992.100	added m3/h	€ 407.555.297
Planning and engineering costs					
Material costs				€ 407.555.297	
Labour costs					
Implementation costs (stedelijk gebied)					
Land use					
Urban implementation (space)					
Management and maintenance costs (PV(M))	5%	per year	50	year	€ 51.064.524
and operation en verbruik?	$20.377.765				
Total costs					**$458.619.821**
Round					**$M 458.6**

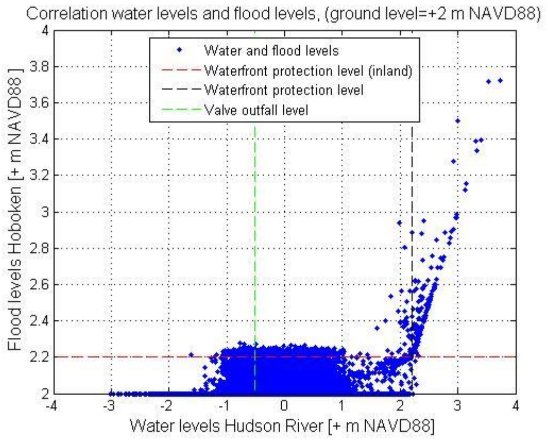
Appendix IV. Model Results: costs of 36 combinations of risk reduction measures

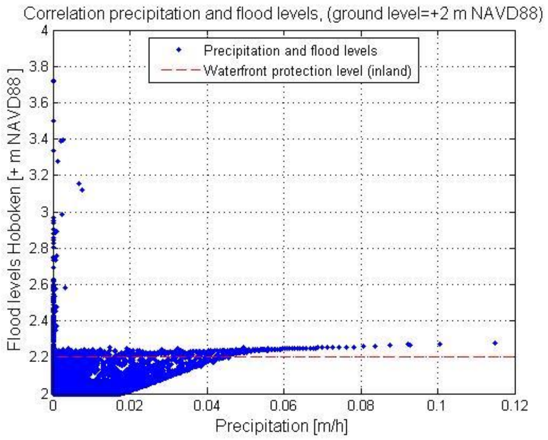
Activity	Resist (m)	Store (ha0.5 m)	Discharge (m^3/h)	I (10^6)	C (10^6)	C_t (10^6)	ΔC (10^6)	ΔC /ΔI
1	0	0	0	$0	$817.248.975	$817.248.975	$0	-
2	0	0	2100 m^3/h	$47.000.000	$798.678.931	$845.678.931	$18.570.043	0,40
3	0	0	92100 m^3/h	$84.600.000	$399.279.340	$483.879.340	$417.969.635	4,94
4	0	0	992100 m^3/h	$458.600.000	$299.547.683	$758.147.683	$517.701.292	1,13
5	0	5 ha * 0.5 m	0	$48.000.000	$499.444.675	$547.444.675	$317.804.299	6,62
6	0	5 ha * 0.5 m	2100 m3/h	$95.000.000	$486.697.032	$581.697.032	$330.551.942	3,48
7	0	5 ha * 0.5 m	92100 m3/h	$132.600.000	$315.706.186	$448.306.186	$501.542.789	3,78
8	0	5 ha * 0.5 m	992100 m3/h	$506.600.000	$234.551.020	$741.151.020	$582.697.955	1,15
9	0	50 ha * 0.5 m	0	$199.000.000	$306.445.471	$505.445.471	$510.803.504	2,57
10	0	50 ha * 0.5 m	2100 m3/h	$246.000.000	$305.587.263	$551.587.263	$511.661.711	2,08
11	0	50 ha * 0.5 m	92100 m3/h	$283.600.000	$288.394.586	$571.994.586	$528.854.389	1,86
12	0	50 ha * 0.5 m	992100 m3/h	$657.600.000	$245.514.048	$903.114.048	$571.734.927	0,87
17	0.8	0	0	$99.000.000	$802.716.466	$901.716.466	$14.532.508	0,15
18	0.8	0	2100 m3/h	$146.000.000	$770.743.803	$916.743.803	$46.505.172	0,32
19	0.8	0	92100 m3/h	$183.600.000	$225.019.238	$408.619.238	$592.229.737	3,23
20	0.8	0	992100 m3/h	$557.600.000	$166.055.124	$723.655.124	$651.193.850	1,17
21	0.8	5 ha * 0.5 m	0	$147.000.000	$351.292.811	$498.292.811	$465.956.163	3,17
22	0.8	5 ha * 0.5 m	2100 m3/h	$194.000.000	$334.499.789	$528.499.789	$482.749.186	2,49
23	0.8	5 ha * 0.5 m	92100 m3/h	$231.600.000	$131.224.639	$362.824.639	$686.024.336	2,96
24	0.8	5 ha * 0.5 m	992100 m3/h	$605.600.000	$106.000.647	$711.600.647	$711.248.327	1,17
25	0.8	50 ha * 0.5 m	0	$298.000.000	$125.886.550	$423.886.550	$691.362.425	2,32
26	0.8	50 ha * 0.5 m	2100 m3/h	$345.000.000	$124.807.182	$469.807.182	$692.441.793	2,01
27	0.8	50 ha *	92100	$382.600.0	$112.092.2	$494.692.2	$705.156.7	1,8

		0.5 m	m3/h	00	33	33	42	4
28	0.8	50 ha * 0.5 m	992100 m3/h	$756.600.000	$106.826.380	$863.426.380	$710.422.595	0,94
33	1.8	0	0	$216.000.000	$692.229.100	$908.229.100	$125.019.874	0,58
34	1.8	0	2100 m3/h	$263.000.000	$660.150.734	$923.150.734	$157.098.241	0,60
35	1.8	0	92100 m3/h	$300.600.000	$114.145.902	$414.745.902	$703.103.072	2,34
36	1.8	0	992100 m3/h	$674.600.000	$61.334.538	$735.934.538	$755.914.436	1,12
37	1.8	5 ha * 0.5 m	0	$264.000.000	$240.037.689	$504.037.689	$577.211.286	2,19
38	1.8	5 ha * 0.5 m	2100 m3/h	$311.000.000	$223.197.351	$534.197.351	$594.051.623	1,91
39	1.8	5 ha * 0.5 m	92100 m3/h	$348.600.000	$20.201.926	$368.801.926	$797.047.049	2,29
40	1.8	5 ha * 0.5 m	992100 m3/h	$722.600.000	$0	$722.600.000	$817.248.975	1,13
41	1.8	50 ha * 0.5 m	0	$415.000.000	$14.061.938	$429.061.938	$803.187.036	1,94
42	1.8	50 ha * 0.5 m	2100 m3/h	$462.000.000	$12.992.138	$474.992.138	$804.256.836	1,74
43	1.8	50 ha * 0.5 m	92100 m3/h	$499.600.000	$687.541	$500.287.541	$816.561.434	1,63
44	1.8	50 ha * 0.5 m	992100 m3/h	$873.600.000	$0	$873.600.000	$817.248.975	0,94

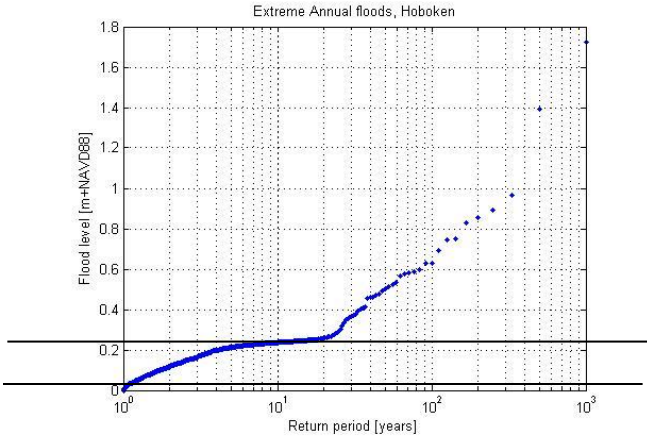
Appendix V. Ranked annual flood levels and damages

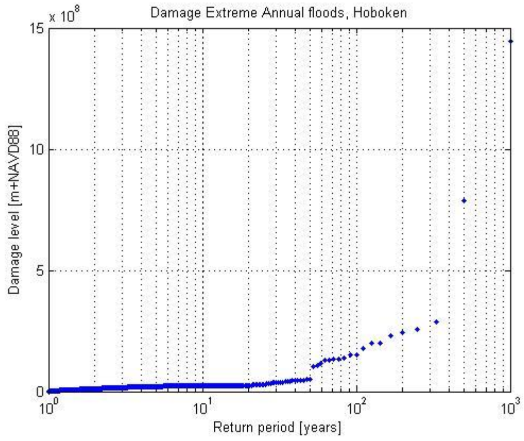
S. Resist = 0 m





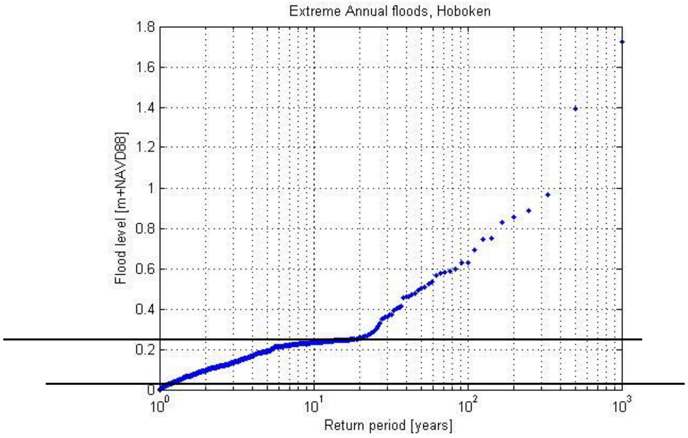
Activity 1: current

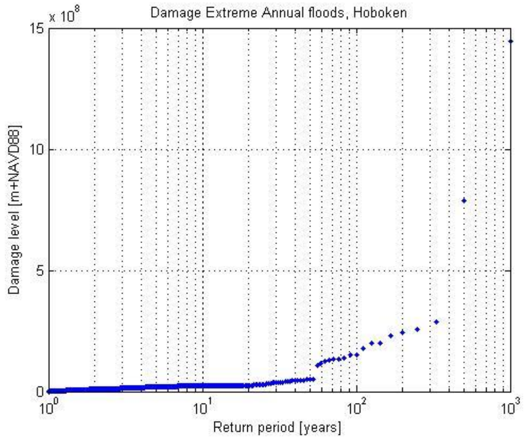




Safety level pluvial: 1 yr
Safety level coastal: 25 yr

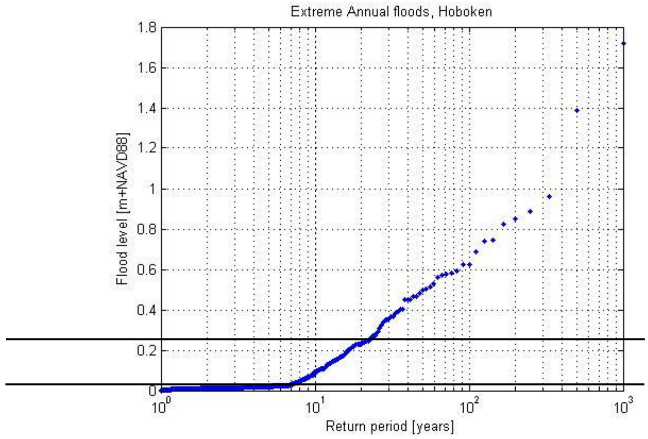
Activity 2: 0 m 0 ha 2,100 m^3/h

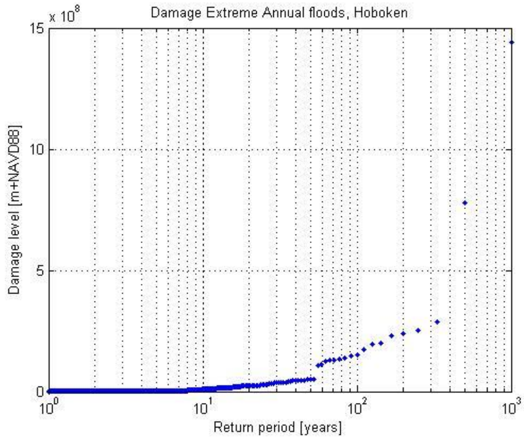




Safety level pluvial: 1 yr
Safety level coastal: 25 yr

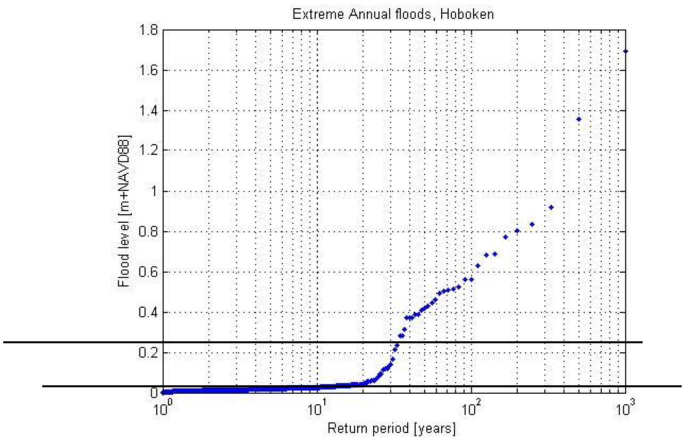
Activity 3: 0 m 0 ha 92,100 m^3/h

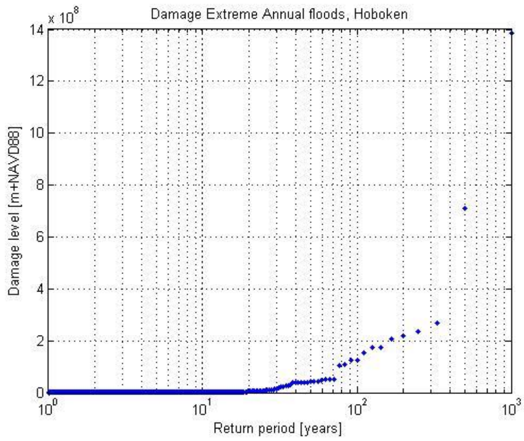




Safety level pluvial: 8 yr
Safety level coastal: 25 yr

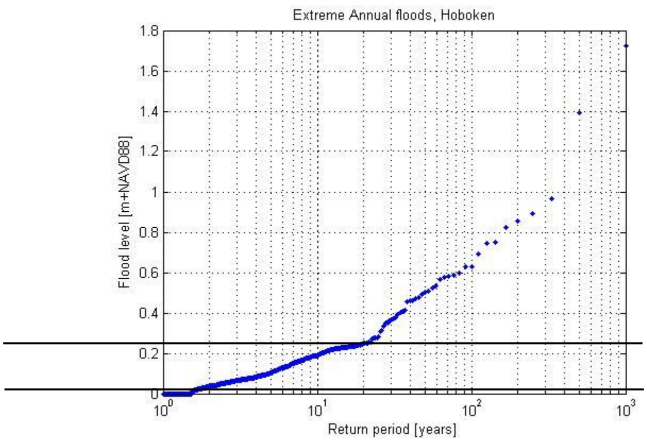
Activity 4: 0 m 0 ha 992,100 m^3/h

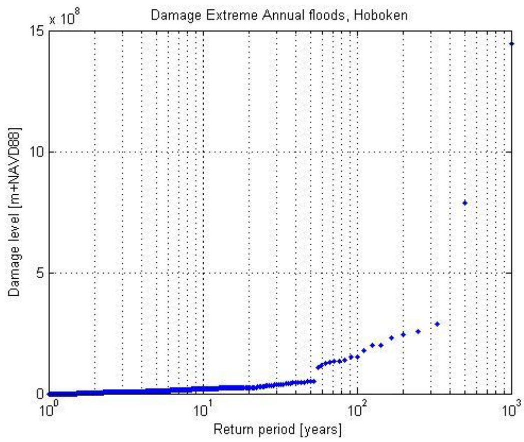




Safety level pluvial: 10 yr
Safety level coastal: 35 yr

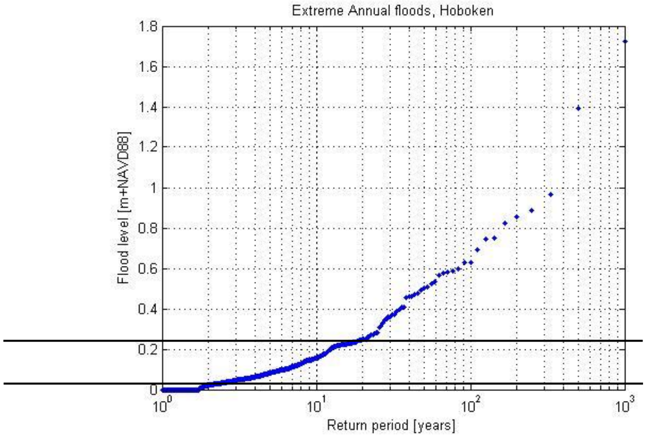
Activity 5: 0 m 5 ha 0 m^3/h

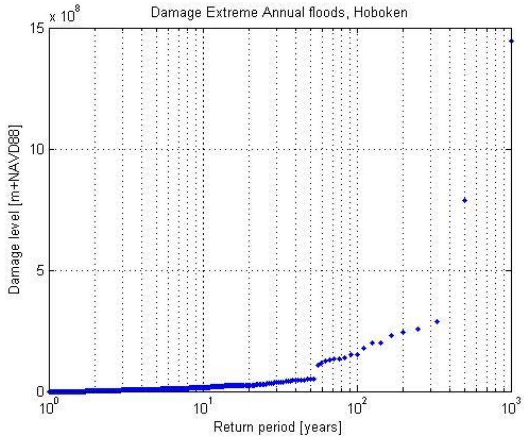




Safety level pluvial: 1.5 yr
Safety level coastal: 25 yr

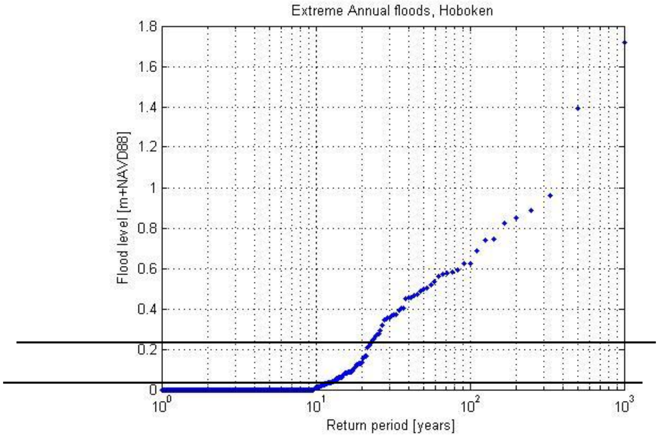
Activity 6: 0 m 5 ha 2,100 m^3/h

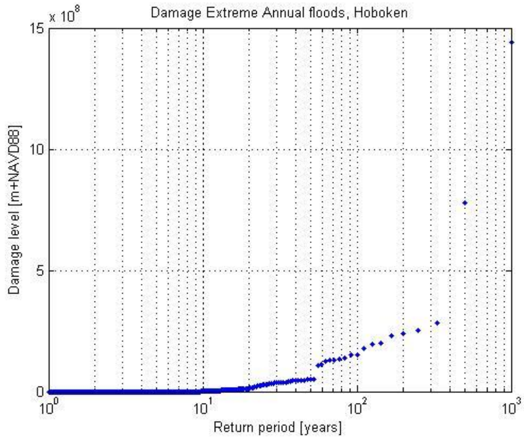




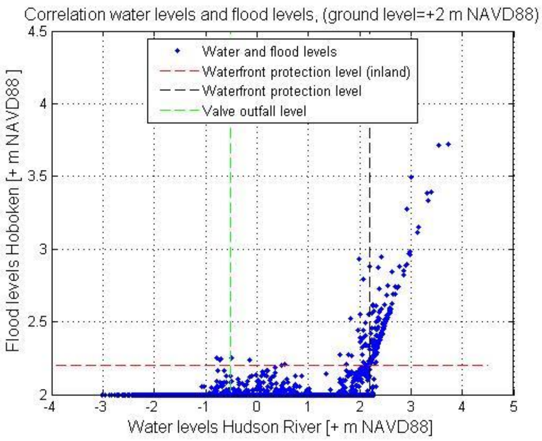
Safety level pluvial: 2 yr
Safety level coastal: 25 yr

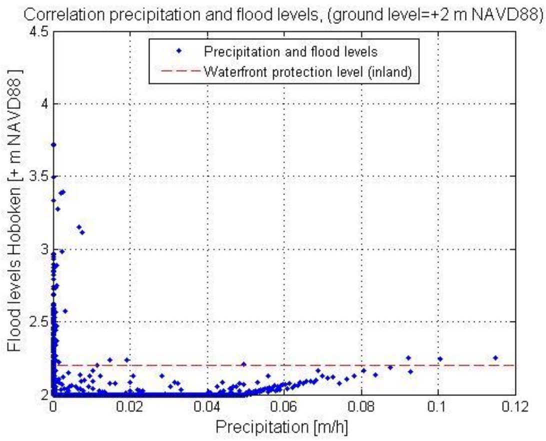
Activity7: 0 m 5 ha 92,100 m^3/h



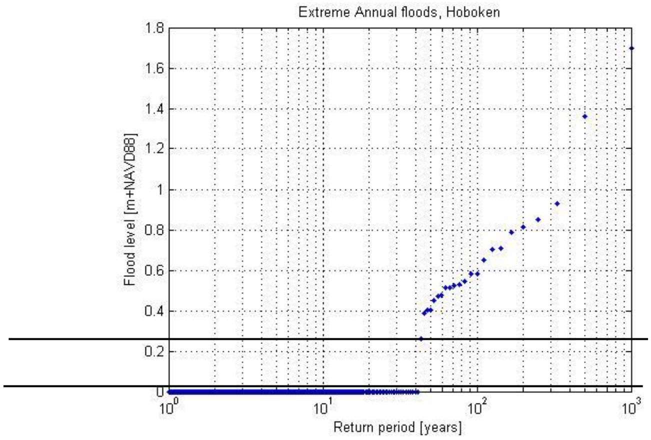


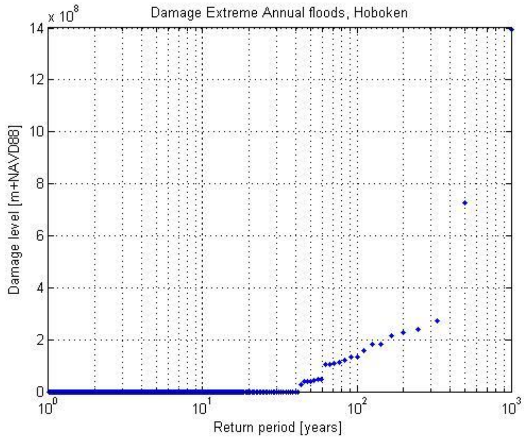
Safety level pluvial: 10 yr
Safety level coastal: 25 yr





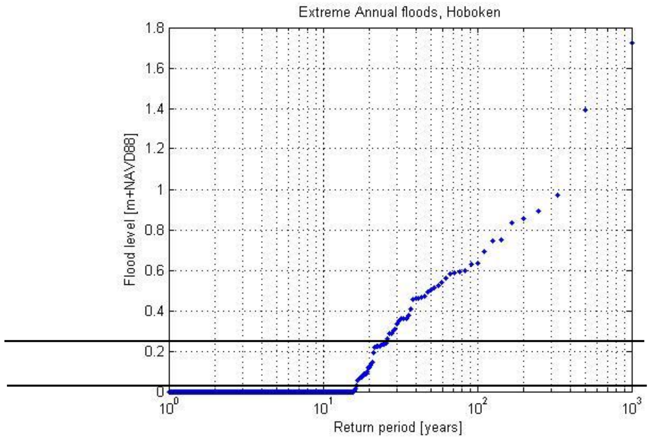
Activity 8: 0 m 5 ha 992,100 m^3/h

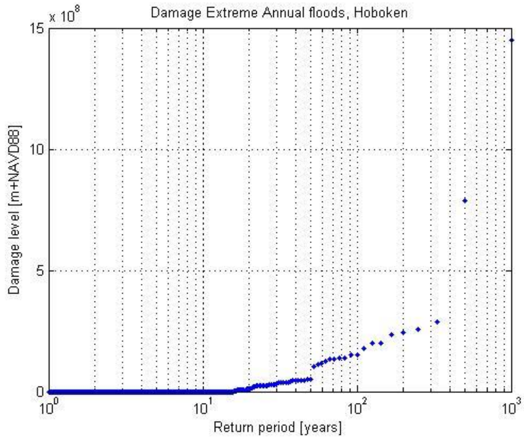




Safety level pluvial: 0 yr
Safety level coastal: 40 yr

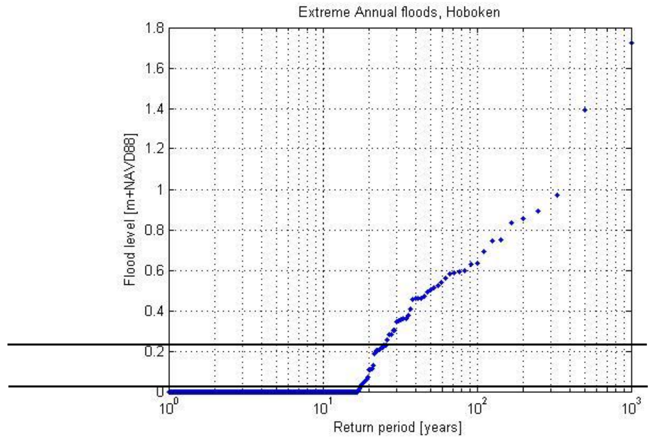
Activity 9: 0 m 50 ha 0 m^3/h

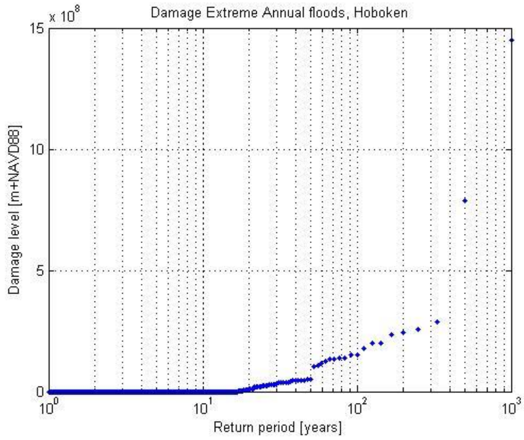




Safety level pluvial: 15 yr
Safety level coastal: 25 yr

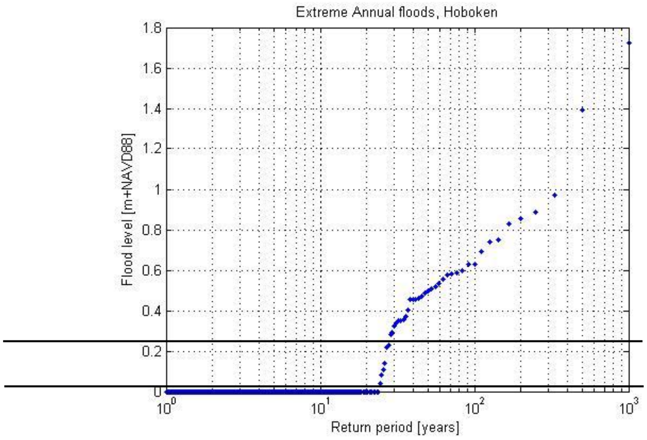
Activity 10: 0 m 50 ha 2,100 m^3/h

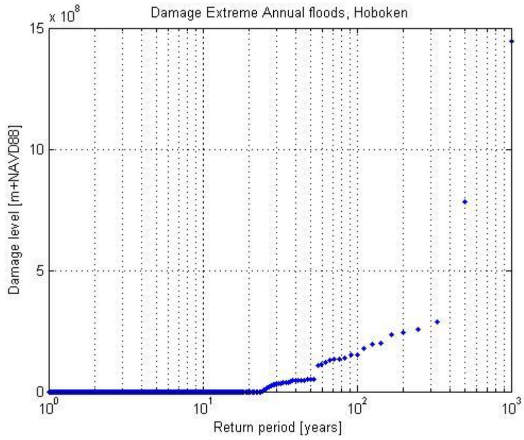




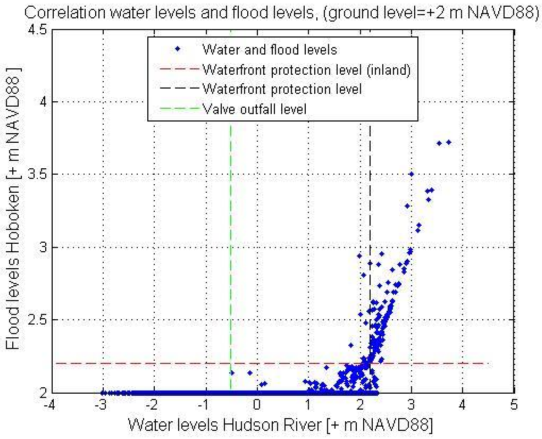
Safety level pluvial: 15 yr
Safety level coastal: 25 yr

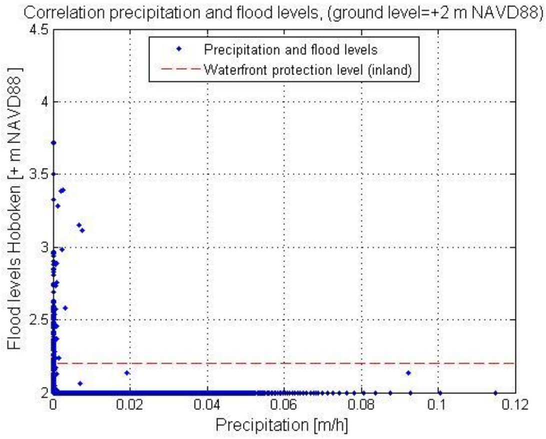
Activity 11: 0 m 50 ha 92,100 m^3/h



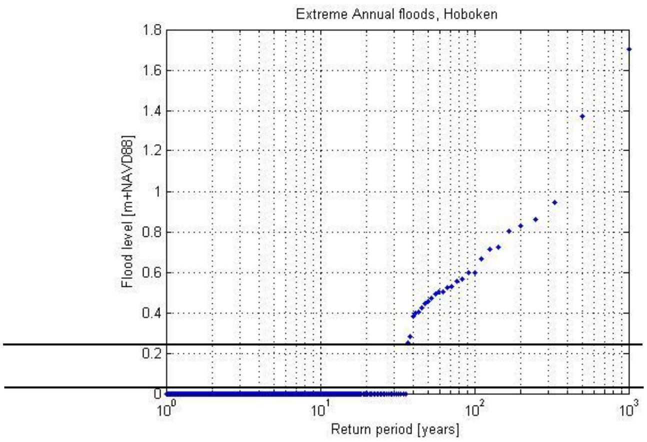


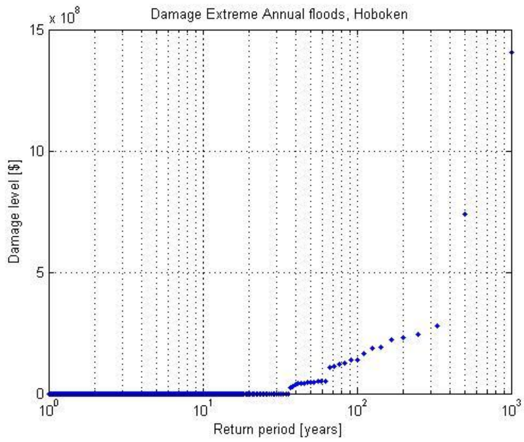
Safety level pluvial: 25 yr
Safety level coastal: 30 yr



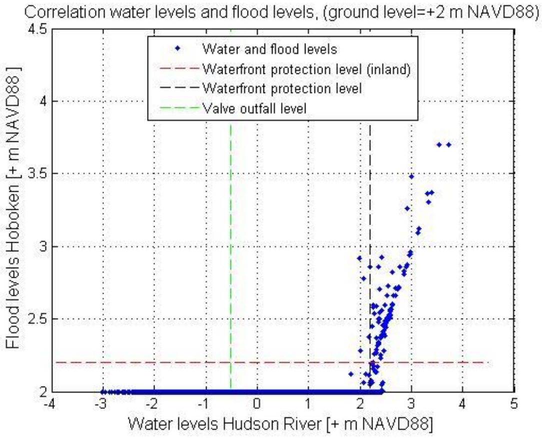


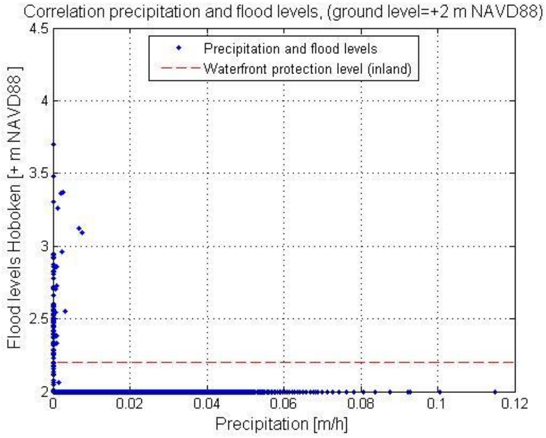
Activity 12: 0 m 50 ha 992,100 m^3/h



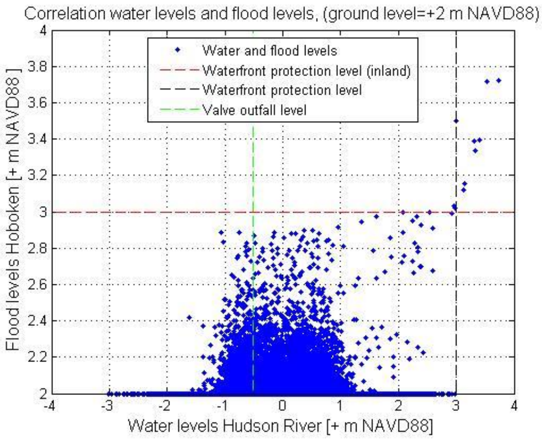


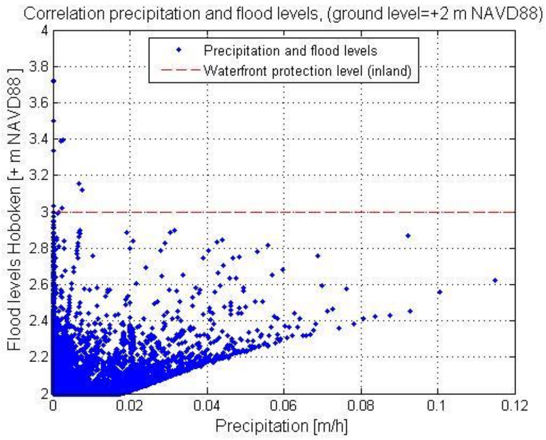
Safety level pluvial: 1000+
Safety level coastal: 35 / 40 yr



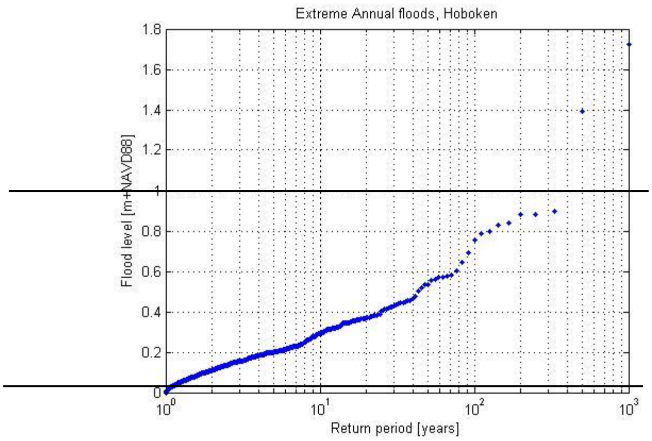


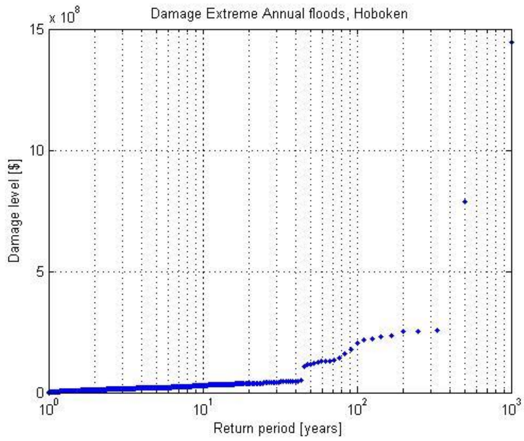
T. Resist = 0.8 m





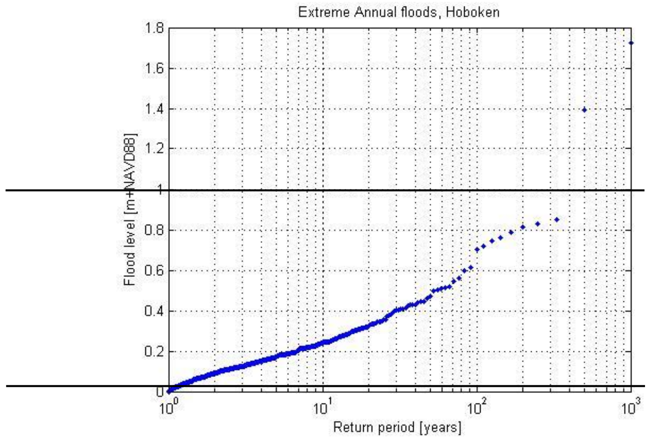
Activity 17: 0.8 m 0 ha 0 m^3/h

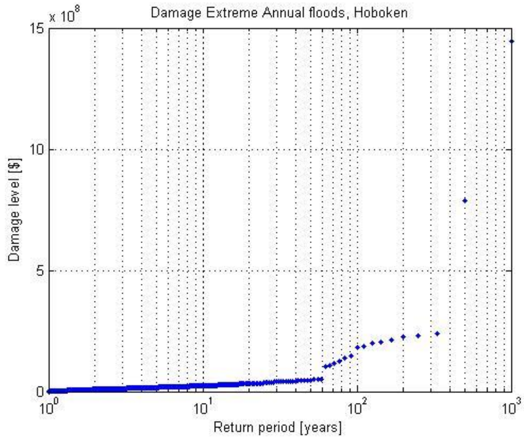




Safety level pluvial: 1 yr
Safety level coastal: 500 yr

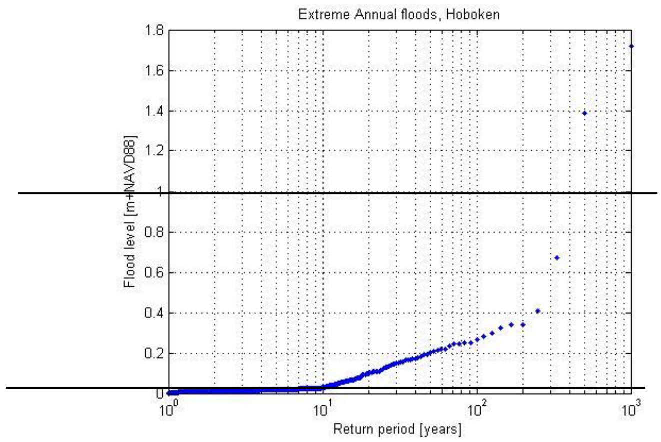
Activity 18: 0.8 m 0 ha 2,100 m^3/h

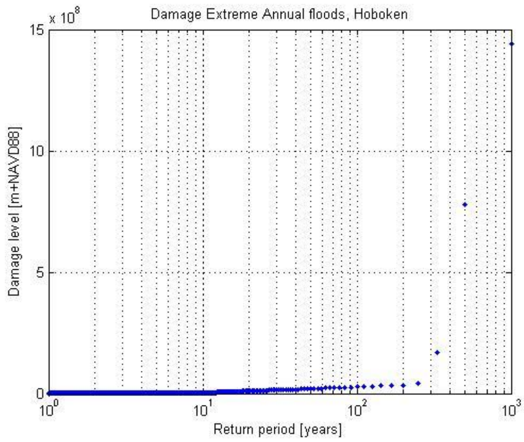




Safety level pluvial: 1 yr
Safety level coastal: 500 yr

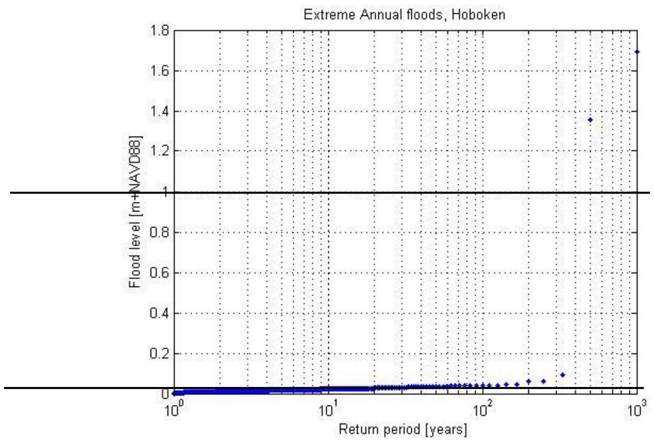
Activity 19: 0.8 m 0 ha 92,100 m^3/h

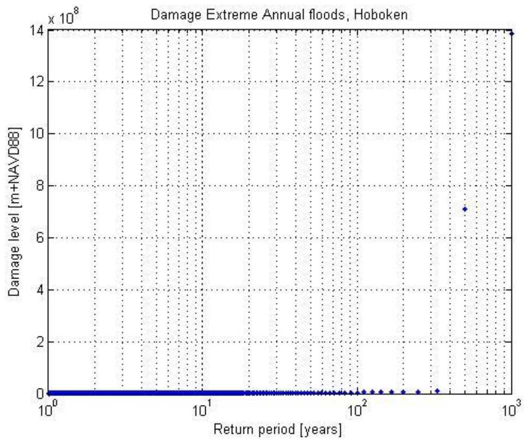




Safety level pluvial: 10 yr
Safety level coastal: 500 yr

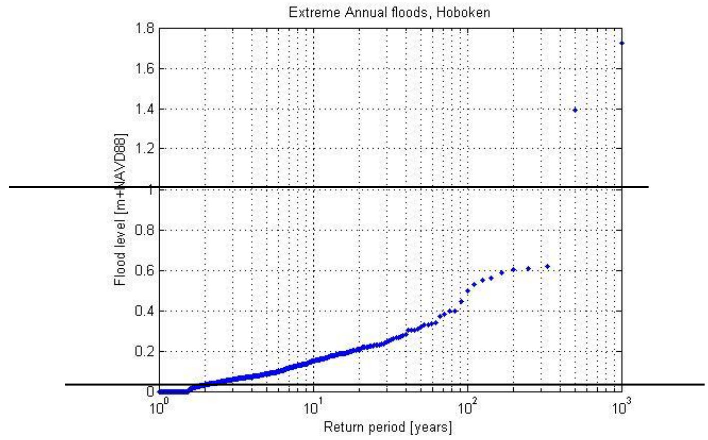
Activity 20: 0.8 m 0 ha 992,100 m^3/h

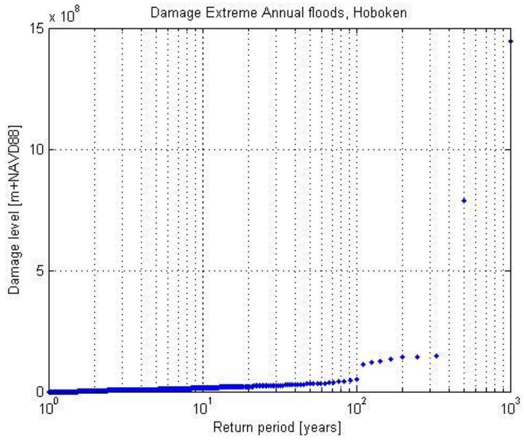




Safety level pluvial: 10 yr
Safety level coastal: 500 yr

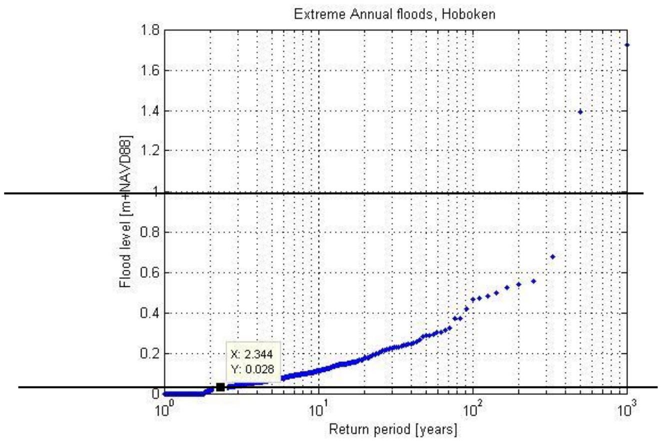
Activity 21: 0.8 m 5 ha 0 m^3/h

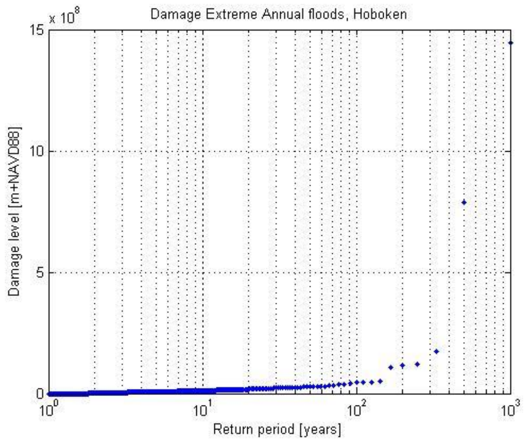




Safety level pluvial: 2 yr
Safety level coastal: 500 yr

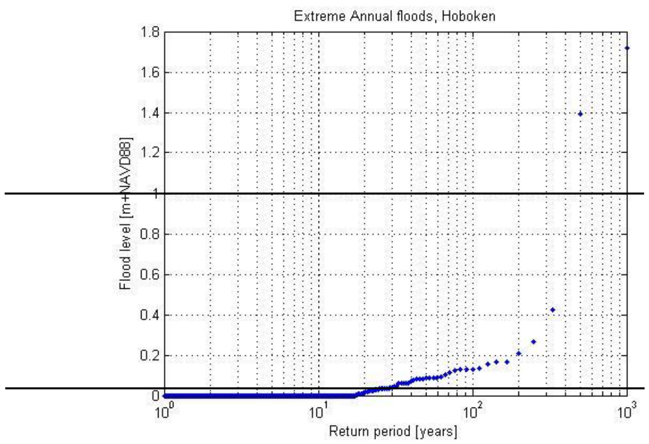
Activity 22: 0.8 m 5 ha 2,100 m^3/h

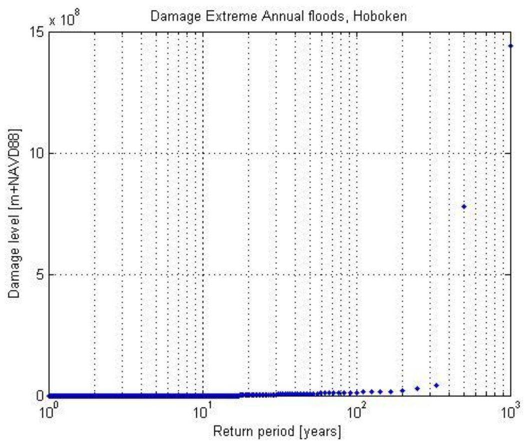




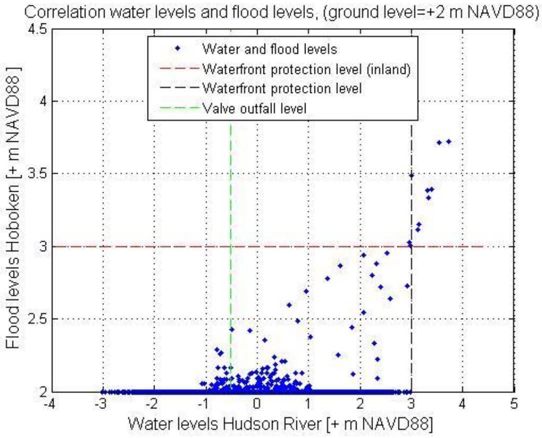
Safety level pluvial: 2 yr
Safety level coastal: 500 yr

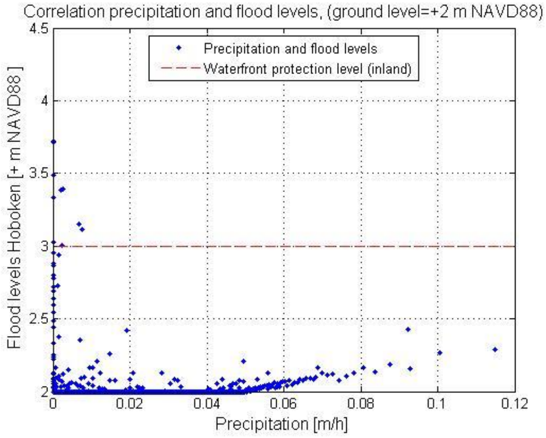
Activity 23: 0.8 m 5 ha 92,100 m^3/h



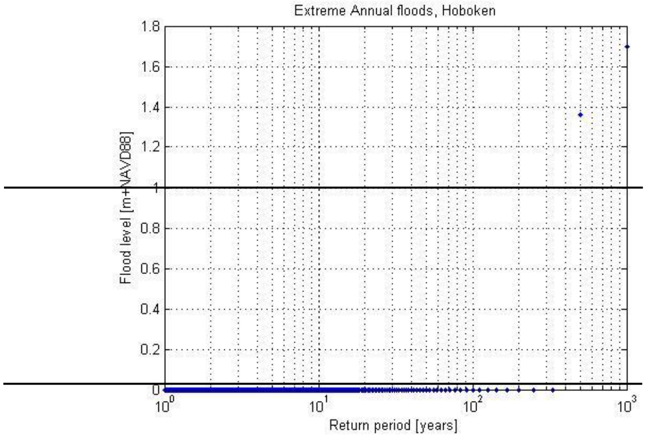


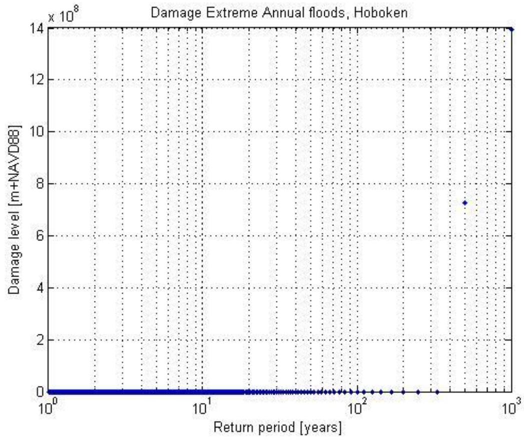
Safety level pluvial: 25 yr
Safety level coastal: 500 yr





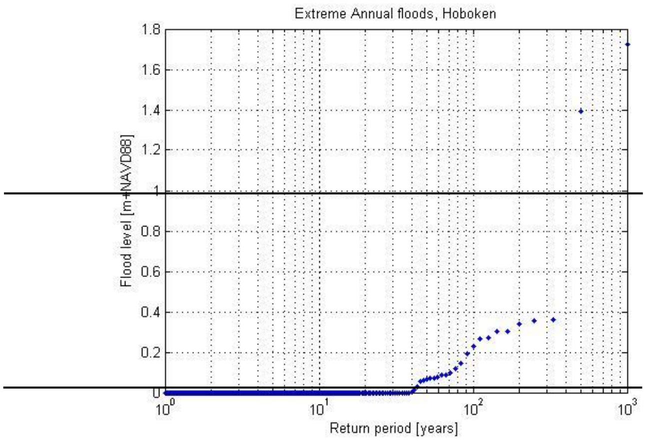
Activity 24: **0.8 m** **5 ha** **992,100 m^3/h**

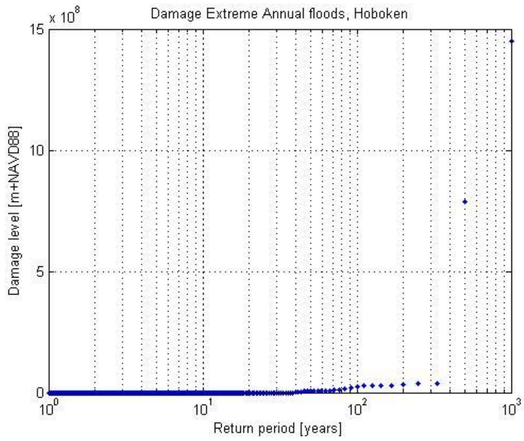




Safety level pluvial: 1000+ yr
Safety level coastal: 500 yr

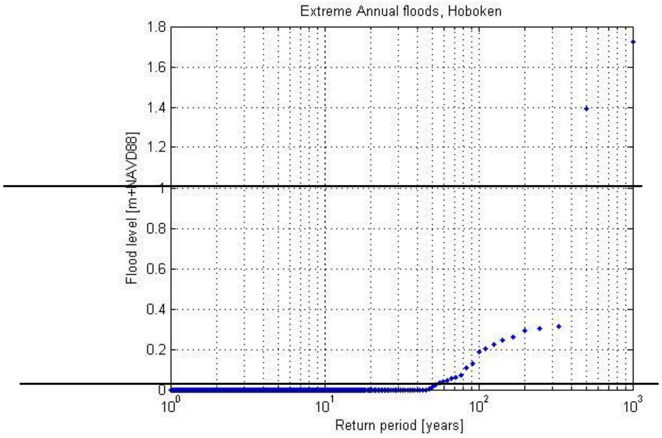
Activity 25: **0.8 m** **50 ha** **0 m^3/h**

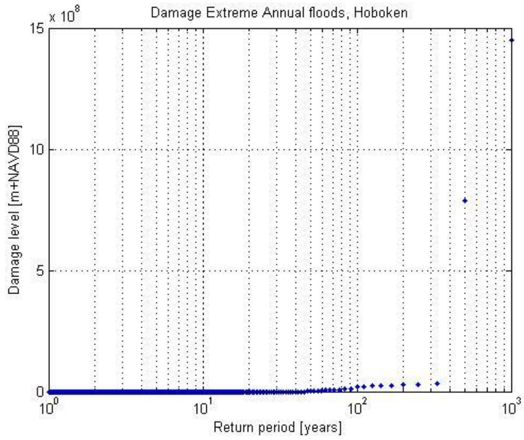




Safety level pluvial: 40 yr
Safety level coastal: 500 yr

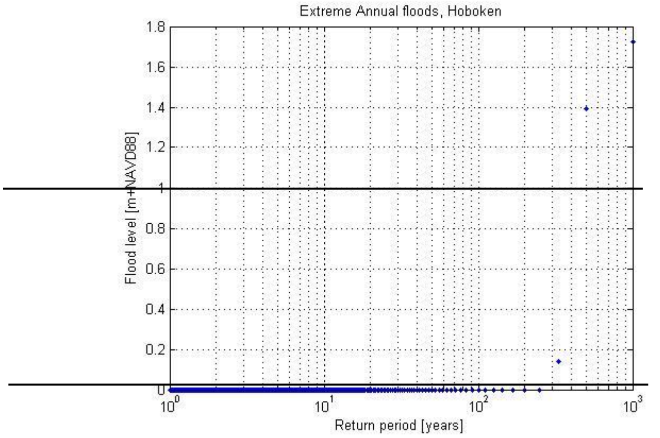
Activity 26: 0.8 m 50 ha 2,100 m^3/h

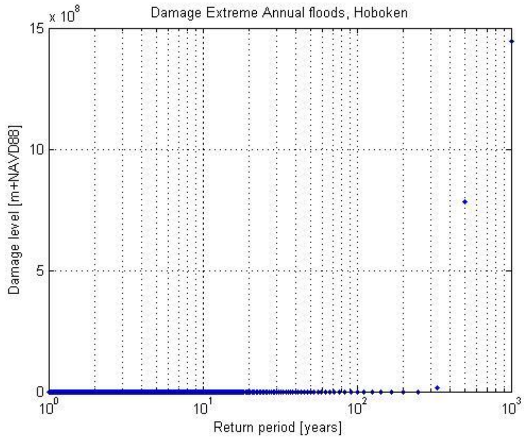




Safety level pluvial: 50 yr
Safety level coastal: 500 yr

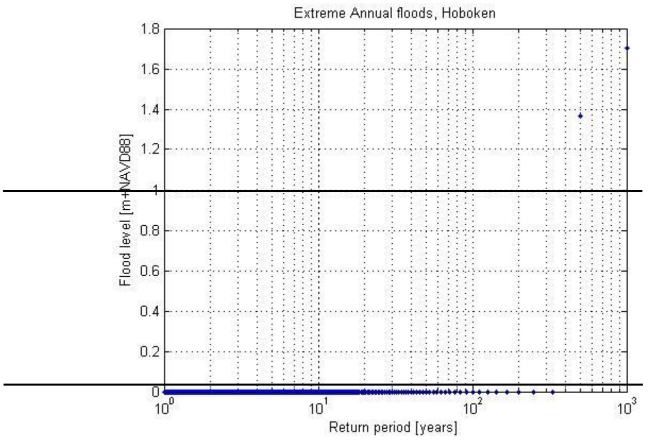
Activity 27: 0.8 m 50 ha 92,100 m^3/h

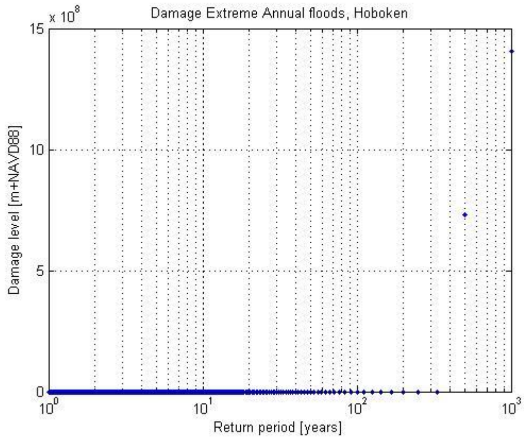




Safety level pluvial: 300 yr
Safety level coastal: 500 yr

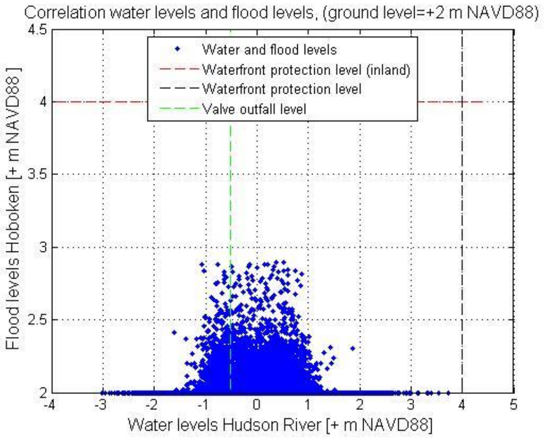
Activity 28: 0.8 m 50 ha 992,100 m^3/h

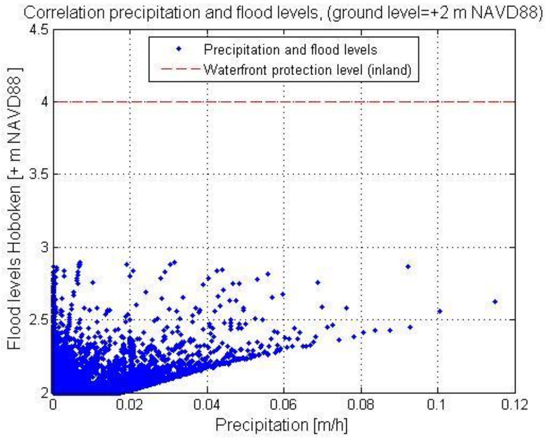




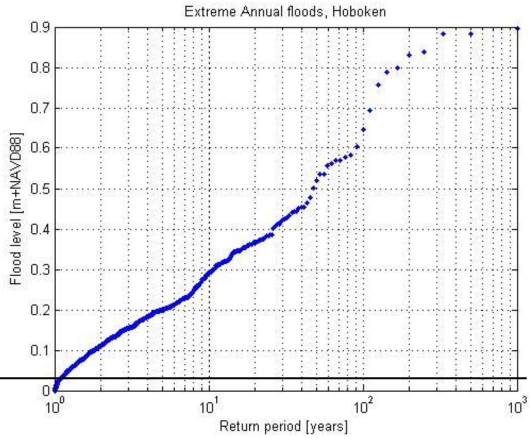
Safety level pluvial: 1000+ yr
Safety level coastal: 500 yr

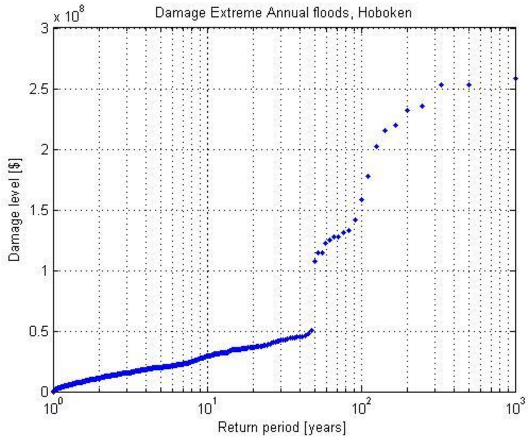
U. Resist = 1.8 m





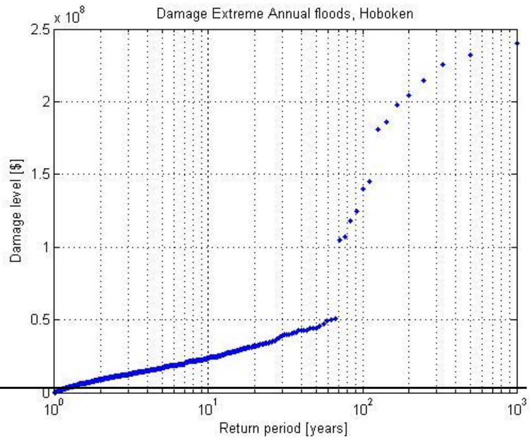
Activity 33: 1.8 m 0 ha 0 m^3/h

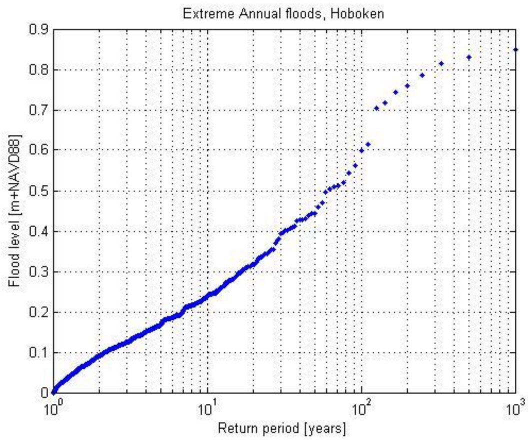




Safety level pluvial: 1 yr
Safety level coastal: 1000+ yr

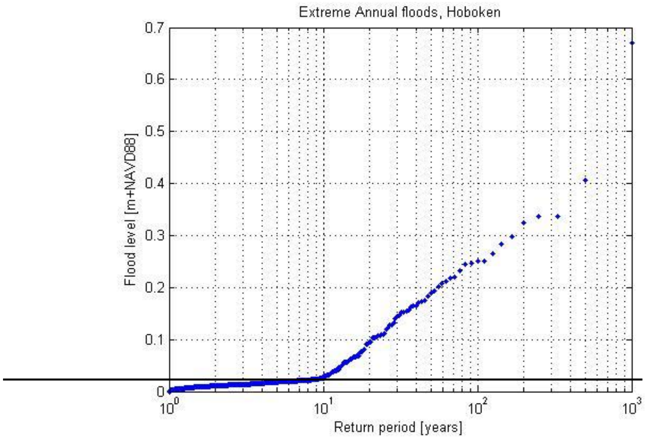
Activity 34: 1.8 m 0 ha 2,100 m^3/h

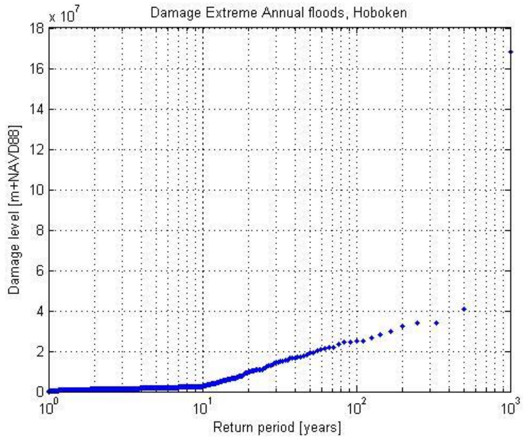




Safety level pluvial: 1 yr
Safety level coastal: 1000+ yr

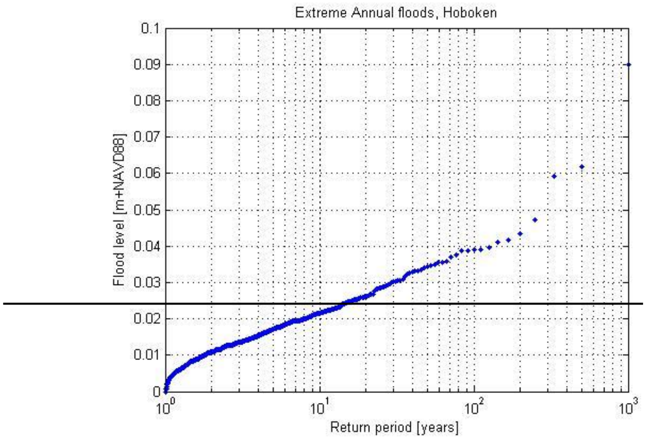
Activity 35: 1.8 m 0 ha 92,100 m^3/h

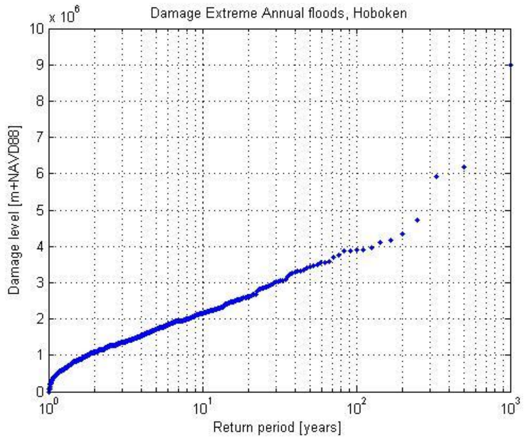




Safety level pluvial: 10 yr
Safety level coastal: 1000+ yr

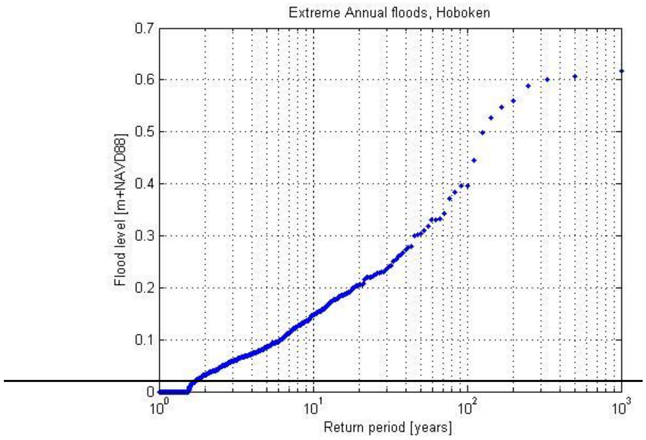
Activity 36: 1.8 m 0 ha 992,100 m^3/h

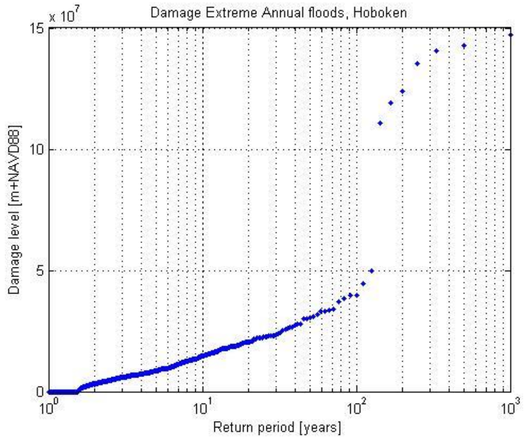




Safety level pluvial: 15 yr
Safety level coastal: 1000+ yr

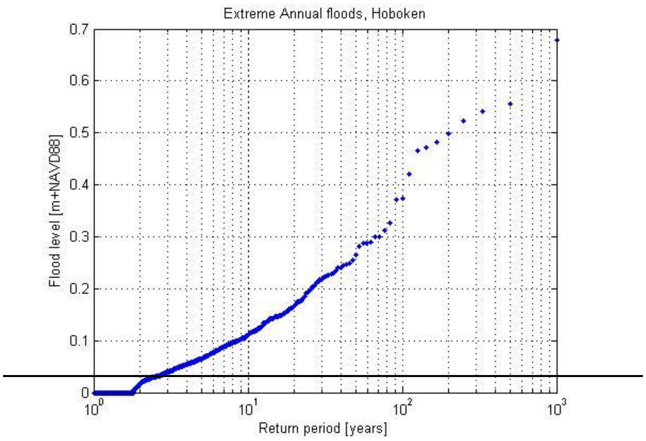
Activity 37: 1.8 m 5 ha 0 m^3/h

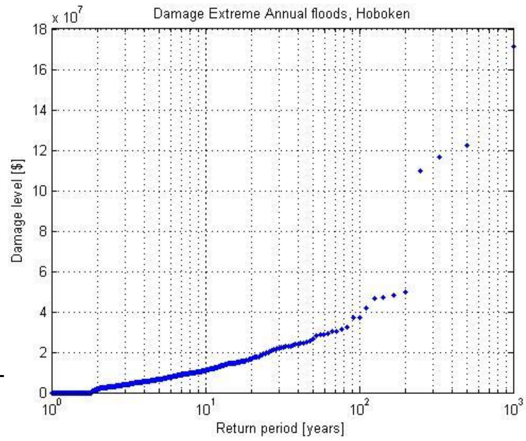




Safety level pluvial: 1.5 yr
Safety level coastal: 1000+ yr

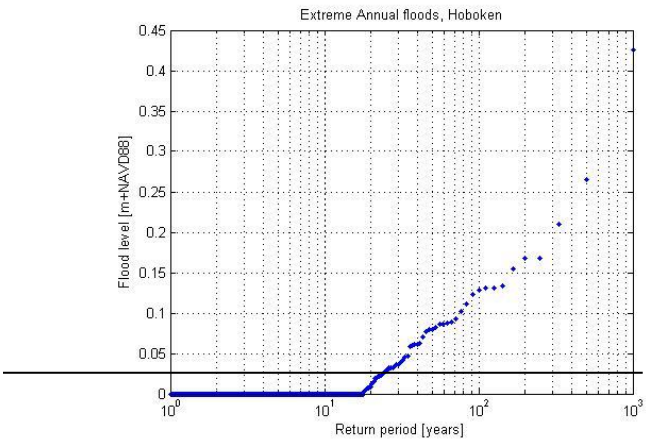
Activity 38: 1.8 m 5 ha 2,100 m^3/h

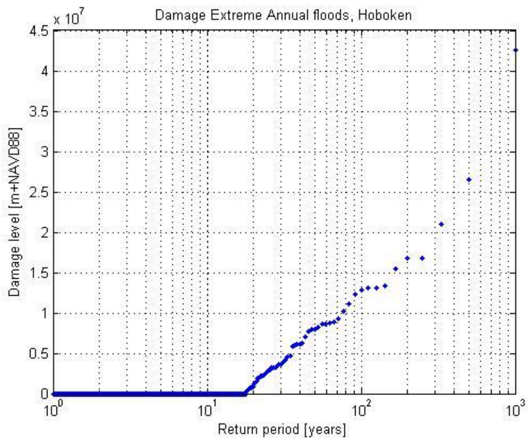




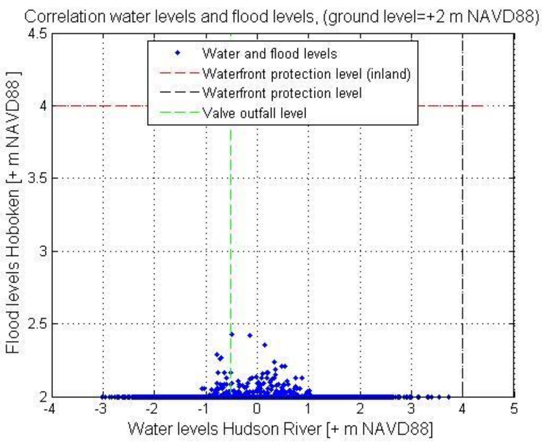
Safety level pluvial: 2 yr
Safety level coastal: 1000+ yr

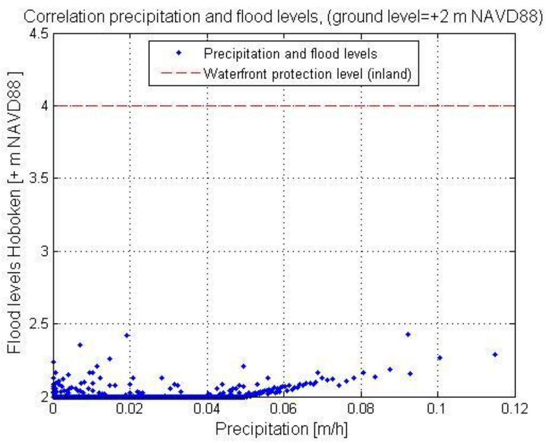
Activity 39: 1.8 m 5 ha 92,100 m^3/h



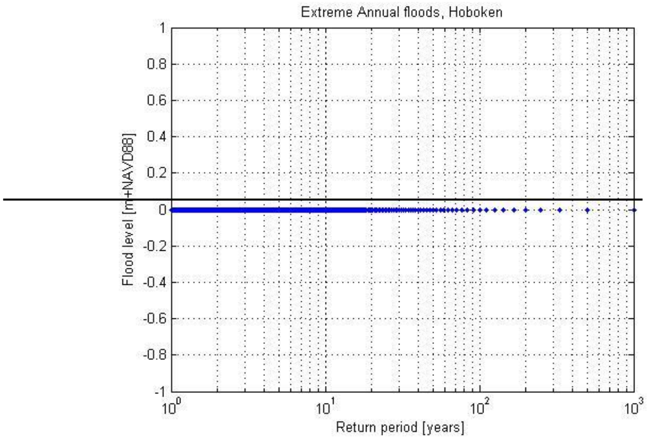


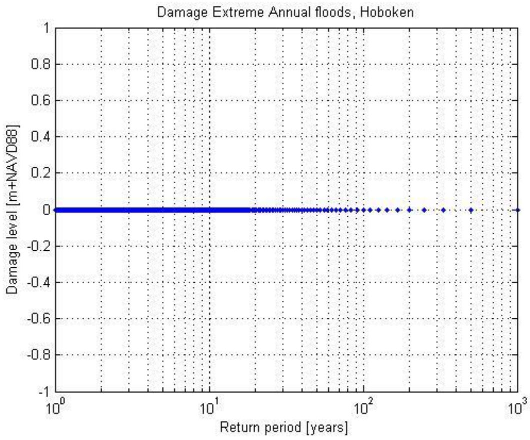
Safety level pluvial: 20/25 yr
Safety level coastal: 1000+ yr





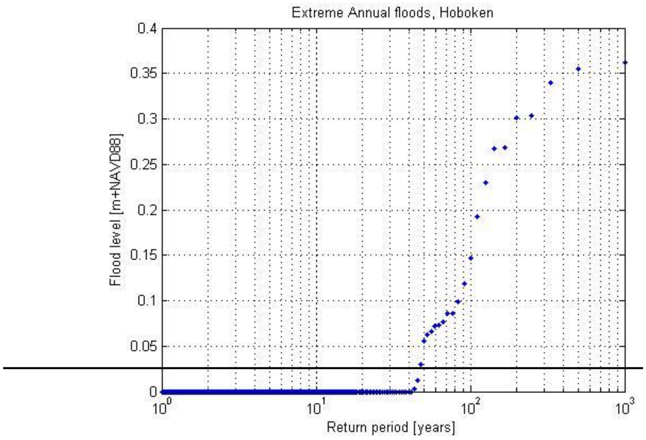
Activity 40: 1.8 m 5 ha 992,100 m³/h

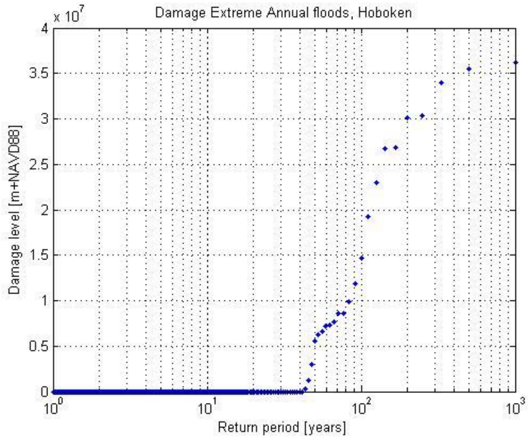




Safety level pluvial: 1000+ yr
Safety level coastal: 1000+ yr

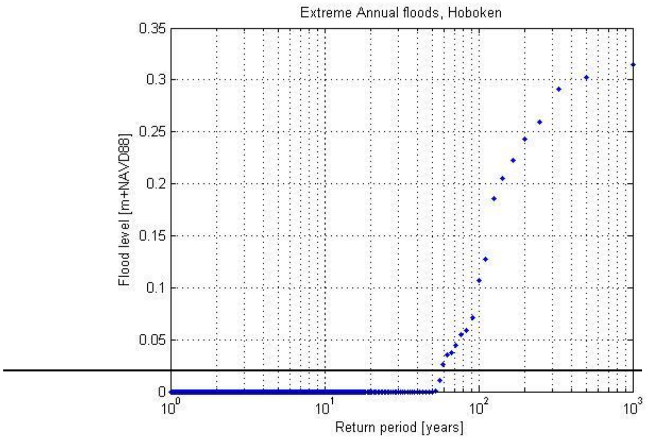
Activity 41: 1.8 m 50 ha 0 m³/h

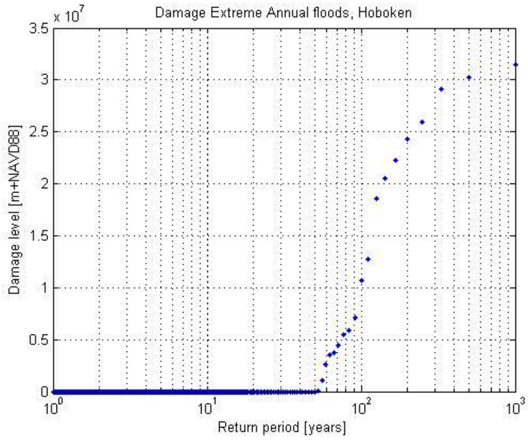




Safety level pluvial: 45 yr
Safety level coastal: 1000+ yr

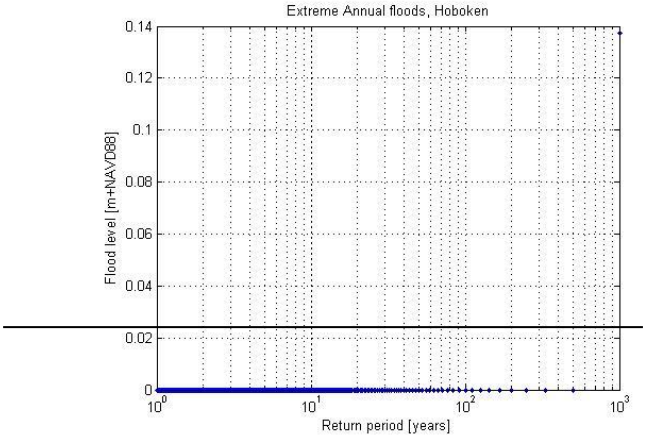
Activity 42: 1.8 m 50 ha 2,100 m³/h

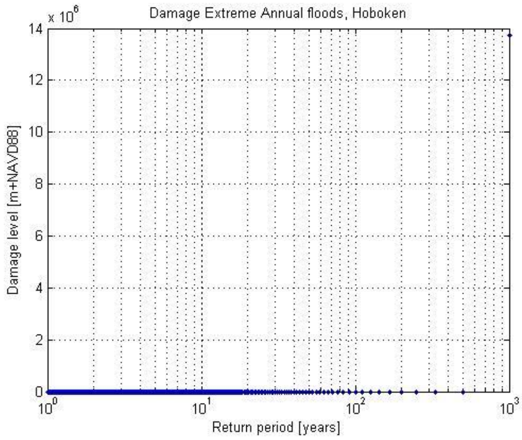




Safety level pluvial: 55/60 yr
Safety level coastal: 1000+ yr

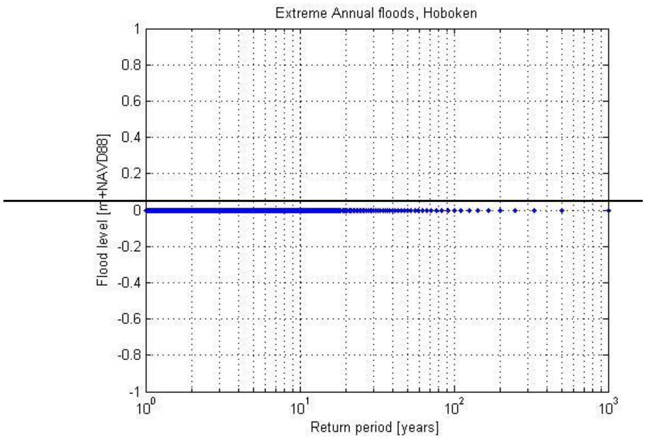
Activity 43: 1.8 m 50 ha 92,100 m^3/h

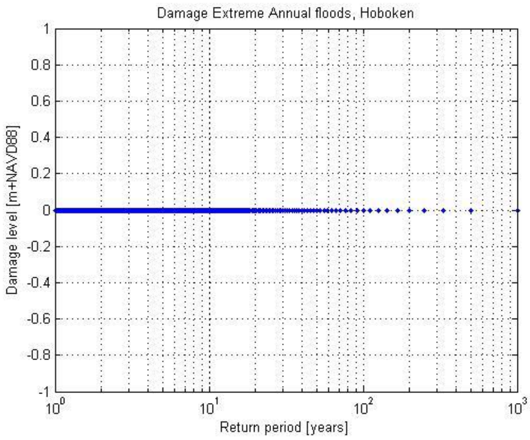




Safety level pluvial: 1000+ yr
Safety level coastal: 1000+ yr

Activity 44: 1.8 m 50 ha 992,100 m^3/h





Safety level pluvial: 1000+ yr
Safety level coastal: 1000+ yr

Appendix VI. Comparison of varying single measures of Resist, Store, Discharge

activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m^3/h)**	**C (10^6)**	**ΔC (10^6)**
1	0	0	0	$817.248.975	$0
5	0	5 ha * 0.5 m	0	$499.444.675	$317.804.299
9	0	50 ha * 0.5 m	0	$306.445.471	$510.803.504
17	0.8	0	0	$802.716.466	$14.532.508
21	0.8	5 ha * 0.5 m	0	$351.292.811	$465.956.163
25	0.8	50 ha * 0.5 m	0	$125.886.550	$691.362.425
33	1.8	0	0	$692.229.100	$125.019.874
37	1.8	5 ha * 0.5 m	0	$240.037.689	$577.211.286
41	1.8	50 ha * 0.5 m	0	$14.061.938	$803.187.036

Resist reduction is 0 – 14 – 125 >> difference of 14 and 111

activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m^3/h)**	**C (10^6)**	**ΔC (10^6)**
2	0	0	2100 m3/h	$798.678.931	$18.570.043
6	0	5 ha * 0.5 m	2100 m3/h	$486.697.032	$330.551.942
10	0	50 ha * 0.5 m	2100 m3/h	$305.587.263	$511.661.711
18	0.8	0	2100 m3/h	$770.743.803	$46.505.172
22	0.8	5 ha * 0.5 m	2100 m3/h	$334.499.789	$482.749.186
26	0.8	50 ha * 0.5 m	2100 m3/h	$124.807.182	$692.441.793
34	1.8	0	2100 m3/h	$660.150.734	$157.098.241
38	1.8	5 ha * 0.5 m	2100 m3/h	$223.197.351	$594.051.623
42	1.8	50 ha * 0.5 m	2100 m3/h	$12.992.138	$804.256.836

Resist reduction is 18 – 46 -157 >> difference of 28 and 111

activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m^3/h)**	**C (10^6)**	**ΔC (10^6)**
3	0	0	92100 m3/h	$399.279.340	$417.969.635
7	0	5 ha * 0.5 m	92100 m3/h	$315.706.186	$501.542.789
11	0	50 ha * 0.5 m	92100 m3/h	$288.394.586	$528.854.389
19	0.8	0	92100 m3/h	$225.019.238	$592.229.737
23	0.8	5 ha * 0.5 m	92100 m3/h	$131.224.639	$686.024.336
27	0.8	50 ha * 0.5 m	92100 m3/h	$112.092.233	$705.156.742
35	1.8	0	92100 m3/h	$114.145.902	$703.103.072
39	1.8	5 ha * 0.5 m	92100 m3/h	$20.201.926	$797.047.049
43	1.8	50 ha * 0.5 m	92100 m3/h	$687.541	$816.561.434

Resist reduction is 417 – 592 -703 >> difference of 175 and 111 (larger pump)

activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m^3/h)**	**C (M)**	**ΔC**
1	0	0	0	$817.248.975	$0
2	0	0	2100 m3/h	**$798.678.931**	**$18.570.043**
3	**0**	**0**	**92100 m3/h**	**$399.279.340**	**$417.969.635**
17	0.8	0	0	$802.716.466	$14.532.508
18	0.8	0	2100 m3/h	$770.743.803	$46.505.172
19	**0.8**	**0**	**92100 m3/h**	**$225.019.238**	**$592.229.737**
33	1.8	0	0	$692.229.100	$125.019.874
34	1.8	0	2100 m3/h	$660.150.734	$157.098.241
35	**1.8**	**0**	**92100 m3/h**	**$114.145.902**	**$703.103.072**

0 – 14 - 125 >> 14 – 111
417 – 592 – 703>> 175 – 111

activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m^3/h)**	**C (10^6)**	**ΔC (10^6)**
5	0	5 ha * 0.5 m	0	$499.444.675	$317.804.299
6	0	5 ha * 0.5 m	2100 m3/h	$486.697.032	$330.551.942
7	**0**	**5 ha * 0.5 m**	**92100 m3/h**	**$315.706.186**	**$501.542.789**
21	0.8	5 ha * 0.5 m	0	$351.292.811	$465.956.163
22	0.8	5 ha * 0.5 m	2100 m3/h	$334.499.789	$482.749.186
23	**0.8**	**5 ha * 0.5 m**	**92100 m3/h**	**$131.224.639**	**$686.024.336**
37	1.8	5 ha * 0.5 m	0	$240.037.689	$577.211.286
38	1.8	5 ha * 0.5 m	2100 m3/h	$223.197.351	$594.051.623
39	**1.8**	**5 ha * 0.5 m**	**92100 m3/h**	**$20.201.926**	**$797.047.049**

317 – 465 – 577 >> 148 – 112
501 – 686 – 797 >> 185 – 111

activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m^3/h)**	**C (10^6)**	**ΔC (10^6)**
9	0	50 ha * 0.5 m	0	$306.445.471	$510.803.504
10	0	50 ha * 0.5 m	2100 m3/h	$305.587.263	$511.661.711
11	**0**	**50 ha * 0.5 m**	**92100 m3/h**	**$288.394.586**	**$528.854.389**
25	0.8	50 ha * 0.5 m	0	$125.886.550	$691.362.425
26	0.8	50 ha * 0.5 m	2100 m3/h	$124.807.182	$692.441.793
27	**0.8**	**50 ha * 0.5 m**	**92100 m3/h**	**$112.092.233**	**$705.156.742**
41	1.8	50 ha * 0.5 m	0	$14.061.938	$803.187.036
42	1.8	50 ha * 0.5 m	2100 m3/h	$12.992.138	$804.256.836
43	**1.8**	**50 ha * 0.5 m**	**92100 m3/h**	**$687.541**	**$816.561.434**

510 – 691 – 803 >> 181 – 112
528 – 705 – 816 >> 177 – 111

Appendix VII. Separate optimization Resist, Store, Discharge

V. Resist

Activity	Resist (m)	Store (ha0.5 m)	Discharge (m^3/h)	I (10^6)	C (10^6)	C_t (10^6)	ΔC (10^6)	ΔC /ΔI
1,00	0	0	0	0	817.248.975	817.248.975	0	-
2	0	0	2100 m3/h	47.000.000	798.678.931	845.678.931	18.570.043	0
3	0	0	92100 m3/h	84.600.000	399.279.340	483.879.340	417.969.635	5
4	0	0	992100 m3/h	458.600.000	299.547.683	758.147.683	517.701.292	1
5	0	5 ha * 0.5 m	0	48.000.000	499.444.675	547.444.675	317.804.299	7
6	0	5 ha * 0.5 m	2100 m3/h	95.000.000	486.697.032	581.697.032	330.551.942	3
7	**0**	**5 ha * 0.5 m**	**92100 m3/h**	**132.600.000**	**315.706.186**	**448.306.186**	**501.542.789**	**4**
8	0	5 ha * 0.5 m	992100 m3/h	506.600.000	234.551.020	741.151.020	582.697.955	1
9	0	50 ha * 0.5 m	0	199.000.000	306.445.471	505.445.471	510.803.504	3
10	0	50 ha * 0.5 m	2100 m3/h	246.000.000	305.587.263	551.587.263	511.661.711	2
11	0	50 ha * 0.5 m	92100 m3/h	283.600.000	288.394.586	571.994.586	528.854.389	2
12	0	50 ha * 0.5 m	992100 m3/h	657.600.000	245.514.048	903.114.048	571.734.927	1

17	0.8	0	0	99.000.000	802.716.466	901.716.466	14.532.508	0
18	0.8	0	2100 m3/h	146.000.000	770.743.803	916.743.803	46.505.172	0
19	0.8	0	92100 m3/h	183.600.000	225.019.238	408.619.238	592.229.737	3
20	0.8	0	992100 m3/h	557.600.000	166.055.124	723.655.124	651.193.850	1
21	0.8	5 ha * 0.5 m	0	147.000.000	351.292.811	498.292.811	465.956.163	3
22	0.8	5 ha * 0.5 m	2100 m3/h	194.000.000	334.499.789	528.499.789	482.749.186	2
23	**0.8**	**5 ha * 0.5 m**	**92100 m3/h**	**231.600.000**	**131.224.639**	**362.824.639**	**686.024.336**	**3**

24	0.8	5 ha * 0.5 m	992100 m3/h	605.600.000	106.000.647	711.600.647	711.248.327	1
25	0.8	50 ha * 0.5 m	0	298.000.000	125.886.550	423.886.550	691.362.425	2
26	0.8	50 ha * 0.5 m	2100 m3/h	345.000.000	124.807.182	469.807.182	692.441.793	2
27	0.8	50 ha * 0.5 m	92100 m3/h	382.600.000	112.092.233	494.692.233	705.156.742	2
28	0.8	50 ha * 0.5 m	992100 m3/h	756.600.000	106.826.380	863.426.380	710.422.595	1

33	1.8	0	0	216.000.000	692.229.100	908.229.100	125.019.874	1
34	1.8	0	2100 m3/h	263.000.000	660.150.734	923.150.734	157.098.241	1
35	1.8	0	92100 m3/h	300.600.000	114.145.902	414.745.902	703.103.072	2
36	1.8	0	992100 m3/h	674.600.000	61.334.538	735.934.538	755.914.436	1
37	1.8	5 ha * 0.5 m	0	264.000.000	240.037.689	504.037.689	577.211.286	2
38	1.8	5 ha * 0.5 m	2100 m3/h	311.000.000	223.197.351	534.197.351	594.051.623	2
39	**1.8**	**5 ha * 0.5 m**	**92100 m3/h**	**348.600.000**	**20.201.926**	**368.801.926**	**797.047.049**	**2**
40	1.8	5 ha * 0.5 m	992100 m3/h	722.600.000	0	722.600.000	817.248.975	1
41	1.8	50 ha * 0.5 m	0	415.000.000	14.061.938	429.061.938	803.187.036	2
42	1.8	50 ha * 0.5 m	2100 m3/h	462.000.000	12.992.138	474.992.138	804.256.836	2
43	1.8	50 ha * 0.5 m	92100 m3/h	499.600.000	687.541	500.287.541	816.561.434	2
44	1.8	50 ha * 0.5 m	992100 m3/h	873.600.000	0	873.600.000	817.248.975	1

W. Store

Activity	**Resist (m)**	**Store (ha0.5 m)**	**Discharge (m^3/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
1	0	0	0	$0	**$817.248.975**	$817.248.975	$0	#DIV/0!
2	0	0	2100 m3/h	$47.000.000	**$798.678.931**	$845.678.931	**$18.570.043**	0,40
3	0	0	92100 m3/h	$84.600.000	$399.279.340	$483.879.340	$417.969.635	4,94
4	0	0	992100 m3/h	$458.600.000	$299.547.683	$758.147.683	$517.701.292	1,13
17	0.8	0	0	$99.000.000	$802.716.466	$901.716.466	$14.532.508	0,15
18	0.8	0	2100 m3/h	$146.000.000	$770.743.803	$916.743.803	$46.505.172	0,32
19	**0.8**	**0**	**92100 m3/h**	**$183.600.000**	**$225.019.238**	**$408.619.238**	**$592.229.737**	**3,23**
20	0.8	0	992100 m3/h	$557.600.000	$166.055.124	$723.655.124	$651.193.850	1,17
33	1.8	0	0	$216.000.000	$692.229.100	$908.229.100	$125.019.874	0,58
34	1.8	0	2100 m3/h	$263.000.000	$660.150.734	$923.150.734	$157.098.241	0,60
35	1.8	0	92100 m3/h	$300.600.000	$114.145.902	$414.745.902	$703.103.072	2,34
36	1.8	0	992100 m3/h	$674.600.000	$61.334.538	$735.934.538	$755.914.436	1,12

Activity	**Resist (m)**	**Store (ha0.5 m)**	**Discharge (m^3/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
5	0	5 ha * 0.5 m	0	$48.000.000	$499.444.675	$547.444.675	$317.804.299	6,62
6	0	5 ha * 0.5 m	2100 m3/h	$95.000.000	$486.697.032	$581.697.032	$330.551.942	3,48
7	0	5 ha * 0.5 m	92100 m3/h	$132.600.000	$315.706.186	$448.306.186	$501.542.789	3,78
8	0	5 ha * 0.5 m	992100 m3/h	$506.600.000	$234.551.020	$741.151.020	$582.697.955	1,15
21	0.8	5 ha * 0.5 m	0	$147.000.000	$351.292.811	$498.292.811	$465.956.163	3,17
22	0.8	5 ha * 0.5 m	2100 m3/h	$194.000.000	$334.499.789	$528.499.789	$482.749.186	2,49
23	**0.8**	**5 ha * 0.5 m**	**92100 m3/h**	**$231.600.000**	**$131.224.639**	**$362.824.639**	**$686.024.336**	**2,96**
24	0.8	5 ha * 0.5 m	992100 m3/h	$605.600.000	$106.000.647	$711.600.647	$711.248.327	1,17
37	1.8	5 ha * 0.5 m	0	$264.000.000	$240.037.689	$504.037.689	$577.211.286	2,19

38	1.8	5 ha * 0.5 m	2100 m3/h	$311.000.000	$223.197.351	$534.197.351	$594.051.623	1,91
39	1.8	5 ha * 0.5 m	92100 m3/h	$348.600.000	$20.201.926	$368.801.926	$797.047.049	2,29
40	1.8	5 ha * 0.5 m	992100 m3/h	$722.600.000	$0	$722.600.000	$817.248.975	1,13

Activity	**Resist (m)**	**Store (ha0.5 m)**	**Discharge (m^3/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
9	0	50 ha * 0.5 m	0	$199.000.000	$306.445.471	$505.445.471	$510.803.504	2,57
10	0	50 ha * 0.5 m	2100 m3/h	$246.000.000	$305.587.263	$551.587.263	$511.661.711	2,08
11	0	50 ha * 0.5 m	92100 m3/h	$283.600.000	$288.394.586	$571.994.586	$528.854.389	1,86
12	0	50 ha * 0.5 m	992100 m3/h	$657.600.000	$245.514.048	$903.114.048	$571.734.927	0,87
25	**0.8**	**50 ha * 0.5 m**	**0**	**$298.000.000**	**$125.886.550**	**$423.886.550**	**$691.362.425**	**2,32**
26	0.8	50 ha * 0.5 m	2100 m3/h	$345.000.000	$124.807.182	$469.807.182	$692.441.793	2,01
27	0.8	50 ha * 0.5 m	92100 m3/h	$382.600.000	$112.092.233	$494.692.233	$705.156.742	1,84
28	0.8	50 ha * 0.5 m	992100 m3/h	$756.600.000	$106.826.380	$863.426.380	$710.422.595	0,94
41	1.8	50 ha * 0.5 m	0	$415.000.000	$14.061.938	$429.061.938	$803.187.036	1,94
42	1.8	50 ha * 0.5 m	2100 m3/h	$462.000.000	$12.992.138	$474.992.138	$804.256.836	1,74
43	1.8	50 ha * 0.5 m	92100 m3/h	$499.600.000	$687.541	$500.287.541	$816.561.434	1,63
44	1.8	50 ha * 0.5 m	992100 m3/h	$873.600.000	$0	$873.600.000	$817.248.975	0,94
57	3.8	50 ha * 0.5 m	0	$716.000.000	$14.061.938	$730.061.938	$803.187.036	1,12
58	3.8	50 ha * 0.5 m	2100 m3/h	$763.000.000	$12.992.138	$775.992.138	$804.256.836	1,05
59	3.8	50 ha * 0.5 m	92100 m3/h	$800.600.000	$687.541	$801.287.541	$816.561.434	1,02
60	3.8	50 ha * 0.5 m	992100 m3/h	$1.174.600.000	$0	$1.174.600.000	$817.248.975	0,70

X. Discharge

Activity	**Resist (m)**	**Store (ha0.5m)**	**Discharge (m³/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
1	0	0	0	$0	**$817.248.975**	$817.248.975	$0	#DIV/0!
5	0	5 ha * 0.5 m	0	$48.000.000	$499.444.675	$547.444.675	$317.804.299	6,62
9	0	50 ha * 0.5 m	0	$199.000.000	$306.445.471	$505.445.471	$510.803.504	2,57
13	0	5000 ha * 0.5 m	0	$16.900.000.000	$68.923.963	$16.968.923.963	$748.325.012	0,04
17	0.8	0	0	$99.000.000	$802.716.466	$901.716.466	$14.532.508	0,15
21	0.8	5 ha * 0.5 m	0	$147.000.000	$351.292.811	$498.292.811	$465.956.163	3,17
25	**0.8**	**50 ha * 0.5 m**	**0**	**$298.000.000**	**$125.886.550**	**$423.886.550**	**$691.362.425**	**2,32**
33	1.8	0	0	$216.000.000	$692.229.100	$908.229.100	$125.019.874	0,58
37	1.8	5 ha * 0.5 m	0	$264.000.000	$240.037.689	$504.037.689	$577.211.286	2,19
41	1.8	50 ha * 0.5 m	0	$415.000.000	$14.061.938	$429.061.938	$803.187.036	1,94

Activity	**Resist (m)**	**Store (ha0.5 m)**	**Discharge (m³/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
2	0	0	2100 m3/h	$47.000.000	**$798.678.931**	$845.678.931	$18.570.043	0,40
6	0	5 ha * 0.5 m	2100 m3/h	$95.000.000	$486.697.032	$581.697.032	$330.551.942	3,48
10	0	50 ha * 0.5 m	2100 m3/h	$246.000.000	$305.587.263	$551.587.263	$511.661.711	2,08
18	0.8	0	2100 m3/h	$146.000.000	$770.743.803	$916.743.803	$46.505.172	0,32
22	0.8	5 ha * 0.5 m	2100 m3/h	$194.000.000	$334.499.789	$528.499.789	$482.749.186	2,49
26	**0.8**	**50 ha * 0.5 m**	**2100 m3/h**	**$345.000.000**	**$124.807.182**	**$469.807.182**	**$692.441.793**	**2,01**
34	1.8	0	2100 m3/h	$263.000.000	$660.150.734	$923.150.734	$157.098.241	0,60
38	1.8	5 ha * 0.5 m	2100 m3/h	$311.000.000	$223.197.351	$534.197.351	$594.051.623	1,91

42	1.8	50 ha * 0.5 m	2100 m3/h	$462.000.000	$12.992.138	$474.992.138	$804.256.836	1,74

Activity	**Resist (m)**	**Store (ha0.5 m)**	**Discharge (m^3/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
3	0	0	92100 m3/h	$84.600.000	$399.279.340	$483.879.340	$417.969.635	4,94
7	0	5 ha * 0.5 m	92100 m3/h	$132.600.000	$315.706.186	$448.306.186	$501.542.789	3,78
11	0	50 ha * 0.5 m	92100 m3/h	$283.600.000	$288.394.586	$571.994.586	$528.854.389	1,86
19	0.8	0	92100 m3/h	$183.600.000	$225.019.238	$408.619.238	$592.229.737	3,23
23	**0.8**	**5 ha * 0.5 m**	**92100 m3/h**	**$231.600.000**	**$131.224.639**	**$362.824.639**	**$686.024.336**	**2,96**
27	0.8	50 ha * 0.5 m	92100 m3/h	$382.600.000	$112.092.233	$494.692.233	$705.156.742	1,84
35	1.8	0	92100 m3/h	$300.600.000	$114.145.902	$414.745.902	$703.103.072	2,34
39	1.8	5 ha * 0.5 m	92100 m3/h	$348.600.000	$20.201.926	$368.801.926	$797.047.049	2,29
43	1.8	50 ha * 0.5 m	92100 m3/h	$499.600.000	$687.541	$500.287.541	$816.561.434	1,63

Activity	**Resist (m)**	**Store (ha0.5 m)**	**Discharge (m^3/h)**	**I (10^6)**	**C (10^6)**	**C_t (10^6)**	**ΔC (10^6)**	**ΔC /ΔI**
4	0	0	992100 m3/h	$458.600.000	$299.547.683	$758.147.683	$517.701.292	1,13
8	0	5 ha * 0.5 m	992100 m3/h	$506.600.000	$234.551.020	$741.151.020	$582.697.955	1,15
12	0	50 ha * 0.5 m	992100 m3/h	$657.600.000	$245.514.048	$903.114.048	$571.734.927	0,87
20	0.8	0	992100 m3/h	$557.600.000	$166.055.124	$723.655.124	$651.193.850	1,17
24	**0.8**	**5 ha * 0.5 m**	**992100 m3/h**	**$605.600.000**	**$106.000.647**	**$711.600.647**	**$711.248.327**	**1,17**
28	0.8	50 ha * 0.5 m	992100 m3/h	$756.600.000	$106.826.380	$863.426.380	$710.422.595	0,94
36	1.8	0	992100 m3/h	$674.600.000	$61.334.538	$735.934.538	$755.914.436	1,12
40	1.8	5 ha * 0.5 m	992100 m3/h	$722.600.000	$0	$722.600.000	$817.248.975	1,13
44	1.8	50 ha * 0.5 m	992100 m3/h	$873.600.000	$0	$873.600.000	$817.248.975	0,94

Appendix VIII. All combinations sorted (lowest costs)

#	*Activity*	Resist (m)	Store (ha0.5 m)	Discharge (m^3/h)	I (10^6)	C (10^6)	C_t (10^6)	ΔC (10^6)	ΔC /ΔI
1	*23*	0.8	5 ha * 0.5 m	92100 m3/h	$231.600.000	$131.224.639	$362.824.639	$686.024.336	2,96
2	*39*	1.8	5 ha * 0.5 m	92100 m3/h	$348.600.000	$20.201.926	$368.801.926	$797.047.049	2,29
3	*19*	0.8	0	92100 m3/h	$183.600.000	$225.019.238	$408.619.238	$592.229.737	3,23
4	*35*	1.8	0	92100 m3/h	$300.600.000	$114.145.902	$414.745.902	$703.103.072	2,34
5	*25*	0.8	50 ha * 0.5 m	0	$298.000.000	$125.886.550	$423.886.550	$691.362.425	2,32
6	*41*	1.8	50 ha * 0.5 m	0	$415.000.000	$14.061.938	$429.061.938	$803.187.036	1,94
7	*7*	0	5 ha * 0.5 m	92100 m3/h	$132.600.000	$315.706.186	$448.306.186	$501.542.789	3,78
8	*26*	0.8	50 ha * 0.5 m	2100 m3/h	$345.000.000	$124.807.182	$469.807.182	$692.441.793	2,01
9	*42*	1.8	50 ha * 0.5 m	2100 m3/h	$462.000.000	$12.992.138	$474.992.138	$804.256.836	1,74
10	*3*	0	0	92100 m3/h	$84.600.000	$399.279.340	$483.879.340	$417.969.635	4,94
11	*27*	0.8	50 ha * 0.5 m	92100 m3/h	$382.600.000	$112.092.233	$494.692.233	$705.156.742	1,84
12	*21*	0.8	5 ha * 0.5 m	0	$147.000.000	$351.292.811	$498.292.811	$465.956.163	3,17
13	*43*	1.8	50 ha * 0.5 m	92100 m3/h	$499.600.000	$687.541	$500.287.541	$816.561.434	1,63
14	*37*	1.8	5 ha * 0.5 m	0	$264.000.000	$240.037.689	$504.037.689	$577.211.286	2,19
15	*9*	0	50 ha * 0.5 m	0	$199.000.000	$306.445.471	$505.445.471	$510.803.504	2,57
16	*22*	0.8	5 ha * 0.5 m	2100 m3/h	$194.000.000	$334.499.789	$528.499.789	$482.749.186	2,49
17	*38*	1.8	5 ha * 0.5 m	2100 m3/h	$311.000.000	$223.197.351	$534.197.351	$594.051.623	1,91
18	*5*	0	5 ha * 0.5 m	0	$48.000.000	$499.444.675	$547.444.675	$317.804.299	6,62
19	*10*	0	50 ha * 0.5 m	2100 m3/h	$246.000.000	$305.587.263	$551.587.263	$511.661.711	2,08
20	*11*	0	50 ha * 0.5 m	92100 m3/h	$283.600.000	$288.394.586	$571.994.586	$528.854.389	1,86
21	*6*	0	5 ha * 0.5 m	2100 m3/h	$95.000.000	$486.697.032	$581.697.032	$330.551.942	3,48
22	*24*	0.8	5 ha * 0.5 m	992100 m3/h	$605.600.000	$106.000.647	$711.600.647	$711.248.327	1,17
23	*40*	1.8	5 ha * 0.5 m	992100 m3/h	$722.600.000	$0	$722.600.000	$817.248.975	1,13
24	*20*	0.8	0	992100	$557.600.0	$166.055.1	$723.655.1	$651.193.8	1,17

				m3/h	00	24	24	50	
25	*36*	1.8	0	992100 m3/h	$674.600.000	$61.334.538	$735.934.538	$755.914.436	1,12
26	*8*	0	5 ha * 0.5 m	992100 m3/h	$506.600.000	$234.551.020	$741.151.020	$582.697.955	1,15
27	*4*	0	0	992100 m3/h	$458.600.000	$299.547.683	$758.147.683	$517.701.292	1,13
28	*1*	0	0	0	$0	$817.248.975	$817.248.975	$0	-
29	*2*	0	0	2100 m3/h	$47.000.000	$798.678.931	$845.678.931	$18.570.043	0,40
30	*28*	0.8	50 ha * 0.5 m	992100 m3/h	$756.600.000	$106.826.380	$863.426.380	$710.422.595	0,94
31	*44*	1.8	50 ha * 0.5 m	992100 m3/h	$873.600.000	$0	$873.600.000	$817.248.975	0,94
32	*17*	0.8	0	0	$99.000.000	$802.716.466	$901.716.466	$14.532.508	0,15
33	*12*	0	50 ha * 0.5 m	992100 m3/h	$657.600.000	$245.514.048	$903.114.048	$571.734.927	0,87
34	*33*	1.8	0	0	$216.000.000	$692.229.100	$908.229.100	$125.019.874	0,58
35	*18*	0.8	0	2100 m3/h	$146.000.000	$770.743.803	$916.743.803	$46.505.172	0,32
36	*34*	1.8	0	2100 m3/h	$263.000.000	$660.150.734	$923.150.734	$157.098.241	0,60