Design opportunities for flash flood reduction by improving the quality of the living environment

A Hoboken City case study of environmental driven urban water management

Figure 1 Impression of Hoboken (illustration by author)

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Master thesis
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“The most fundamental concepts in science are basically simple and can usually be formulated in a way to make them comprehensible to everyone”

Albert Einstein

Preface

The previous words by Albert Einstein capture the essence of finding simple solutions for complex problems, and making them comprehensive to everyone. Cities are complex systems with high population densities, high occupation of infrastructure, and high economic activity. With an increasing amount of people living in cities, combined with the effects of climate change and sea level rise, Delta cities allow additional attention to meet future expectations. My favour for urban water management grew when I visited the "Water and the City" conference. I joined a workshop about water challenges in New Orleans, led by David Waggonner: architect, urban planner, and pioneer in developing water management strategies in New Orleans. It made me realize how combining urban planning and water management creates opportunities in designing more sustainable and beautiful cities. During my exploration for opportunities in urban water management master thesis projects, I was driven by the impact of Hurricane Sandy on New York City. As it turned out, Royal HaskoningDHV was, for the "Rebuild by Design" competition, working on a comprehensive water management strategy for Hoboken, New Jersey.

This work is the final result of months of reading, analysing, modelling, writing, discussing and rewriting to understand the complex urban water system of Hoboken, to experience the damage Sandy caused to people and properties, and to find solutions to flash floods that have been ravaging the city for years. The thesis is executed as a Master of Science graduation project within the Water Resources Management specialization at the faculty of Civil Engineering & Geosciences of the Delft University of Technology, in collaboration with Royal HaskoningDHV.

Acknowledgements

The last few months were months of many new experiences, ideas and thoughts. I learned from working by myself on my own project for several months., I learned from working on a design competition with high political sensitivity, I learned how to model complex urban water systems and learned from the difficulties associated with that, and I learned how to combine water management with urban planning. I received plenty of substantive assistance and personal support from my graduation committee in, for which I would like to thank all of the individually: Frans van de Ven, Nanco Dolman, Fransje Hooimeijer and Nick van de Giesen.

I would also like to thank the people supporting me at Royal HaskoningDHV. Marius for the GIS support and Defne for sharing thoughts on Hoboken flood related problems. I would like to thank my fellow water management students, especially the ones in graduation room 4.84, for the brainstorm sessions, and sharing ideas, experiences and knowledge. I would like to thank my parents for always being there for me, supporting me and keeping faith in me, even in hard times. I would like to thank my friends Carine and Ruben, for late-night study sessions and I would like to thanks Eva and Willemijn for supporting me in the final phase of the project.

Anna,

Rotterdam, March 26th 2015

Executive Summary

Introduction

The overarching aim of this research project was to establish a sustainable urban water management design for Hoboken City to decrease vulnerability to extreme precipitation and improve urban quality. By carrying out a functional analysis of the area and the technical analysis of the water system, recommendations were made for soft and natural spatial solutions (i.e. blue-green measures). The base of the design is the existing urban environment, which is characterized by low area elevations, dense urban development, and high impermeability. The gravity based sewer system drains storm water into the Hudson River through combined sewer overflow valves. During high tide, the overflow valves close, preventing the storm water to overflow, whereby the surplus water remaining in the sewer pipes overflows in low-lying areas.

Natural processes were used to recreate a naturally oriented water cycle. The main goals of the urban design were to reduce storm water floods, reduce the number of combined sewer overflows into the Hudson River, and improving the urban living environment. Urban quality was indicated by air quality, public green- and recreational space, and the reduction of urban heat island effects. The research question as a guide for the thesis reads: *'What system of blue-green adaptation measures is most beneficial for Hoboken in terms of flood reduction and improving the urban quality?'* Various research methods are used to answer this question. To gain knowledge regarding urban water management and nature based flood adaptation measures, a literature review is conduced. tudies towards flooding and flood reduction in Hoboken were used as input for the water assignment. To design sets of blue-green measures, a functional analysis of the area is done using the six-layer approach for urban areas. With the approach, design opportunities and constraints for different layers are identified. The design strategies of appropriate blue-green measures for Hoboken are tested in a hydrology-hydraulic water management model.

Results

Hoboken suffers both flash flooding overwhelming the sewer system and storm surge. Low elevations and high groundwater levels influence infiltration capacity and efficiency of the drainage system. Combined sewer outlets with valves to the Hudson River carry excess water directly into the river during storms. When heavy rainfall coincides with high tide, excess water backs up in the sewer, causing flood nuisance in particular the low-lying areas.

In terms of the required storage and drainage capacity, the water assignment for Hoboken is calculated. This technical assignment provides a rough measure of the required delay and storage capacity in urban areas for given rain events that exceed the existing storage and pumping capacity. With a basic hydrological model, the storage is determined on the basis of 100 years of precipitation data. The water assignment isn't normative. It does not take detailed area characteristics, elevation profile and sewer layout into account and therefore cannot determine the locations where flooding occurs.

With statistics afterwards, the storage volumes for 1, 2, 10 and 50 years design storms is determined. The table below shows the water assignment for these storm events. The volumes of water in the water assignment show the pressure on the current drainage system. During a T1 storm event, the required storage capacity is already twice the available sewer storage of 8.3 MG. For a T10 the excessive volume is 40.9 MG, corresponding to 62 Olympic swimming pools spread over the city. Based on the current storage capacity of 0.5 inch/day, SDF curves show that for a T10 storm, a pumping capacity of more than 15 inch per day would be needed. Due to interconnections, the calculated volumes per sub basin may differ from the actual volumes.

Future regulations may require the North Hudson Sewerage Authority (NHSA), to reduce the flooding frequency on average once every 4 years or a T4 return period (HobokenNJ, 2013). The preferred T10 drainage capacity (5.0 inch in 24h) as set out in the US urban drainage design manual even corresponds with a required T10 storage capacity.

A number of blue-green adaptation measures have been selected for Hoboken based on site suitability. The six-layer approach, which integrates urban planning and subsoil characteristics, gives an overview of the opportunities and constraints for blue and green measures in the area. Well-fitting measures appeared to be subsurface detention storage in the higher elevated areas, storm water flow-through planters, (storm water infiltration) trees and permeable pavement in infrastructure. In public space, parks, water squares, green squares, detention below sports fields, open water and urban farming would fit well. The buildings in Hoboken found to be suitable for rainwater harvest tanks, blue- and green roofs, green facades and urban farming on rooftops. To maximize blue-green benefits, a citywide network of waterways, green areas, green streets and common gardens is proposed.

Five design strategies were developed with combinations of blue-green measures, applied to different layers in the urban system. The first (1) design strategy improves the current situation with the application of subsurface adaptation measures. With a functional analysis, storage possibilities beneath parking lots and sports fields are determined. Two deep storage basins will are proposed. The remaining sports fields and parking lots will be equipped with shallow storage facilities. The second (2) design strategy improves the current situation with the application of infrastructural adaptation measures. This includes surface measures like permeable pavement, storm water infiltration planters and trees along major roads, and green in the streetscape. The third (3) design strategy applies adaptation measures on public space. Undeveloped public areas suitable to rain gardens, storm water trees and flow-through planters, water squares, detention below sport fields, parks, retention ponds (in new/existing green space), urban agriculture, bio retention swales, rainwater harvest cistern and seasonal storage are here for identified. For the fourth (4) design scenario, adaptation measures were applied on private space and buildings. Buildings suitable to place green roofs in the area are analysed. The fifth (5) strategy in the end, combines all proposed measures by in an urban blue-green network. Additional green is applied to the public space. Hollow roads discharge storm water towards open water bodies and green in the streetscape connects green area and open water in the city centre to green belt.

The mitigation performance of every design strategy regarding the water assignment is tested on the basis of a Storm Water Management Model (SWMM). The five design scenarios were added to the basic model by Low Impact Development controls (i.e. green roofs, permeable pavement, bio swales). To quantify the contribution of the design strategies to the water assignment, a number of criteria and parameters are identified. The criteria for design performance are (a) flood volume reduction during heavy rainfall events, (b) CSO reduction, (c) vulnerability reduction of critical public buildings and infrastructure (f.e. Hoboken terminal, hospitals, wastewater treatment plant, electricity distribution locations), and (d) improvement the urban quality of living. Four parameters to evaluate the to evaluate the contribution to flood mitigation and overflow reduction are (1) the flood volume in the drainage area (internal outflow), (2) the runoff per sub-basin, (3) the total storm water storage per sub-basin (excluding sewer storage), (4) critical facilities threatened by flash floods.

All strategies showed contribution to flood volume reduction and creating urban quality, but not all strategies were as effective. Strategy 1 can store about 10% of the total flood volume. It has the least contribution to urban quality, since only subsurface storage, and no vegetated measures were used. Strategy 2 on the other hand, has a very broad effect on the green experience of the city. It includes the greening of three major roads. Strategy 3 uses undeveloped space to create a green network throughout the city. It has the least effect on total flood reduction of all strategies, but uses space that would otherwise lie fallow. In strategy 4, green roofs are applied on all suitable buildings throughout the city. This had a positive effect on both flood reduction, reduction of the urban heat island effect, and air quality. When the roofs are large enough, they can even function as a roof garden, roof restaurant or private kitchen garden. Strategy 5 ultimately, combines all design strategies into a citywide system of blue-green measures. Modeling showed that Hoboken benefits most from design strategy 5 in terms of quantitative flood reduction. This design strategy also has the most additional green through a citywide network of vegetated measures.

The proposed spatial typology of design strategy 5 is elaborated with a number of illustrations. Green roofs, permeable pavement, bio-retention gardens, storage basins, an urban farm, urban wetlands and water squares are included in the adaptation design. Through the urban grid system, vegetated areas are connected to create a pleasant experience throughout the city. The riverbeds in the east and the areas at the bottom of the cliff are surrounding the city with a green belt. The green belt along the cliffs serves for both storage and infiltration of water. The three major roads with trees and plants create green veins through the heart of the city. In every part between the major roads parks, urban farms or wetlands can be found. A solid footpath or bicycle lane can be applied along the city borders to create an uninterrupted route. This citywide system of flood prevention measures provides a pleasant, physical appearance.

Recommendations

For future work, a number of suggestions can be presented towards the reliability and effectiveness of this study. To fill up data gaps in the current model, a follow up study regarding the costs and support of the proposed design is meaningful. The suggested design strategy 5 is the most extensive urban design is the most extensive one and therefor also the most costly. Historical research on blue-green measures resulted in implementation costs indications. These results need to be revised for the proposed design and with up to date financial taxes. Support for the design is needed when it comes to realization. Inhabitants, businesses, landowners, the NJ transit and the governance are important stakeholders. Based on the outcome of this research, the improvement of the storm water management model is of biggest interest.

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PART I THEORETICAL AND PRACTICAL BACKGROUND

PART II ANALYSIS OF THE WATER SYSTEM

PART III URBAN WATER DESIGN

List of Abbreviations

AST	Adaptation Support Tool
BGD	Blue Green Dream
BMP	Best Management Practice
CSO	Combined Sewer Overflow
DDF	Depth Duration Frequency (curve)
EPA	(United States) Environmental Protection Agency
FEMA	Federal Emergency Flood Zone
IUWM	Integrated Urban Water Management
LID	Low Impact Development
NAVD88	North American Vertical Datum of 1988
NCDC	National Climatic Data Centre
NHSA	North Hudson Sewerage Authority
NOAA	National Oceanic and Atmospheric Administration
SDF	Storage Discharge Frequency (curve)
SUDS	Sustainable Urban Drainage System
SWMM	Storm Water Management Model
UCF	Urban Climate Framework
UWC	Urban Water Cycle
WWP	Wet Weather Pump
WWTP	Waste Water Treatment Plant
WSUD	Water Sensitive Urban Design

List of Definitions

Adaptation	Definition by IPCC, adaptation is “an adjustment in natural or human systems in response to actual or expected climatic stimuli (variability, extremes, and changes) or their effects, which moderates harm or exploits beneficial opportunities” (IPCC, 2013).
Blue-green measures	Concept applied in an urban context, providing a network to solve urban and climatic challenges by building with nature. It combines green and blue infrastructure by using underlying ecosystems to reduce multiple vulnerability capacities. Benefits are for example reducing rainfall runoff, cooling by evaporation and groundwater recharge.
Climate Change	Climate change refers to global warming created by human activities such as the combustion of fossil fuel and land use changes. This phenomenon is also known as the greenhouse effect: the increasing level of greenhouse gases. The expected climate change has significant effects on extreme weather: heavy rainfall frequency and intensity, frequency and intensity of droughts, and heat waves. The impact of heat and drought is aggravated by the urban heat island effect.
Grey Measures	‘Hard’ construction measures to prevent areas from flooding (f.e. dikes, drainage systems, pumping stations, etc.).
Integrated Urban Water Management (IUWM)	Framework for planning, designing and managing of urban water systems in a flexible so that it can respond to external changes. It integrates environmental, economic, social (high stakeholder involvement), technical and political aspects of water management (Bahri , 2012).
Sustainability	Sustainability has its origin in ecology and was developed to describe the requirements for the ecosystem to sustain itself over the long term.

Sustainable development	“Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED, 1987)
Sustainable urban development	Relationship between water, energy and land use in urban areas. Sustainable planning and management stimulates inter connected green space and multi-functional land use and transportation.
Urban quality	In terms of blue-green measures, the U.S. Environmental Protection Agency (EPA), urban quality can be increased when contributing to air quality, decreased energy demand (natural climate control), increased carbon storage, additional wildlife habitat, recreational space and higher land values (up to 30%) (Foster, Lowe, & Winkelman, 2011).
Urban resilience	The ability of a system (the city) to adapt and adjust to changing internal or external processes (Pickett, Cadenasso, & Grove, 2004).
Vulnerability	Definition by The Intergovernmental Panel on Climate Change (IPPC): “the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability therefore implies not only exposure to hazard factors but also the capacity to recover from their effect” (Srinivas, 2007).
Water Cycle	Storage and circulation of water between the biosphere, atmosphere, lithosphere, and hydrosphere.

Chapter 1 Introduction

1.1. Introduction to flood problems in urban areas

The climate is changing. Due to global heating, we are facing more extreme precipitation, longer periods of drought, and increasing temperatures. Heavy rainstorms result in more water in the sewers and in the streets. Globally increasing temperature and extended periods of drought are threatening water supplies and river transport due to low runoff. In the United States, expectations of increased extreme precipitation are shown in Figure 2 with most extreme increases.

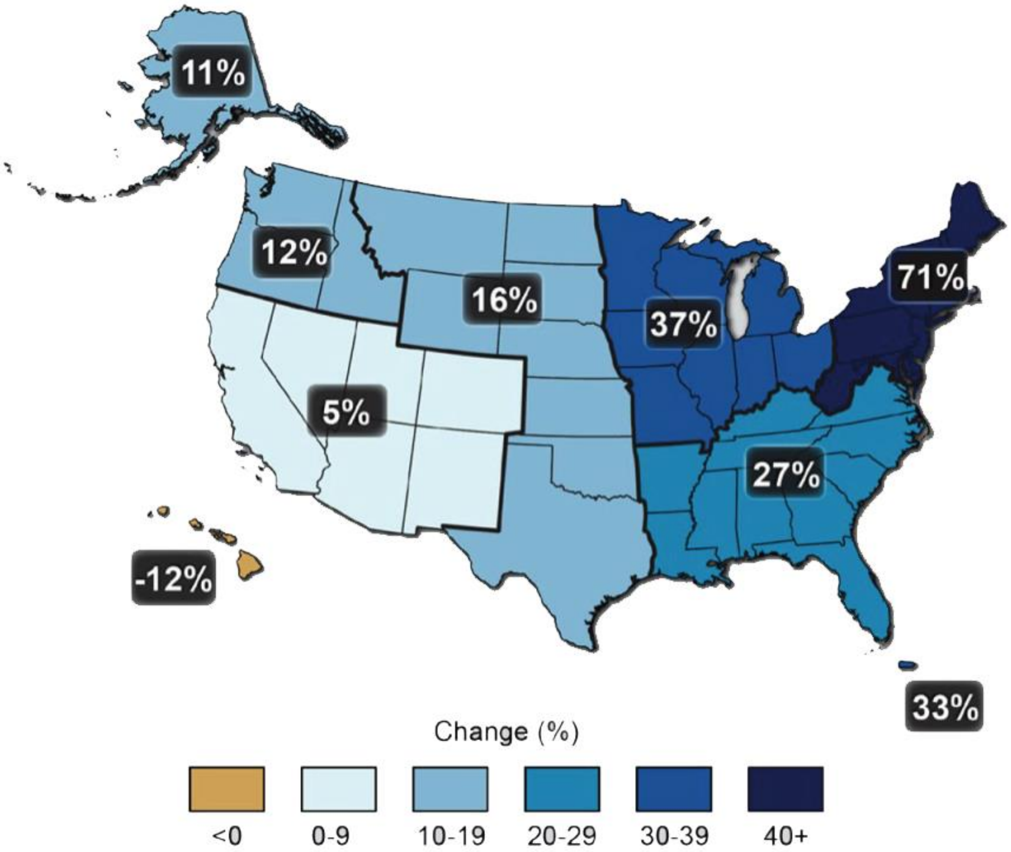

Figure 2 Change in extreme precipitation (top 1%) between 1958 and 2012 in the United States of America (National Climate assessment, 2014)

Delta cities are inherently vulnerable to natural hazards like storms and floods with locations along the coast and river planes, paired with high densities of people and development (UN, 2011; McKinsey&Company, 2012). It is expected that two thirds of the world's large cities will be vulnerable to rising sea levels and climate change, with millions of people being exposed to the risk of extreme storms and flooding (UN, 2011; McKinsey&Company, 2012). Between 2011 and 2050, the world population is expected to increase from 7.0 billion to 9.3 billion (UN, 2011). At the same time, the population living in urban areas is projected to increase from 3.6 billion in 2011 to 6.3 billion in 2050. The majority of the world's population lives and works in low-lying coastal areas and deltas. As a consequence, a global increase of the vulnerability of people, nature, infrastructure and economic sectors in urban areas is expected in the coming decades (Rosenzweig, 2001).

Hurricane Sandy's devastation in October 2012 was the biggest natural disaster ever to hit the urban dense American west coast (The New York Times, 2012). More than one hundred people lost their lives, many more lost their homes and businesses and entire communities were destroyed by the storm, the storm water and the water flooding the Hudson River banks. Besides the damage Sandy caused, it also made clear that climate risks are not only a future concern. Only rebuilding the affected areas would not be enough, but improved ways of implementing designs and policy-making were required to keep affected cities safe, accessible and attractive. For that purpose, the Hurricane Sandy Rebuilding Task Force and the HUD (U.S. Department of Housing and Development) initiated the Rebuild by Design competition. This multi-stage regional design competition aimed to find locally contextual and resilient solutions to rebuild the by Hurricane Sandy affected areas in New York and New Jersey (Rebuild by Design, 2013). Team OMA is one of the Rebuild by Design project teams to which this research is dedicated. The aim of the team is to design a comprehensive flood defense strategy for the City of Hoboken, New Jersey (Rebuild by Design, 2013),

Figure 3 Geographical orientation of Hoboken (Google maps, 2013)

The delta city of Hoboken (Figure 3) is vulnerable to two types of flooding: floods caused by extreme storm water surplus (pluvial flooding) and coastal flooding from high river- or sea water levels (coastal and fluvial flooding). In 2012, Hurricane Sandy caused a combination of both. Prior to the hurricane, extreme precipitation filled up the sewer system. This pressurized the capacity of the (combined) sewer system, resulting in a storm surge, mixed with fuel and sewage, to flood into the streets. During Sandy, the river water levels became higher than the riverbanks, causing the water to flow straight into the city (Figure 4). Half the city flooded, cars drifted away, many residents were stranded in their homes for days, two fire stations were evacuated and large parts of the City had no gas and electricity for days (City of Hoboken, 2014).

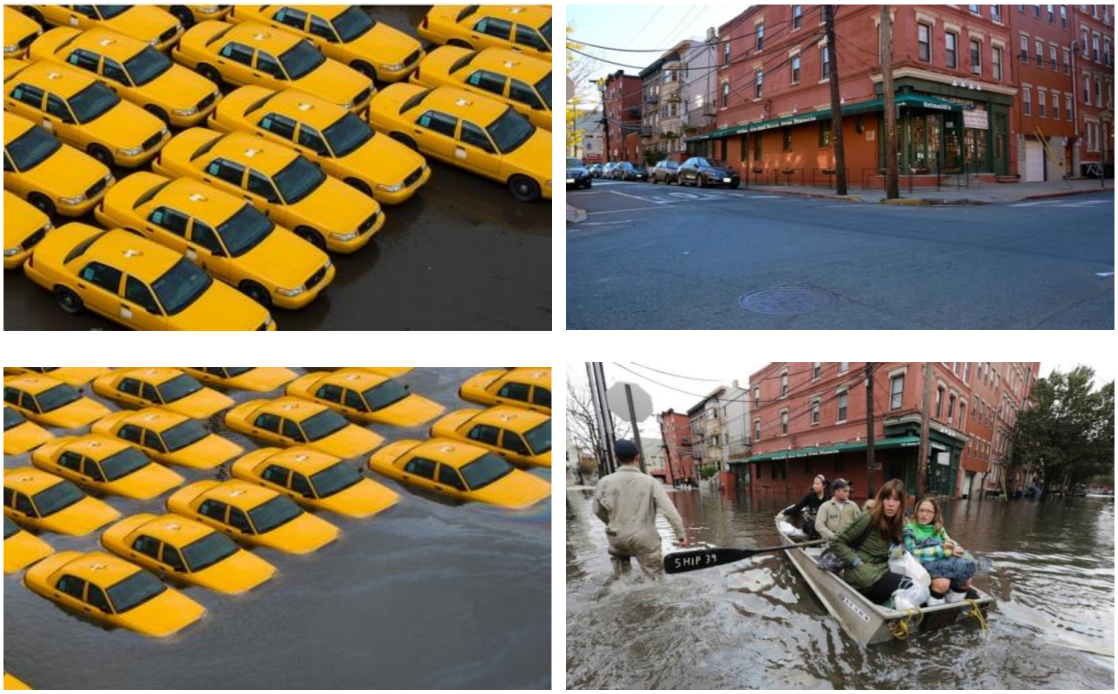

Figure 4 Yellow cabs in parking (Salvatore & Entelis, 2012) Grimaldi's Pizza (Gebhardt, 2012)) and People in boat in front of Grimaldi's (politics down dirty, 2012)

The aim of this research is to explore the contribution of natural and vegetated spatial solutions (i.e. blue-green adaptation measures) to reduce Hoboken's vulnerability to flash floods from extreme storm water surplus. By restoring the natural water cycle, and uniting water management and urban planning, climatic challenges can be solved (Figure 5).

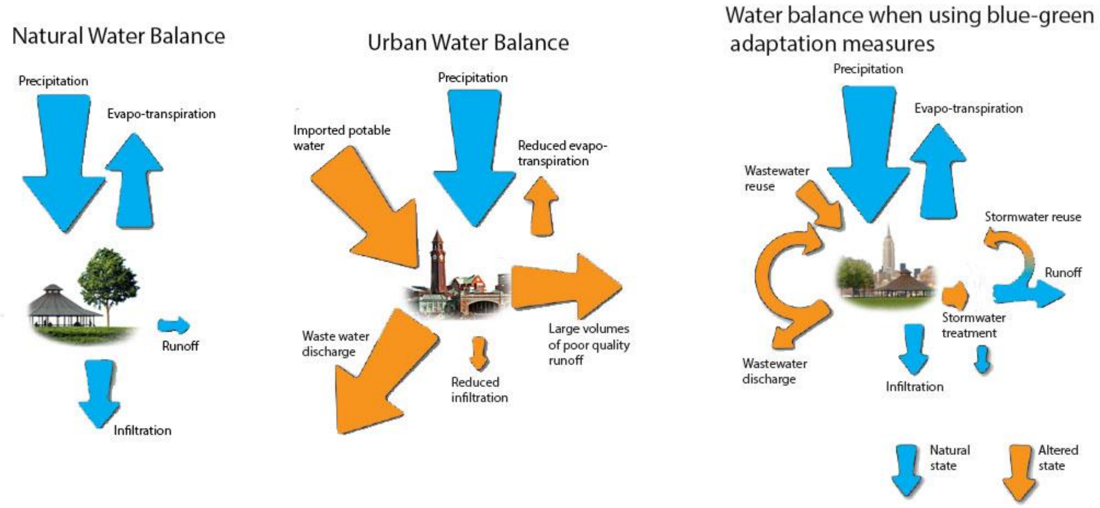

Figure 5 Changes in water balance for urban areas (Illustration by author; based on Hoban and Wong, 2006)

1.2. Case Description and Problem Statement

To protect Hoboken from future floods, it is important to understand the urban water system and the different layers of urban development. This paragraph will give an impression of the current state and hazards to flood risk in Hoboken and the future expectations. This will lead to the problem statement of this research.

Case Description of Hoboken

Hoboken’s topography varies from a high elevation of approximately seventy feet in the eastern part, to less than five feet in a few areas in the western half of the city. The City was once an island with tidal lands to the west (Figure 6). Wetland in the areas south, west, and north of Hoboken Island covered 561 acres in 1811 (Bykowski, 2013). Industrial landfill achieved to develop Hoboken into the current urban environment, including residential, commercial, industrial, public, and institutional land uses. Wetlands don’t exist anymore and are replaced by tiles and asphalt, resulting in almost 90 percent impermeable surface.

Figure 6 View of Hoboken and Manhattan (Shannon and Rogers, 1868)

The sewer system is gravity-driven. Storm water is drained directly into the Hudson River by combined sewer overflows (CSOs) (EmNet, 2013; EmNet, 2011). During high tide, the CSO valves are closed. When this coincides with heavy rainfall, the water cannot be drained into the river and stays in the sewer pipes (Roberts, 2004; EmNet, 2013; EmNet, 2011). Once the pipes are full and the water has nowhere to go, the water level in the manholes increases rapidly, causing the water to flood out into the street and filling depressions on the land surface (EmNet, 2013; EmNet, 2011).

Current water management in Hoboken is not sufficient. Due to high impermeability, 90 percent of the rainwater quickly ends up in the sewer systems. The North Hudson Sewerage Authority (NHSA), responsible for the operation and maintenance of the sewage collection and treatment system, completed the first flood pump in 2011 (EmNet, 2013). With this wet weather pumps, Hoboken is transitioning to a polder system with embankments and an artificial hydrological entity. The pump alleviates, although not eliminated flooding (Hoboken, 2013; EmNet, 2013). Hoboken residents live with the knowledge of frequent flooding from extreme rainfall. When the predicted risk on flooding is high, residents are encouraged to take the necessary preparations, for example to move vehicles from flood-prone to safer areas (HobokenNJ, 2013). With almost eighty percent of the city placed in the Federal Emergency Flood Zone (FEMA) and over a hundred Combined Sewer Overflows per year (RoyalHaskoningDHV, 2014), only FEMA flood hazard data and the installation of flood pumps is not enough (HobokenNJ, 2013).

Problem Statement

To ensure Hoboken of being a safe, accessible and water robust city in the future, the current urban water system needs to be improved by effective adaptation measures. Not only flood volume reduction is required, also the polluted CSO volume that is drained into the Hudson River during storm water events needs to be limited. Blue-green measures have been proven to be sustainable adaptations to reduce flooding through storage and infiltration. Besides that, more green in the urban landscape benefits urban energy consumption, air quality, CO2 reduction, urban heat island, common liveability, habitat improvement and public education. Advantages of blue and green measures include efficient use of limited space in creating a better live-able and safer city. Focussing on both flash flood reduction and urban landscape benefits, the problem statement for this study is formulated as follows:

> *Establish a climate adaptive and robust urban water management design for Hoboken City to decrease vulnerability to extreme precipitation and improve the quality of the living environment by carrying out a functional analysis of the area and the technical water system.*

Climate adaptation relates to the contributing of an entire urban area, to alleviate the system from the effects of climate change and create resilience. By restoring the natural water balance, the sponge function of the city keeps the rainwater where it falls through storage so that it can slowly be drained (ClimateAPP, 2014; RCI, 2013). Frequent application of small-scale adaptation measures to store and infiltrate rainwater, creates self-sustaining ecosystem and reduces urban vulnerability (WCED, 1987).

Extreme climate events are defined as lying in the most unusual ten percent of a place's history (NOAA, 2014). Extreme precipitation events have longer durations and/or a higher precipitation depth than average storm events. Because of climate change effects, extreme precipitation is expected to happen more frequent in the future.

Urban quality is a complex concept which many researchers tried to interpret and measure. Besides moderating the impact of extreme precipitation and temperature, the U.S. Environmental Protection Agency (EPA) had identified blue-green measures as contributors to improved human health and air quality, decreased energy demand (natural climate control), increased carbon storage, additional wildlife habitat, recreational space and higher land values (Foster, Lowe, & Winkelman, 2011).

A functional analysis of the area is done to identify feasibility of proposed measures at spatial scale (i.e. building-, street-, neighbourhood-, or city scale level) and site suitability (land use, requirements, and multi-functionality on spatial functions). The analysis is done using the six-layer approach for urban areas (Maring & Hooimeijer, 2013).

The technical system was analyzed, using a water system analysis and a dynamic hydrology-hydraulic storm water management model. The water system analysis includes an analysis of the (hydrological) area characteristics and calculation of the Hoboken water assignment. The sewer system is modelled and simulated in a storm water management model (SWMM).

1.3. Research Question

The overarching aim of this research project is to develop understanding and make recommendations for soft and natural spatial solutions (i.e. blue-green measures) to increase Hoboken's resiliency to water quantity and water quality problems from extreme stormwater surplus. The base of the design is the existing urban environment. Natural processes based adaptation measures are used to recreate a naturally oriented water cycle. The goals of the proposed urban design solution are to reduce flash flood volumes, reduce the number of combined sewer overflows, and to improve the quality of the living environment.

Blue-green infrastructure provides techniques for solving urban and climatic challenges by building with nature. Integrating blue, green and grey infrastructure could be necessary to create sustainable solutions fitting in the existing urban system in the most effective and (space and cost) efficient way (Andoh, 2011). The effects of infiltration (slow) and storage (store) on urban drainage are shown in Figure 7. When an urban area has little to no infiltration and storage facilities, water is drained through sewer pipes to pumping stations, which discharge the water out of the drainage area. Storage and infiltration reduce rainfall runoff (peaks) and alleviate the pressure on the sewer system.

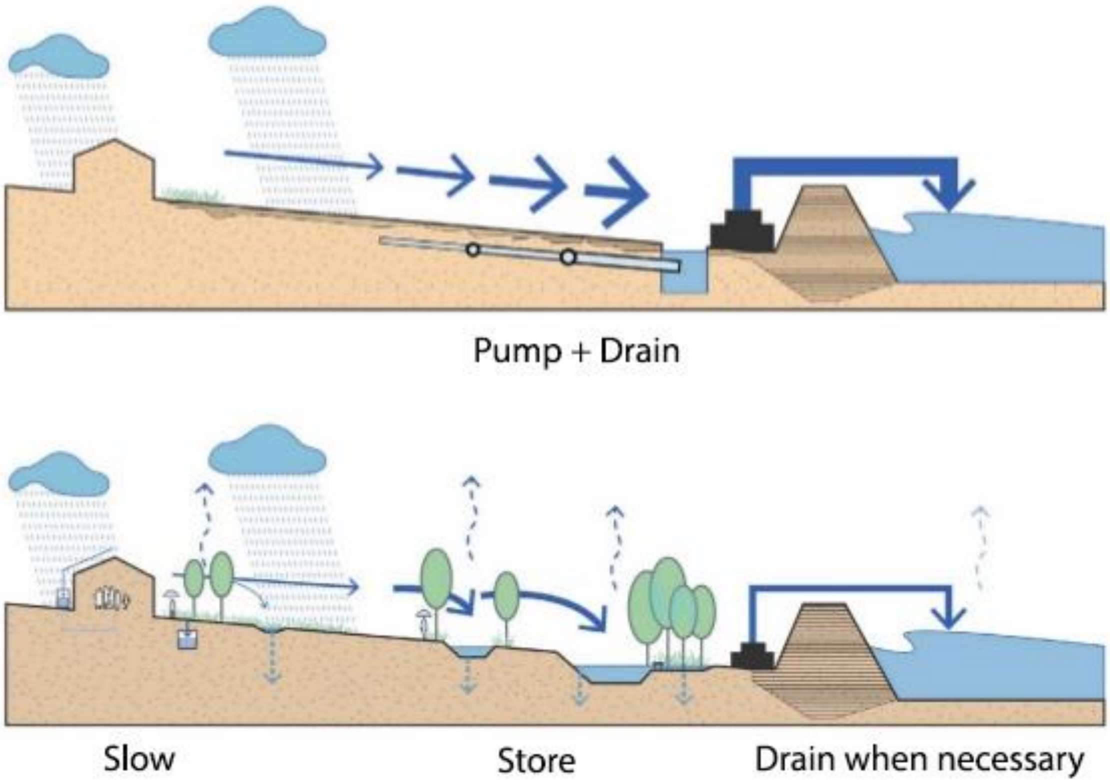

Figure 7 Living with water principles (Waggoner & Ball Architects, 2012)

Storage capacity depends on open water bodies. Water can be stored in retention and detention ponds. Retention ponds are permanently filled with water. Detention ponds can temporarily store water when required.

Infiltration capacity of soils relates to the permeability and soil type. In urban areas, infiltration capacity is significantly smaller than in rural areas, due to pavement and site preparation. Infiltration can be increased by removing pavement or replace it by permeable paving's.

In highly urbanized areas though, lack of space makes blue-green adaptation measures sometimes not feasible solutions on their own. Sewers pipes redirect the water directly out of the area to surface waters or to treatment plants. If a system becomes increasingly overloaded due to increasing urbanization, the compact, highly efficient and low in maintenance 'grey' infrastructure might be needed.

The three main objectives: to reduce sewer floods -to decrease the combined sewer overflow volume into the Hudson River, and to improve urban quality- form the basis of the main question, which is defined as:

'What system of blue-green adaptation measures is most beneficial for Hoboken in terms of flood reduction and to improve the quality of the living environment?'

The sub research questions based on the main question are:

1. *'What are the key issues of increased vulnerability towards storm water flooding in Hoboken?'*
2. *'What adaptation measures are available to increase urban resiliency to storm water flooding in Hoboken?'*
3. *'How can hydro dynamical modelling be used to come to smart solutions for urban design?'*
4. *'How can water management be effectively integrated in urban planning and design?'*

1.4. Specification of operational questions

With respect to the case study and the literature reviews, operational questions will help to answer the scientific sub research questions:

1. 'What are the key issues of increased vulnerability towards flooding in Hoboken?'
   - *'What are Hoboken's vulnerabilities in terms of (storm water) flooding and climate change?'*
   - *'When does flooding occur in the current urban water system and what are future flooding expectations for the current drainage system?'*
   - *'What are the current bottlenecks in the drainage system?'*

2. 'What adaptation measures are available to increase urban resiliency to flooding in Hoboken?'
   - *'What adaptation measures can be used in urban water management to mitigate the effects of storm water floods?'*
   - *'What blue-green measures are suitable for Hoboken in terms of spatial typologies?'*
   - *'What is the water assignment for Hoboken?'*

3. 'How can hydro dynamical modelling be used to come to smart solutions for urban design?'
   - *'What dynamic hydrology-hydraulic model can be used to simulate the urban water system in Hoboken?'*
   - *'What data is required for a reliable model of the Hoboken water system?'*

4. 'How can water management be effectively integrated in urban planning and design?'
   - *'What urban design strategies are suitable for the existing urban environment?'*
   - *'What is the most efficient design strategy to reduce rainfall runoff?'*
   - *'How will the suggested urban water design improve the current situation?'*

1.5. Research Context

The research context, in which the research questions and problems arise, is within the optimization of suitable measures to decrease flooding from extreme precipitation and improve urban quality. Fluvial flooding (from the Hudson River) is outside the scope of the research. A wide range of sustainable blue-green measures for climate adaptive urban design has been researched. The challenge is to find an optimal combination of these measures to storage and infiltrate in such a way that it benefits the existing urban living environment.

Issues, Concerns and Interests

To address the research questions, a literature survey is done to overview the theoretical concepts. The Hoboken City case study gives additional insight into urban water management issues and the technical feasibility of innovations and practices. For Hoboken, a vulnerability analysis is done using literature study, desk research and a field study. A functional analysis of the existing urban environment is done with help of the Blue Green Dream Adaptation Support Tool (BGD, 2013) and the six-layer approach (Maring & Hooimeijer, 2013) which will be discussed in chapter 3 and 4. A technical analysis is done by calculating the urban water assignment (paragraph 4.3) and modelling the sewer system in a dynamic Storm Water Management Model (SWMM, chapter 5) (EPA, 2013). The Blue Green Dream tool carries out a set of best fitting blue-green measures based on site selection, technical feasibility and site suitability. The urban water assignment makes rough estimations of the required storage capacity of the area. The six-layer approach integrates urban planning and subsoil characteristics and gives an overview of the opportunities and constraints in the area. The EPA Storm Water Management Model (SWMM) simulates the hydraulic operation of the existing storm water systems and after adding the proposed design strategies.

Literature study and desk research is done at the Delft University of Technology and the Royal HaskoningDHV office in Rotterdam. Literature study involves the evaluation of scientific articles, policy documents and position papers. The desk research includes evaluation of documents on the existing drainage system, existing drainage models and building a new storm water management model using SWMM. Some research on the state of the drainage system, the land use, elevation levels, the City's vulnerabilities and the effects of flooding for the inhabitants' lives is done in Hoboken City.

Knowledge gaps

Knowledge is needed on how to combine flood mitigation measures to increase urban resiliency to extreme weather and improve the quality of living (Maksimovic, Stankovic, Liu, & Lalic, 2013). There have been studies on integrated approaches to combine engineering, ecology, landscape architecture, policy and management, in order to make strategic choices on reducing the impact of extreme weather. There is a need for urban planners to understand the water behaviour and find the key challenges at improving water management in urban areas and measures to improve the green urban environment that can produce interesting benefits.

Integrating technical and urban characteristics of the area to bridge gaps between urban planners and engineers is required to create water robust cities. Redevelopment of urban areas becomes more complex with higher urban density. Land cover characteristics, subsurface infrastructure, ownership and soil contamination determine site complexity (Sauerwein, 2011; Fryd, et al., 2013). Blue-green measures are space consuming and influence the pressure on available land. Multi functionality of the measures therefor, is a great advantage. Besides water reducing capacity as a criterion, a stakeholder analysis is an important part of the selection of measures. The selection of measures is a negotiation process in which no best or most robust solution exists. Creating a water resilient city is a challenge, but it is feasible and affordable (van de Ven, 2011).

The knowledge gap on how technologies and concepts could be used to develop an integral concept for building climate resilient, flood proof cities, with the collaboration of blue, green and grey assets, will be tried to fill in using the Blue Green Dream approach, the six-layers approach, and the storm water management model (Maksimovic, Stankovic, Liu, & Lalic, 2013). For actual implementation also knowledge on required skills, capacities and development methods are needed to create transformations on larger scale by developing and integral concept (Graaf, 2012). The BGD Adaptation Support Tool (AST), a map-based tool developed by Deltares, is used to fit blue green measures within the existing urban environment and evaluate their efficiency and effectiveness (Deltares, 2014). The six-layer approach can then provide design strategies based on blue-green measures based on urban planning and subsoil characteristics. The SWMM model is built to give understanding of the hydraulic functioning of the existing water system and the proposed design strategies to meet future principles.

Research approach and methods

The problem statement and (sub) research questions were the basis for an extended literature review. The methodology can be divided into the four phases: first by addressing suitable blue-green adaptation measures for Hoboken. Secondly by calculating the water assignment for rough flood volume estimations, third through the six-layer approach to develop design strategies, and fourth by developing a Storm Water Management Model to simulate the hydraulic operation of the existing storm water system and the proposed design strategies. The final outcome is an urban water design of the proposed design strategy.

1.6. Reading Guide

Section 1: *Theoretical and Practical Background*

The first section contains two chapters with literature review. ‘Chapter 2 Urban Water Management in Hoboken’, describes, summarizes, evaluates, and clarifies gained literature on the topic of urban water management. It aims to understand the urban water system of Hoboken to reduce vulnerability to flooding and create a more attractive city with a blue-green flood mitigation plan. ‘Chapter 3 Blue-green Measures’ reviews the concept of blue-green measures, which aim to solve urban and climatic challenges by restoring the natural water cycle. The benefits, a performance indication and tools to integrate blue-green measures in urban water management and urban planning are described.

Section 2: *Water System Analysis*

The second section gives an introduction to the Hoboken water, followed by an illustration on modelling the existing sewer system in a storm water management model. ‘Chapter 4 Water System Analysis Hoboken’ provides of a technical background to understand the urban water system. In a functional analysis, urban characteristics regarding subsurface, infrastructure, public space, buildings, metabolism and people were identified. The relation between precipitation depth, storage and discharge is important to understand the behaviour of the drainage system. The water assignment is there for calculated to give an approach of the required storage capacity of the drainage system. In ‘Chapter 5 Testing the Design Strategies’, the SWMM model is used to provide general understanding of the key aspects of the sewer system and the influence of different design strategies on the current situation.

Section 3: *Urban Water Design*

In the third section, a number of urban design strategies were developed and tested, followed by the discussions and recommendations regarding the proposed design strategy and the conclusion, in which the sub research questions are answered. ‘Chapter 6 Urban Design Strategies’ illustrates the prosed systems of blue-green measures as resulted from the system analysis. Chapter 6 also includes the results of the design strategies from the storm water management model. ‘Chapter 7 Discussion and Recommendations’ reflects on the findings of this research and makes recommendations for future work. ‘Chapter 8 Conclusion’ provides answers to the sub-questions to give a general conclusion on the research.

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Theoretical and Practical Background

Urban water management combines urban planning and water management. It is a respond on rapidly escalating urban demands for water as well as the need to make urban water systems more resilient to climate change. The second chapter gives a literature review on urban water management in Hoboken, covering urbanization, the urban water cycle, the urban water system and the vulnerabilities of large cities to climate change. The third chapter literature gives an introduction to the term blue-green measures. Commonly used measures will be analysed and evaluated on possibilities and complications for implementation in Hoboken.

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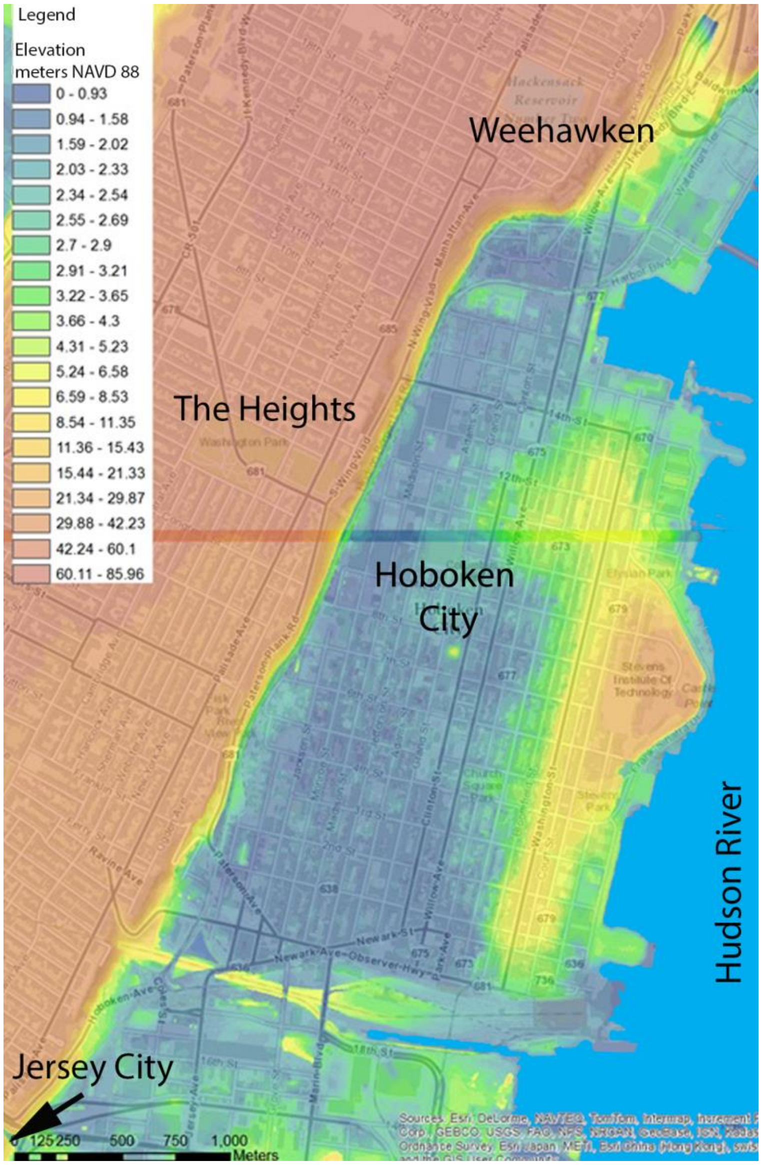
Chapter 2 Urban Water Management in Hoboken

This literature review gives a theoretical framework on the topic of urban water management and aims to understand urban water in Hoboken. Key terms, definitions, and terminology are identified by reading academic sources and public webpages. The review describes, summarizes, evaluates and clarifies the literature gained from books, journal articles, published studies and other relevant materials.

2.1. Introduction to the Hoboken case study

Hoboken, being part of the New York metropolitan area, lies directly across Manhattan on the west side of the Hudson River. The city was once an island of outcropping serpentine rock with tidal lands to the west (Hoboken Planning Board, 2004). Starting in 1843, the son of Hoboken's founder, Colonel John Stevens, chose to drain and develop the tidal marshlands on the western side of the island (



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Appendices

Appendix I Map of Hoboken sewer system

Figure 50 City of Hoboken Sewer Atlas 1995 (Source: North Hudson Sewerage Authority)

Appendix II Blue green measures

Parks and urban forests

By decreasing the total acreage of paved surfaces, parks and urban forests (Figure 51) increase the infiltration capacity of the soil and therefor have a big impact on flooding mitigation. Additionally, parks increase the quality of urban living by reducing the urban heat island effects, improving air quality and creating a more beautiful environment with more recreational area. Parks don't have to require a lot of space and are easy to maintain. If needed, open water can be created for additional storage. The geomorphology of the soil is an important factor for infiltration capacity, meaning that parks and urban forests only function well on rainfall reduction when the soil drains well. Also groundwater levels need to be relatively deep so that infiltration doesn't create a critical rise of the groundwater table .

Figure 51 Left: New Orleans City Park (Source: tripadvisor.com) and right: Houtan Park, Shanghai (source: policyinnovations.org)

Urban farms

Urban farms (Figure 52) provide increased infiltration capacity of the soil, together with benefits such as recreation, food production, and organic agricultural management. Urban farms can fulfil various roles, such as stock breading and fruit and vegetables growth, which can be combined with patients care or for educational purposes . Urban farms require some space, but if available they suit well in high dense inner-city areas.

Figure 52 urban farms in Philadelphia (left, source: ediblegeography.com) and Boston (source: inhabitat.com)

Storm water infiltration or flow-through planters

Planters are small, vegetated reservoirs to collect and filter storm water runoff. Infiltration planters (Figure 53, left) collect storm water on top of the soils and allow it to flow through vegetation, soil, and gravel. The soil in the planter filters sediment and pollutions as the water infiltrates down through the planter. Flow-through planters (Figure 53, right) store water temporarily on a waterproof layer and include an overflow and a subsurface drainage system to discharge the water

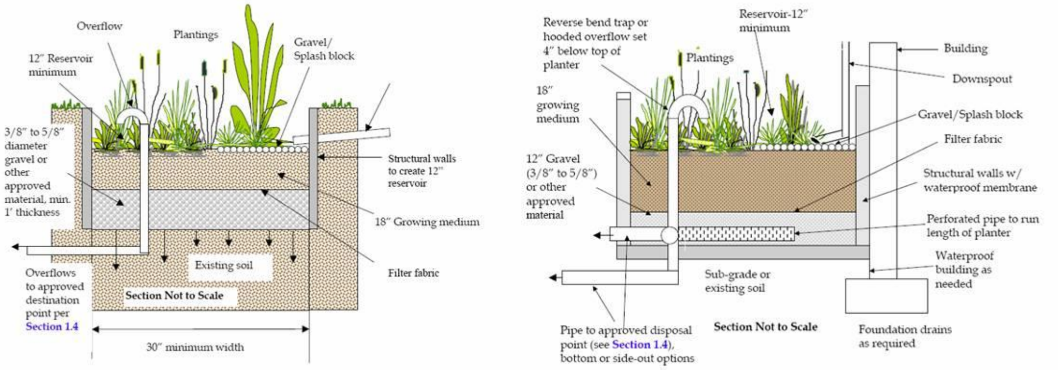

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Figure 53 Infiltration planter (left) and flow-through planter (source: ci.sandy.or.us)

Infiltration planters can be applied on poorly drained sites with contaminated soils. They are ideal to apply on space-limited sites. Besides the reduction and delay of storm water runoff, infiltration planters have a positive effect on water quality and air temperature due to vegetation. It also increases attractiveness of the area. Storm water infiltration planters can be deep or shallow, depending on the wanted buffering capacity. Depending on their size, they can receive disconnected rainwater from surrounding areas. Infiltration measures are low in construction costs since no drain has to be constructed. The maintenance of the plants is often required . Examples of infiltration planters are given in Figure 54 and Figure 55.

Figure 54 Storm water infiltration/flow-through planter San Francisco (source: spur.org)

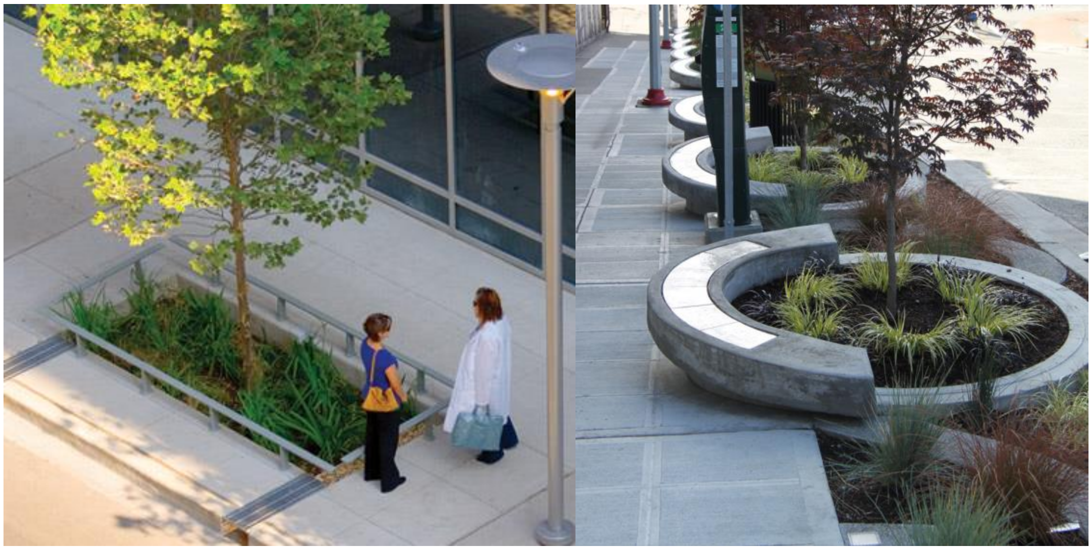


Figure 55 Storm water Infiltration/flow through Planters in Illinois (left) and Seattle (source: spur.org)

Permeable pavement

Permeable pavement (Figure 56) can substitute concrete or tiling to allow storm water to pass through and infiltrate in the soil. Permeable pavement is placed on top of a porous surface layer and an underlying aggregate layer. This bottom layer allows temporary storage before the water infiltrates into the soil. Sometimes the permeable paving contains an aggregate layer with a subsurface pipes to discharge storm water to the sewer system (which makes is then a detention measure). Permeable pavements may be constructed from pervious concrete, porous asphalt, permeable interlocking pavers and several other materials

Permeable pavement can be applied on parking lots, low-traffic streets, driveways, bike paths, patios, plazas and sidewalks. The advantages are the reduction of the storm water runoff volume (up to 70-90%). Also it improved water quality by reducing pollutants in the water. When adding vegetation, it also helps reducing the urban heat island effects. A study in Los Angeles showed that increasing pavement reflectivity by 10-30% could produce a 0.8°C decrease in average temperature, which results to estimated savings of $90 million per year based on less energy use and reduced ozone levels . Disadvantages are that it is limited to paved areas with little traffic, it can only be applied on slopes less than 5 percent , and it is more difficult to construct on sites with compacted soils like in cities.

Figure 56 Permeable Pavement Vancouver (source: blur.org)

Green roofs and blue roofs

Green roofs (Figure 57 and Figure 58) are vegetated green areas on roofs that can retain or detain water from precipitation. Blue roofs (Figure 57) store water on top of roofs without vegetation. Green roods are composed of multiple layers including a waterproof membrane, subsurface drainage pipes, suitable soils and special selected plants. Green roofs can be applied different types of roofs on both small and large scale. There are two types of green roofs: extensive and intensive. Extensive roofs have a thin system planted with only (drought tolerant) plants and grasses. Intensive roods are deeper and can contain trees, complete gardens with terraces, and roof farms.

Blue and green roofs suit best on flat roofs, but grass can also be placed on sloping areas (less than 20 degrees). Commercial, private, multifamily and industrial buildings are all suitable for blue or green roofs. Both new and existing roofs can be rebuilt to green or blue ones. Green and blue roofs affect in particular the runoff from small storms and can reduce runoff up to 50%. . This reduction depends on the type of (green) roof (layers and depth) and vegetation density. The life cycle of green roofs has been estimated to be 40% higher than a conventional roof in terms of storm-water management; electricity costs reductions and air quality benefits. Green roofs provide additional isolation and noise reduction to buildings and it reduces urban heat island effects. The energy savings from green roofs can be a15-45% on annual energy consumption. This is mainly because of its cooling capacity in summer . Green roofs, at last, increase biodiversity and habitat and provide aesthetic amenities. Disadvantages are the limits of roof slope, the additional structural support that may be needed to bear increased weight and the maintenance of the vegetation . Compared to other green measures it is quite expensive. Green roofs have the difficulty that they often need to be constructed on private space. Grants can be given to stimulate the construction of green roofs.

Figure 57 Left: Green roof, Vancouver (Source: nationalgeographic.com) and blue roof (water roof) (source: reducerunoff.org)

Figure 58 Left: Green roofs in Stuttgart and right: New York City (source: nationalgeographic.com)

Seasonal Storage and Rainwater Harvesting

Seasonal storage basins store water in periods of excessive rainfall, which can be used in periods of drought. Seasonal storage can be provided by vegetated ponds, but also by (subsurface) storage tanks or on rooftops . Storage in a large basin needs a stable site or flat area. They are a good alternative at sites with little infiltration possibility. Seasonal storage basins are low in maintenance.

Rainwater can be harvested in small rainwater tanks (like in private gardens) or in large rainwater cisterns in for example parks. Public rainwater harvest cisterns can efficiently store large volumes of water, like the one in Cumberland Park, Nashville (Figure 59, right). This cistern can store 133,700 cubic feet of storm water per year to reuse for irrigation . Private rainwater tanks (Figure 59, left) collect rainwater from impervious areas during peak flows. Rainwater tanks are often known as rain barrels (US) or rain butts (UK) and typically store water from rooftops via rain gutters. The stored water can be used for watering gardens, agriculture, flushing toilets, washing cars, and other non-potable purposes. Private rain barrels can yield 83 cubic feet of water from a 1inch storm event on a 1,000square feet roof . To function properly, both large and small rainwater harvest tanks must be empty prior to a rainfall event.

Figure 59 Private rainwater tank (left) and Cumberland Park, Nashville (source: musiccityblog.wordpress.com)

Detention ponds or tanks

Detention tanks or ponds (Figure 60) can be surface or subsurface structures to harvest rainwater during peak flows and slowly release those flows in the sewer. When no rainfall occurs, the tanks are typically empty . Detention tanks are usually constructed out of concrete. Perforated subsurface retention systems that release stored storm water to infiltrate into the subsoil are recommended only for areas with well drained soils and where the water table is low enough to permit recharge.

Subsurface storage tanks can be placed below for example parking lots, sport fields, playgrounds, buildings or parking garages. Subsurface storage below parking lots, playgrounds and sport fields are covered with pervious pavement or other material. Both the infiltration water and water from surrounding areas can be stored in these pipes or boxes. Tanks underneath buildings can be used to store rainwater stored captured from the rooftops or along the sides of the building. A storage tank below a parking garage cannot be built below an existing one and therefore the whole garage has to be newly constructed. The tanks can efficiently store a large volume of water. The storage below the parking lot in the picture below in Illinois can hold 33,300 cubic feet of storm water and is constructed beneath a 27,500 square feet parking lot with permeable pavement. The storage below the parking garage in Rotterdam can store 353,000 cubic feet (10,000m3 or 2.64MG) in a 23,000 square feet basin . Storage tanks are effective at sites where no storm water infiltration is possible or where the soil is contaminated. A disadvantage of subsurface tanks is the high costs (Illinois storage tank $1.3million, Rotterdam storage $9.1 million). Also they are difficult to maintain and have no multifunctional benefits for the environment.

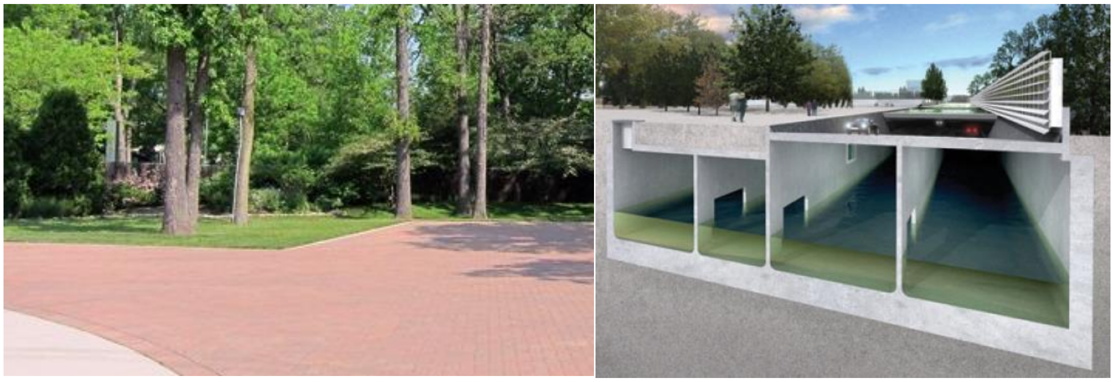


Figure 60 Left: Parking lot on top of storage tank, Illinois (Source: la foundation) and right: storage beneath parking garage, Rotterdam (source: Nooijer, 2011)

Open detention ponds are surface structures that fill with water during and right after a (heavy) rainfall. Detention ponds can either be close to water bodies (to store flooding water temporarily) or in inner-city areas as (green) water squares. The Benthem square in Rotterdam (Figure 61) is most of the year dry and only fills during heavy rainfall. The square can store up to 60,000 cubic feet (0.4 MG) in different layers in the square . In dry periods it can be used as a recreational square for sports, play and hangout. The square only fills with rainwater from the surrounding environment during extreme rainfall. Water squares are generally used in densely built up areas with little space left.

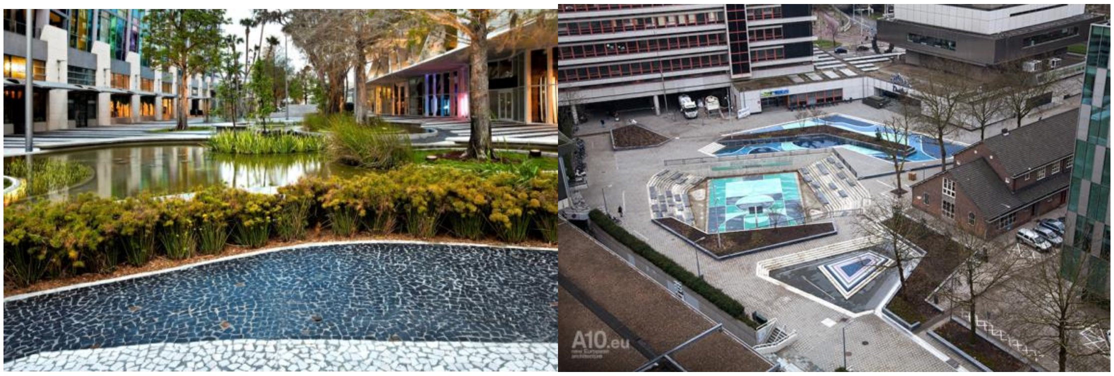


Figure 61 Left: Lincoln Road, Miami Beach (source: huffingtonpost.com) and right: Benthem watersquare, Rotterdam (source: de Urbanisten, 2013)

Green facades

Green facades (Figure 62), vertical vegetation against the wall of a building, have a minimal impact on rainfall runoff, but have a lot of additional benefits. It can reduce the interior surface temperatures by as much as 10°C, it reduces sound reflection, it reduces air pollution and through shading, green walls can lower temperatures in summer and reduce energy costs by 23 percent .

Figure 62 Left: vertical garden, CaixaForum Madrid (source: blogspot.com) and right: green façade (source: MMA architecture)

Retention ponds

Retention ponds or retention basins (Figure 63, Figure 64) are open water bodies that are used to store storm water runoff and prevent downstream erosion and improve water quality. Retention ponds are artificial lakes that are permanently filled with water and vary in water level depending on receiving waters. Retention ponds differ from infiltration ponds, which are designed to direct storm water to the groundwater through permeable soils. They also differ from detention ponds that are typically empty and only sill with water during or after a storm event.

The advantages of retention ponds are rainfall runoff reduction, water quality improvement, it creates biodiversity and it benefits the aesthetic value or the area.

Figure 63 Urban retention ponds (source: left, ASCE's, right, landscapeonline.com)

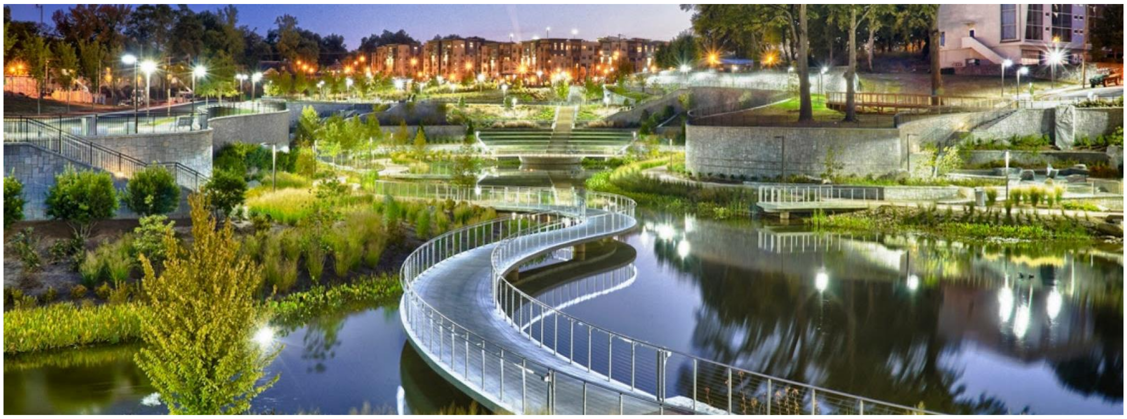


Figure 64 Historic Fourth Ward Park Atlanta (source: beltline.net)

Add green to the streetscape and open (private) space

Green can be added to the streetscape and (private) open space in the form of vegetation, grass, or shrubbery (Figure 65). This decreases the permeability so that more water can infiltrate in the ground. When water infiltrates in the soil, it removes pollutants, which increases water quality and replenishing of the groundwater. Also vegetation benefits heat reduction, biodiversity, and air quality . Green in the streetscape does not have a big impact on the rainfall runoff, but has many other advantages towards the quality of urban life and is easy and cheap to implement on a large variety of sites.

Figure 65 Left: green square, Sydney (source: cityofsydney.nsw.gov.au) and right: urban green (source: urbangreen-space.co.uk)

Artificial urban wetlands

Urban wetlands (Figure 66) are man-made overflow areas for rivers. They are designed to reduce, detain and treat storm water runoff. Constructed wetlands have many functions corresponding to natural wetlands, like flood control, improving water quality and the growing of wetland plants, and they simulate natural wetland ecosystems.

Wetlands must be applied on relatively flat areas (less than 2 percent grade). They can be applied to various sizes site conditions and budgets. Wetlands can receive water form upstream slopes. Besides the great addition to rainfall runoff reduction, urban wetlands improve water quality, heat reduction, biodiversity, air quality, and they benefit the socio economic value of the area . Urban wetlands can also been constructed in combination with a wastewater treatment plant. When both are combined, the costs will decrease from $10.00 per gallon to $5.00 per gallon, due to reduced advanced treatment costs . Urban wetlands are, due to limited space in the city, not suitable to place next to the riverside. Disadvantages are that urban wetlands are relatively space consuming and therefor high in costs. Also it requires periodic maintenance to vegetation and to remove debris .

Figure 66 Qunli Wetland Park (source: turenscape.com)

Hollow roads

Increasing the height difference between street level and ground floor level can provide storage and drainage capacity of storm water (Figure 67). The road needs to be on a slope to direct the water flow to a gutter, water body, or an infiltration field . Raised sidewalks/curbs can even increase storage capacity. The roads can still be accessible by traffic when it rains, but can cause some nuisance due to splashing water. Accessibility for disabled can be a problem due to the slope .

Figure 67 Hollow Road (source: Atelier Dreiseitl)

Storm water trees

Storm water trees are placed next to roads and can be combined with subsurface trenches (Figure 68). Storm water runoff flows into the highly permeable storm water tree trenches, which are connected underground. When storage capacity is exceeded, the storm water overflows into a bypass . Planting trees on streets, squares and parking lots also creates shade. Evaporation will have a cooling effect. Studies have shown the net economic benefits of urban trees range from $30-90 per tree per year. This includes storm water benefits (average $0.66/cubic foot of storage), carbon storage (700 million tons storage in urban trees in 2005) and the cooling savings when trees canopy over a house (annual heating savings of 2-8%). Also studies have found that residential property values increase up to 37% with the presence of trees and vegetation on the property . Hoboken has already many streets lined with trees. More trees would create more shade and evaporation, but also less sunshine to penetrate into the streets.

Figure 68 Left: storm water trees Ohio (Source: continuingeducation.construction.com) and right: impression of storm water trees with subsurface chamber (Source: waterworld.com)

Open channel water

Open channel water, for example in ditches, channels, or streams (Figure 69), can be the construction of a new, or uncovering and restoring the natural water behavior of a historical water. This can improve rainfall runoff; it increases storage and enhances local neighborhoods. Since it is often very hard to uncover historic creeks in urban dense areas, they can also be applied through existing low-lying open space. When applied on natural soil, open water has as an additional benefit that infiltration and groundwater recharge is increased. Also is improves biodiversity and provides aesthetic benefits. A disadvantage of open water streams is the high installation and maintenance costs, and requires much space, which often includes land acquisition.

Figure 69 Left: Thornton Creek, Seattle (Source: spur.org) and right: Seoul (Source: kennislink.nl)

Bio retention swales

Bio retention swales are ditches with vegetation, made of porous soil (Figure 70). Below the visible layer, a layer with large empty spaces (infiltration boxes, gravel, etc.) is constructed. Disconnected rainwater from the environment can be discharged into the bio swale. Water from the swale flows to the sewer system through an infiltration drain/pipe in the third layer. When the water level rises above a certain level it will enter the drain via an overflow . Bio swales can help enhance biodiversity and an improved living environment.

Figure 70 Bio retention swales (Source: both the University of Washington)

Rain gardens

Rain gardens or bio retention cells (Figure 71) collect rainwater runoff from impervious areas like roofs, parking lots and walkways, and hold it in a (often) vegetated, depressed area to infiltrate in the soil. Rain gardens and bio retention cells can be connected to the sewer systems through an overflow (that makes it then a detention measure), but are usually sized to infiltrate the collected storm water runoff into the ground . (Bio) retention swales

Rainwater gardens are suitable for residential yards, offices and commercial storefronts, parks, right-of-ways and parking lots. Advantages are that they are relatively easy to install, can be applied on a wide range of scales. Assessment of bio retention areas and rain gardens has shown a peak flow reduction of at least 96.5% for small to medium sized storm events . Besides rainfall runoff reduction it improves air and water quality. Also they are aesthetically pleasing for residents . A disadvantage is that it requires relatively flat site.

Figure 71 Rain garden in Malmo, Sweden (source: nerdyplanner.blogspot.com)

Appendix III Precipitation analysis

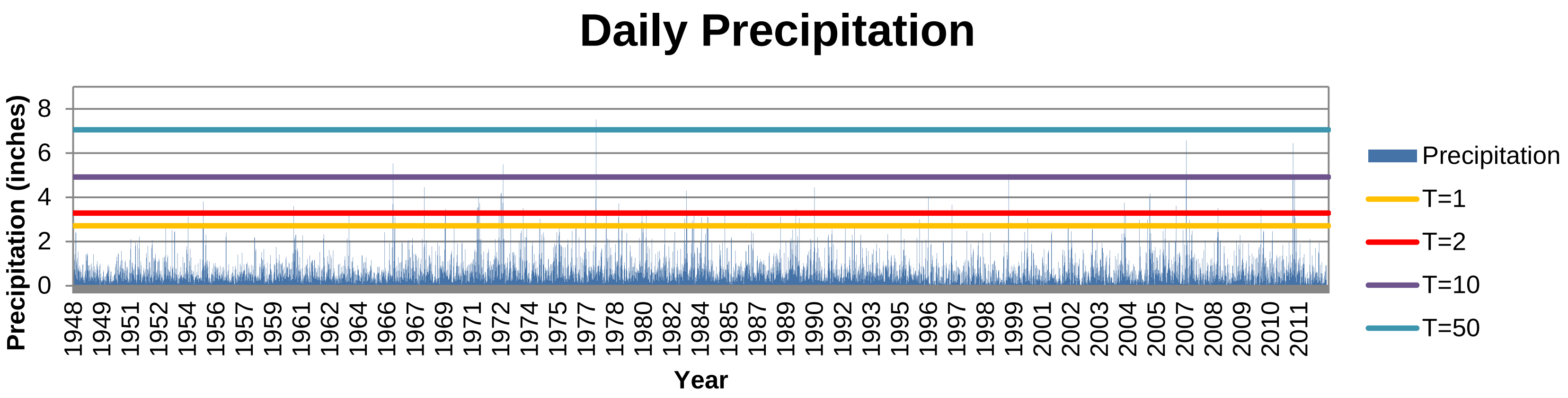


Figure 72 Daily precipitation in Hoboken (source: NOAA, 2014)

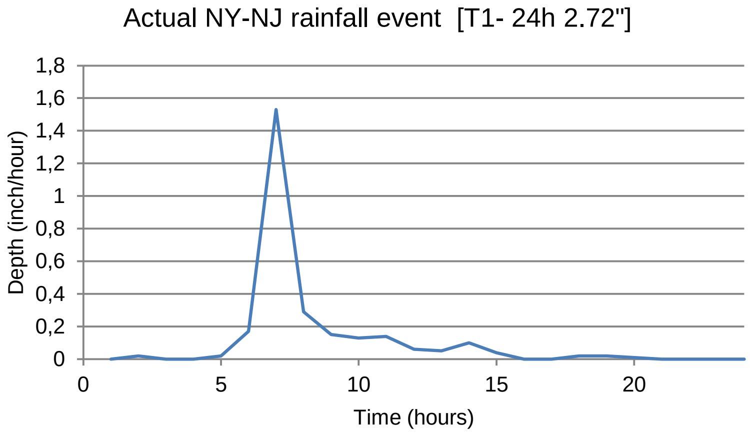


Figure 73 Actual T1 rainfall event NY-NJ

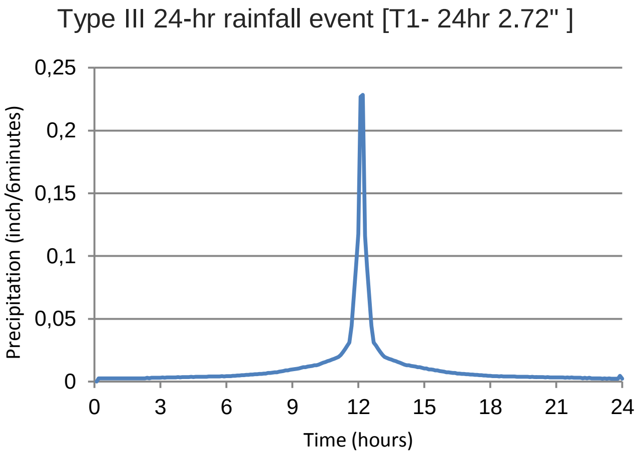


Figure 74 Type III rainfall event for T1

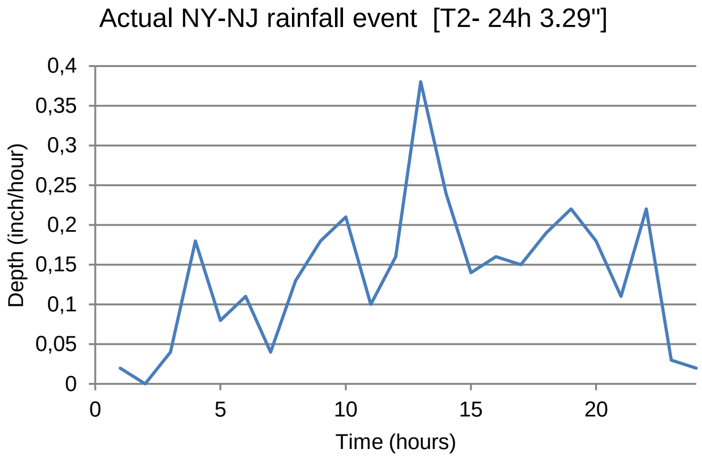


Figure 75 Actual T2 rainfall event NY-NJ

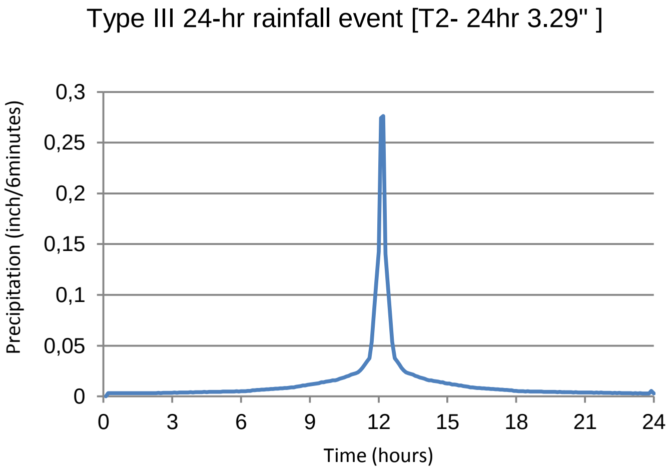


Figure 76 Type III rainfall event for T2

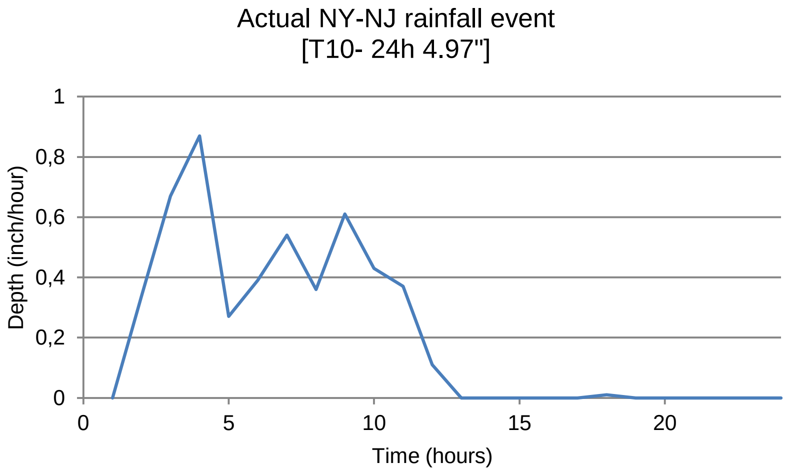


Figure 77 Actual T10 rainfall event NY-NJ

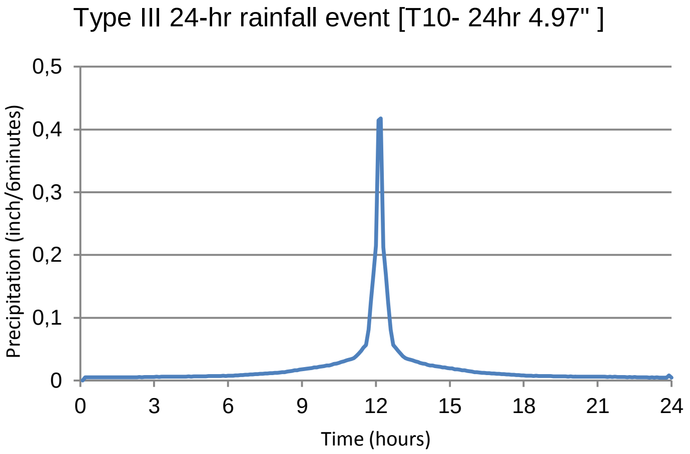
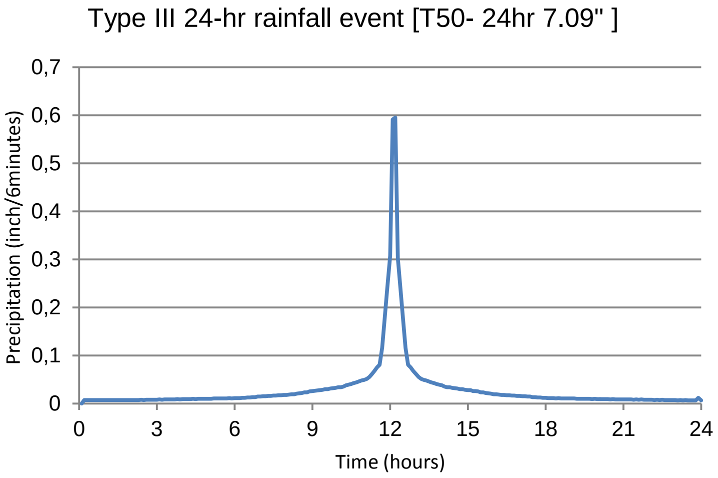


Figure 78 Type III rainfall event for T10



Actual T50 rainfall event not available

Figure 79 Type III rainfall event for T50

Appendix IV Water Assignment calculation

Table 19 Summary of area distribution (source: NLDC, 2006)

	Total surface [acre]	Open water [acre]	Impermeable surface [acre]	Permeable surface [acre]	Impermeable [%]
H1	263	0	220	43	84
H2	30	0	23	7	77
H3	68	0	52	16	76
H4	107	0	85	22	79
H5	159	0	115	44	72
H6	28	0	23	5	82
H7	81	0	62	19	77
Total	**736**	**0**	**581**	**155**	**79**

Table 20 area characteristics that influence rainfall runoff

Basin	Area [acre]	Sewer storage [inch/ac]	Rainfall runoff [%]	Pumping capacity [inch/(ac*day)]
H1	264	0.55	83.8	2.5
H2	30	0.35	75.7	2.5
H3	68	0.52	76.0	2.5
H4	107	0.69	79.7	2.5
H5	153	0.35	77.3	2.5
H6	28	0.12	82.9	2.5
H7	80	0.51	74.7	2.5
Total basin	730	0.44	78.9	2.5

Table 21 Potential water storage in sewer system

Sub basin	Sewer Storage [ft^3]	Sewer Storage [MG]	Sewer Storage [inch/acre]
H1	400,694	3.00	0.55
H2	33,377	0.25	0.35
H3	106,663	0.80	0.52
H4	239,563	1.79	0.69
H5	160,322	1.20	0.35
H6	11,578	0.09	0.12
H7	159,570	1.19	0.51
Total	**1,111,768**	**8.32**	**0.44**

Table 22 Water Assignment calculations

					T1 = 2.72		T2= 3.29		T10= 4.96		T50 =7.07	
Basin	**Area [acre]**	**Sewer storage [in/ac]**	**Rainfall runoff [%]**	**Pump cap. [in/(ac* d)]**	**Volume [acre*ft]**	**Depth [in/acre]**	**Volume [acre*ft]**	**Depth [in/acre]**	**Volume [acre*ft]**	**Depth [in/acre]**	**Volume [ac*feet]**	**Depth [in/acre]**
H1	264	0.55	83.8	2.5	15.5	0.71	23.0	1.05	53.7	2.45	92.4	4.22
H2	30	0.35	75.7	2.5	1.6	0.62	2.3	0.92	5.5	2.18	9.5	3.78
H3	68	0.52	76.0	2.5	3.0	0.53	4.4	0.84	12.0	2.12	21.2	3.74
H4	107	0.69	79.7	2.5	4.5	0.50	7.4	0.82	19.2	2.16	34.3	3.84
H5	153	0.35	77.3	2.5	7.0	0.53	10.7	0.81	26.7	2.02	47.0	3.54
H6	28	0.12	82.9	2.5	2.3	0.99	3.1	1.33	6.4	2.73	10.5	4.49
H7	80	0.51	74.7	2.5	3.6	0.53	5.6	0.83	14.2	2.11	25.1	3.72
Total basin	**730**	**0.44**	**78.9**	**2.5**	**37.5**	**0.61**	**56.8**	**0.93**	**137.7**	**2.24**	**239.9**	**3.91**

Appendix V Model calibration and verification

Table 23 Flooded nodes and flood volumes calibration 1-year data series

Node	Total Volume (MG)	Maximum Flood Rate (CFS)	Subbasin
J5	0.06	14.0	H5_4
J70	0.08	3.8	H6
J71	0.20	11.1	H6
J149	0.06	7.4	H7_1
J153	0.07	8.7	H7_1
J160	0.22	4.2	H5_1
J177	0.12	18.4	H3_1
J190	0.07	6.0	H1_10
J194	0.45	56.9	H1_11
J205	0.02	1.4	H1_6
J206	0.14	17.7	H1_6
TOTAL FLOODING	**1.63**		

Appendix VI Design Strategies

Table 24 Area characteristics

Basin	**Area** [acre]	**Percent impervious** [%]	**Impervious area** [acre]	**Pervious area** [acre]	**Parks** [acre]	**Parking** [acre]	**Flat Roofs** [acre]	**Undevelope land** [acre]
H1_1	17.4	86.3	15	2.4	0.0	0.0	2.2	
H1_2	19.9	85.5	17	2.9	0.2	1.2	0.3	
H1_3	24.2	76.0	18.4	5.8	1.9	0.8	0.7	
H1_4	19.0	85.7	16.2	2.8	0.3	4.1	2.7	
H1_5	24.9	86.3	21.5	3.4	0.1	0.0	0.3	
H1_6	28.6	81.1	23.2	5.4	0.0	0.0	0.0	
H1_7	20.6	86.3	17.8	2.8	0.0	1.4	1.7	
H1_8	25.1	85.8	21.5	3.6	0.5	2.6	4.5	
H1_9	17.3	83.2	14.4	2.9	0.0	0.3	2.2	
H1_10	27.7	82.8	22.9	4.8	0.1	2.9	5.2	
H1_11	38.9	83.2	32.4	6.5	0.4	3.9	4.8	
Total H1	**263.5**	**83.8**	**220.2**	**43.3**	**3.5**	**17.0**	**24.4**	
H2	30.0	75.7	22.7	7.3	0.0	3.9	4.4	
Total H2	**30.0**	**75.7**	**22.7**	**7.3**	**0.0**	**3.9**	**4.4**	
H3_1	38.6	78.1	30.1	8.5	1.7	1.0	1.1	
H3_2	20.0	73.4	14.7	5.3	1.7	0.0	1.8	
H3_3	9.5	76.6	7.3	2.2	0.2	0.5	4.1	
Total H3	**68.2**	**76.0**	**52.1**	**16.0**	**3.6**	**1.4**	**7.0**	
H4_1	23.0	74.6	17.1	5.9	2.	0.0	1.9	
H4_2	24.7	78.7	19.4	5.3	1.4	0.0	1.0	
H4_3	30.1	81.2	24.5	5.6	0.0	0.0	4.8	
H4_4	28.9	84.2	24.4	4.5	0.3	1.2	5.7	
Total H4	**106.7**	**79.7**	**85.4**	**21.3**	**3.7**	**1.2**	**13.4**	
H5_1	45.5	53.6	24.4	21.1	2.8	1.9	0.0	
H5_2	32.2	81.5	26.3	5.9	0.0	2.4	3.8	
H5_3	38.0	88.3	33.5	4.5	0.0	0.4	5.8	
H5_4	20.4	87.8	17.9	2.5	0.8	1.9	6.7	
H5_5	17.3	75.2	13.0	4.3	5.4	0.0	0.0	
Total H5	**153.4**	**77.3**	**115.1**	**38.3**	**9.1**	**6.6**	**16.4**	
H6	28.2	82.9	23.4	4.8	0.3	3.4	4.4	
Total H6	**28.2**	**82.9**	**23.4**	**4.8**	**0.3**	**3.4**	**4.4**	
H7_1	35.3	88.8	31.4	3.9	0.0	5.7	7.3	
H7_2	24.0	82.2	19.8	4.2	0.0	3.4	2.1	
H7_3	20.3	53.1	10.8	9.5	2.0	1.7	4.5	
Total H7	**79.7**	**74.7**	**62.0**	**17.7**	**2.0**	**10.9**	**13.9**	
Total basin	**729.6**	**78.9**	**580.9**	**148.7**	**22.1**	**44.4**	**83.8**	

Figure 81 Washington Street (source: Google street view)

Figure 82 Willow Avenue (source: Google street view)

Figure 83 Jefferson Street (source: google street view)). Landfill created space to the area and build streets, piers and buildings (City of Hoboken, Hoboken , 2014). As a result, Hoboken has elevation levels varying between 70 feet above average sea level at Castle Point, and less than 5 feet in the western part of the city. Figure 9 shows the elevation map of Hoboken. The lowest lying parts are in the western part of the city, along the Palisade Cliffs. Some of these areas are even below sea level (Hoboken Planning Board, 2004). The Palisade Cliff surrounds the city with a steep slope upwards to Jersey City.

Figure 9 Hoboken elevation map (Source: RoyalHaskoningDHV, 2014)

Figure 8 Photo of Hoboken Plank roads, 1890 (Source: Rutgers University Community Repository)

Hoboken is listed 4th on most population density of all cities in the United States (City-Data, 2012). Almost 100% of the city is cultivated (Figure 10). Fifty-three percent of Hoboken's population lives in areas less than five feet above sea level (UCSUSA, 2014). When excess flow backs up in the system, flooding occurs in the lowest lying areas (EmNet, 2013). With the impacts of climate change on precipitation, these flooding problems are expected only to increase.

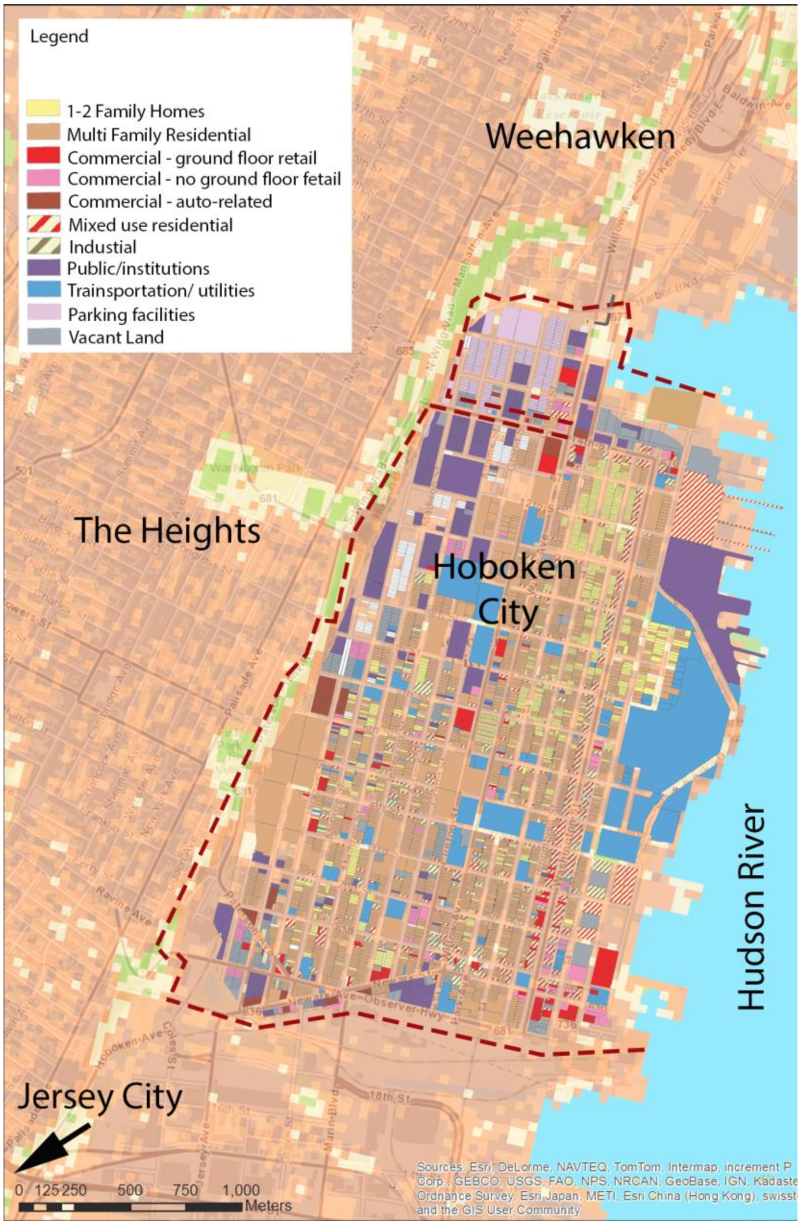


Figure 10 Hoboken land use (Illustration by author, based on HobokenNJ, 2013)

Increasing rainfall intensity, combined with higher frequency of rain events, and almost 90 percent impervious surfaces, has created significant challenges to Hoboken's storm water management infrastructure (EmNet, 2013). With a gravity-driven sewer system and storage capacity limited to the sewer pipes volume (since no open water exists), the performance of the cities' combined sewer depends on the tide of the Hudson River. After the maximum capacity of the wastewater treatment plant is reached, the excess water is discharged into the river by 8 combined sewer overflows (CSO's). The most flood prone areas when the 8 outlet valves are closed with high tide and the sewer is overloaded are indicated in Figure 11.

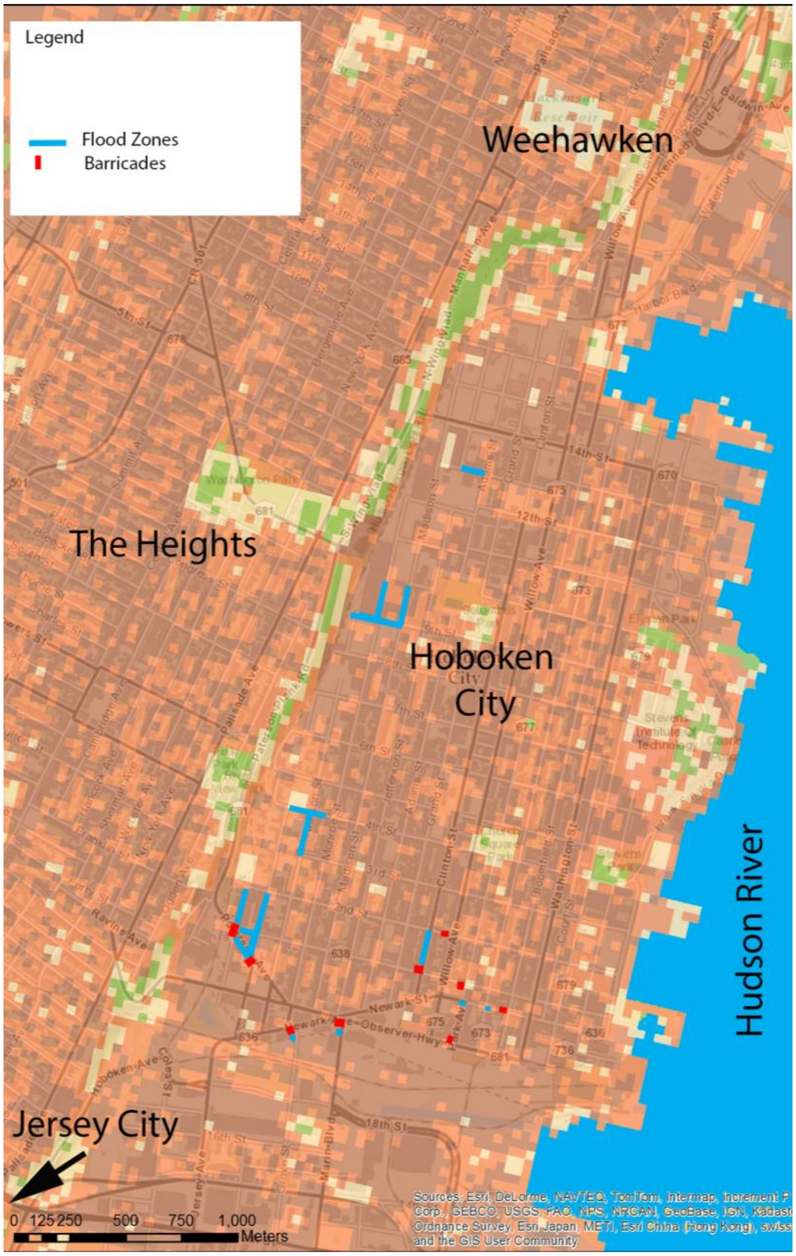


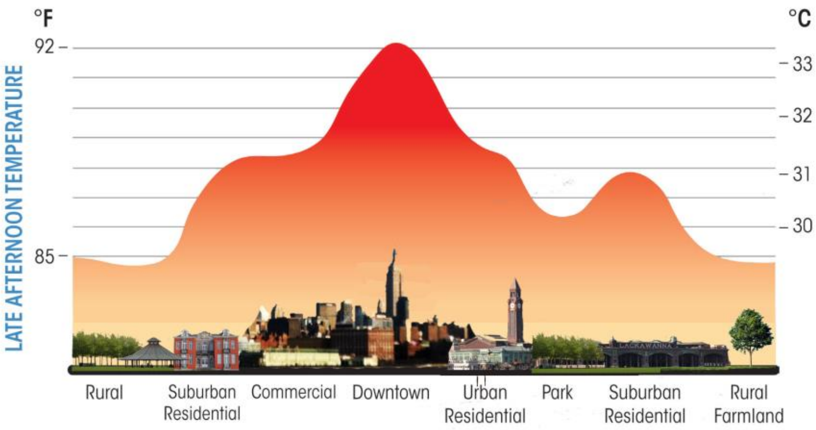
Figure 11 Storm Flood Zones (Illustration by author, based on City of Hoboken, 2010)

The construction of the cities' first a wet weather pump decreased the number of floods. Nevertheless, since all water that is pumped and discharged into the Hudson River is polluted, it is desired to keep more water out of the combined sewer. The number and volume of CSOs affect the (ground) water quality and can result in economical, health and social damage, asking for a different approach to deal with urban storm water.

2.2. Effects of urbanization on the urban water system

To understand the complete and integrated picture of the urban water system, knowledge of the (urban) hydrological cycle in combination with the water balance is essential. Urban water management includes five different types of water: precipitation, groundwater, surface water, drinking water and wastewater (Fryd, et al., 2013; Foster, Lowe, & Winkelman, 2011; Leenaers, 2006). The relation between these hydrological elements and their urban

Figure 12 Urban Heat Island (UHI) effect (Illustration by author, based on clean air partnership, 2010)



environment is described in the hydrological cycle (Savenije, 2006). The main influences of urbanization on water management are the presence of paved area, the compact soil (due to site preparation), the sewerage system and the inflow of drinking water (van de Ven, 2013). Urbanization includes residential, commercial, industrial, public and institutional land use. The impact of urbanization on the natural water balance is shown in Figure 13.

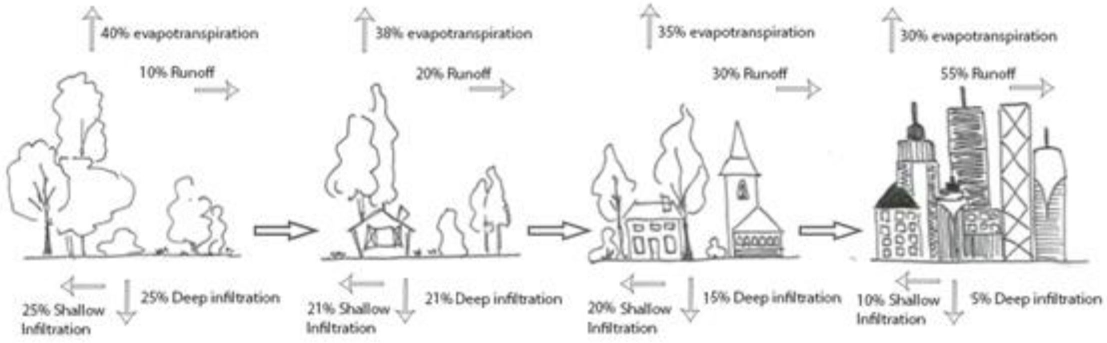


Figure 13 Effects of urbanization on runoff, infiltration and evaporation (Illustration by author, based on FISRWG, 2009)

The most important effect of urbanization on the urban water cycle is its impact on rainfall runoff. Hoboken is highly impermeable with 80-90% paved surface (EmNet, 2013; EmNet, 2011). Large amounts of rooftops, streets, and driveways and little soil infiltration associated with site preparation, contribute to larger volumes of post-urbanization runoff. In addition, removal of vegetation, paving the surface, grading the land surface, and the construction of drainage systems increase runoff volumes, peak discharge, and frequency of floods, and decrease runoff time (USGS, 2014).

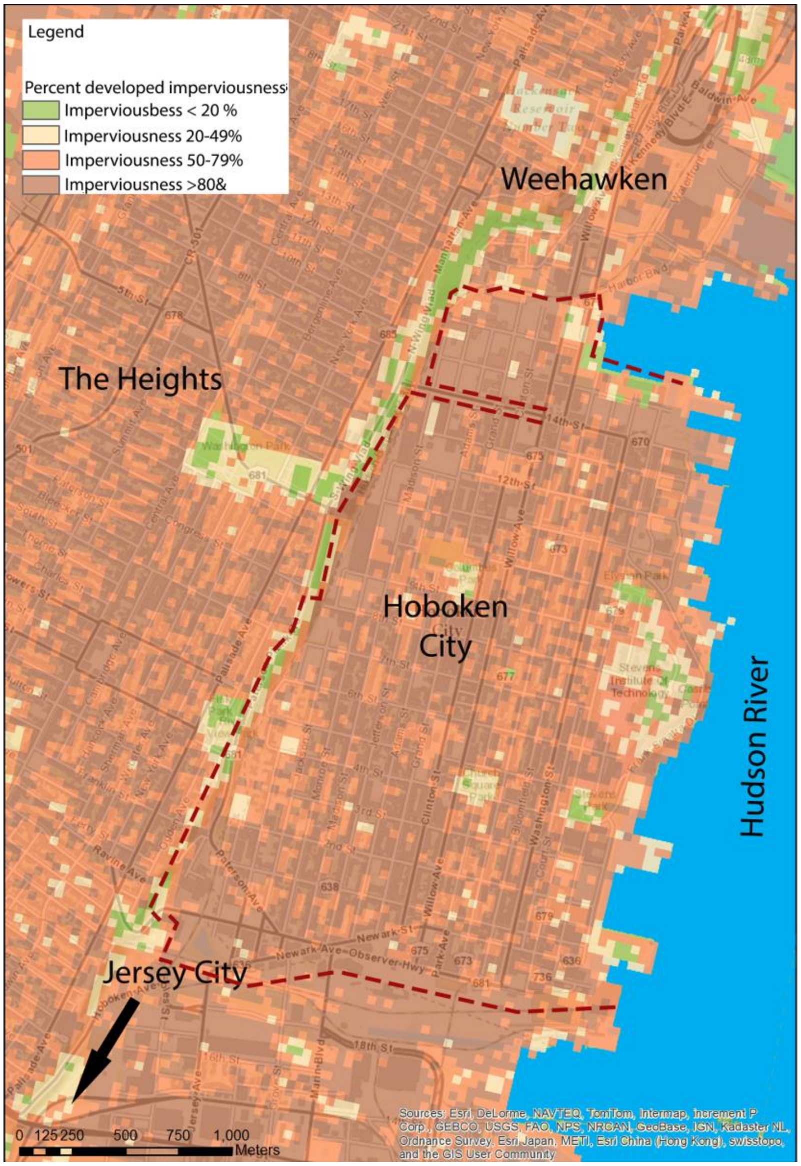
Not only it increases rainfall runoff, paved surfaces also collect solar heat. In combination with increasing temperatures and less vegetation, this can lead to the Urban Heat Island (UHI) phenomenon (EPA, 2008; van de Ven, 2009; Santamouris, 2014). Urban heat islands, urban areas that have higher temperatures than surrounding rural areas (Figure 13) can affect as much as energy use, air quality, human health, and water quality (EPA, 2008). Amongst the measures falling within the Urban Heat Island confines, there is a range of strategies, including vegetation, landscaping and improvements to buildings and roads available (EPA, 2008; van de Ven, 2009).

2.3. Hoboken physical layout

The urban dense distribution of buildings, infrastructure, parking, parks and vacant land is specified in Figure 14. The total Hoboken land cover is 816 acres (about 3,3 km^2). Buildings cover 265 acres of the total area. Buildings include both residential and industrial development and are mainly low-rise (Hoboken Planning Board, 2004). Hoboken has plenty of asphalted of-street parking places, covering 58 acres in total (Bykowski, 2013). The grid-based infrastructural network, mostly asphalted roads, covers 350 acres in total. Green strips can be found along the river shore and the Jersey Heights the area (Bykowski, 2013). A few parks are located in the centre of the city. Together with vacant land, parks cover about 100 acres (Bykowski, 2013).

Figure 14 Distribution of land types in Hoboken (Illustration by author, based on Bykowski, 2013)

The citywide imperviousness is visualized in Figure 15. The lowest imperviousness is along the Palisade cliffs in the west, and spread over the city in parks. The majority of the city is densely built. Based on GIS data, the impermeable cover was estimated 80% (NLCD, 2006). Other methods estimate impermeability in Hoboken even higher. Using the California EPA Impervious Surface Coefficient Standards, imperviousness was estimated 80-90% (EmNet, 2013). The Hoboken Green Infrastructure Strategic plan (2013) shows estimations of imperviousness around 90%. The impermeability estimations gathered from GIS data are used for the urban water assignment calculations.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 15 Imperviousness Hoboken (Illustration by author, based on RoyalHaskoningDHV, 2014)

2.4. Geological characteristics

Low elevation and high groundwater levels influence infiltration capacity and efficiency of the drainage system. Higher elevation levels along the riverside than inland limits the efficiency of existing gravity based sewerage works. Soil properties influence the performance of the infiltration and retention capacity of the soil. For example gravel and coarse sands have infiltration capacities of more than 0.8 inches per hour, for sandy loams this is 0.4 to 0.8 inches per hour, for loams 0.2 to 0.4 inches per hour and for silty clay loams and clay soils the infiltration capacity is less than 0.2 inches per hour (Savenije, 2006). Due to site preparation, soil suffers significant infiltration decrease.

Little is known about subsoil characteristics in Hoboken. Geological reports about tide marshes and embanked meadows of New Jersey in 1878 found three different types of subsoil, being clay, mud and peat (Ward, 1878). Before reclamation, the Hoboken marshlands were wet and spongy. The subsoil decayed and consolidated after drainage (Ward, 1878). The elevated part in the west of the city is mainly serpentine rock (Ward, 1878). This is a porous type of rock that promptly absorbs surface water (Ward, 1878). Not much subsidence has occurred in the past decades, which makes it likely that current soil is largely peat or mud. For this study, assumptions had to be made for the soil type to estimate the infiltration capacity. The former marshland, covering 450 of the total 730 acres of Hoboken, has a clay, mud and peat soil (20 to 100 feet deep) (Ward, 1878). This means the soil has high runoff potential and very low infiltration rates.

Hoboken has shallow groundwater water tables especially in the lower parts of the city. It is uncertain how the groundwater table relates to the water level of the river. Expected is that the groundwater does not receive much seepage water from the Hudson River. Additional research on soil type and groundwater behaviour is needed to make better-substantiated estimations.

2.5. The Hoboken drainage system

The combined sewer system originates from the mid-1800s. The sewer layout is based on the grid system Colonel John Stevens laid out for Hoboken in 1804 (Figure 16). This was even before it was incorporated as a city in 1855 (Hoboken Planning Board, 2004). Many of the original wooden sewers are still present. Some of them haven't been cleaned for the last 50 years (Bailin, 2014). Back in the years, the system was designed to drain both storm water and sanitary sewage water to the Hudson River without treatment. The first wastewater treatment plant was constructed in 1958. Pumps were built to direct wastewater to the treatment plant. During storms events, the capacity of the treatment plant is insufficient to treat both sewage and rainwater, which means that most of the water is directly discharged to the Hudson River (Hoboken Planning Board, 2004).

Figure 16 Map of Hoboken 1882 (source: Hoboken Historic Waters, 2013)

The current drainage system can be divided into seven primary drainage areas or watersheds, given the names H1 to H7. The distribution of the drainage basins is shown in Figure 17. The basin boundaries are influenced by the topology of the sewer system. Discharge directions have been adapted considering the location of important drainage structures, like combined sewer overflows or a wastewater treatment plants (WWTP). The area along the waterfront is not connected to the sewer system and directly discharges storm water into the Hudson River. Some storm water from adjacent areas also runs off into the Hoboken sewer system. The estimated areas with storm water conveyed from Jersey City, Union City, and Weehawken into the Hoboken drainage systems are added to Table 1 (RoyalHaskoningDHV, 2014). This table also includes the sub-basin areas.

Figure 17 Hoboken Drainage basins (illustration by author, based on www.nj.com)

Basin	Area [acre]
H1	264
H2	30
H3	68
H4	107
H5	153
H6	28
H7	80
Hoboken Stormwater Catchment	**730**
HSI	139
Jersey City to H1	28
Union City to H5&H7	17
Weehawken to H7	3

Table 1 Area Distribution Hoboken

All drainage basins have a trunk line with an outlet valve to the Hudson River. These outlets have weirs from where the regular chamber can overflow into the overflow chamber during wet weather. The outlet designs are shown in Figure 18. Dry weather flow is all discharged to the treatment plant by interceptor pipes. When it rains, wet weather flow enters the overflow chambers over the weir. Overflow chambers contain a drain and an overflow line. The tide is able to enter and leave this chamber freely and prevented by valves to flow into the drainage pipes during high tide (EmNet, 2011).

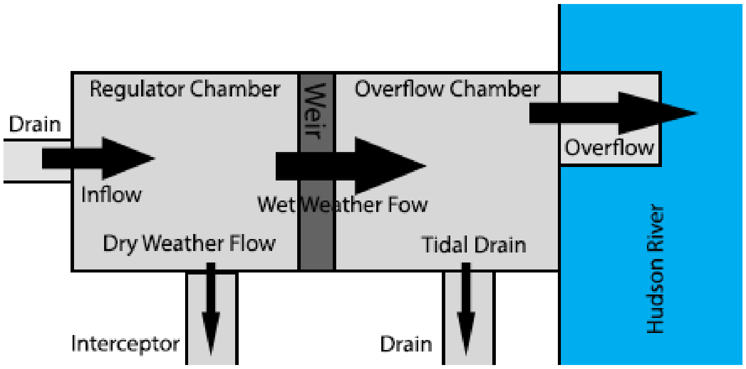


Figure 18 Configuration of tide monitoring location (illustration by author)

The basic sewer layout is visualized in Figure 19. In 2011 the first wet weather pump was installed to pump excess water into the Hudson River when rainfall occurs during high tide (EmNet, 2013). The lifting stations for dry weather flow are located at the height of 5th and 11th street. The most southern one pumps the water from of 5th street towards 11th street, and one that pumps water south of 11th street to the wastewater treatment plant.

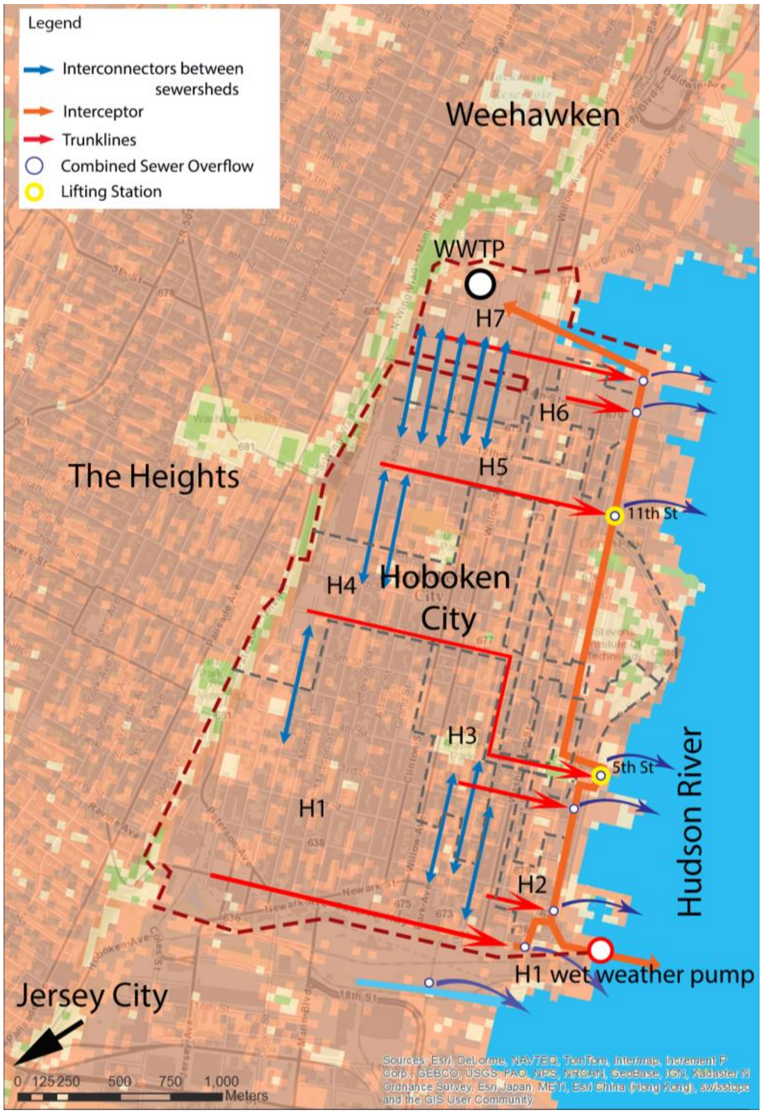


Figure 19 Sewer layout Hoboken (illustration by author, based on Emnet, 2011)

The sewage collection and treatment system is fully owned, operated and maintained by the North Hudson Sewerage Authority (NHSA). The wastewater treatment plant has a maximum capacity of 24 million gallons per day (MGD) or 37.1cfs (1.05m^3/s) (Hoboken Planning Board, 2004). This corresponds to more than 36 Olympic swimming pools per day (with the official size of 5 lanes wide, 50 meters long), or 1.2 inch/day (30 mm/day) over the total acreage of 730 acres (295 hectares). Because of its low altitude, in particular the south-western section experiences capacity problems due to inadequate draining.

Figure 20 illustrates the relative differences between the grade elevation and water levels. This figure doesn't include storm water that can fall at the same time. Both the Digital Elevation Map and the Water Levels are corrected on the North American Vertical Datum of 1988 (NAVD88) (NOAA & National Ocean Service, 2013).

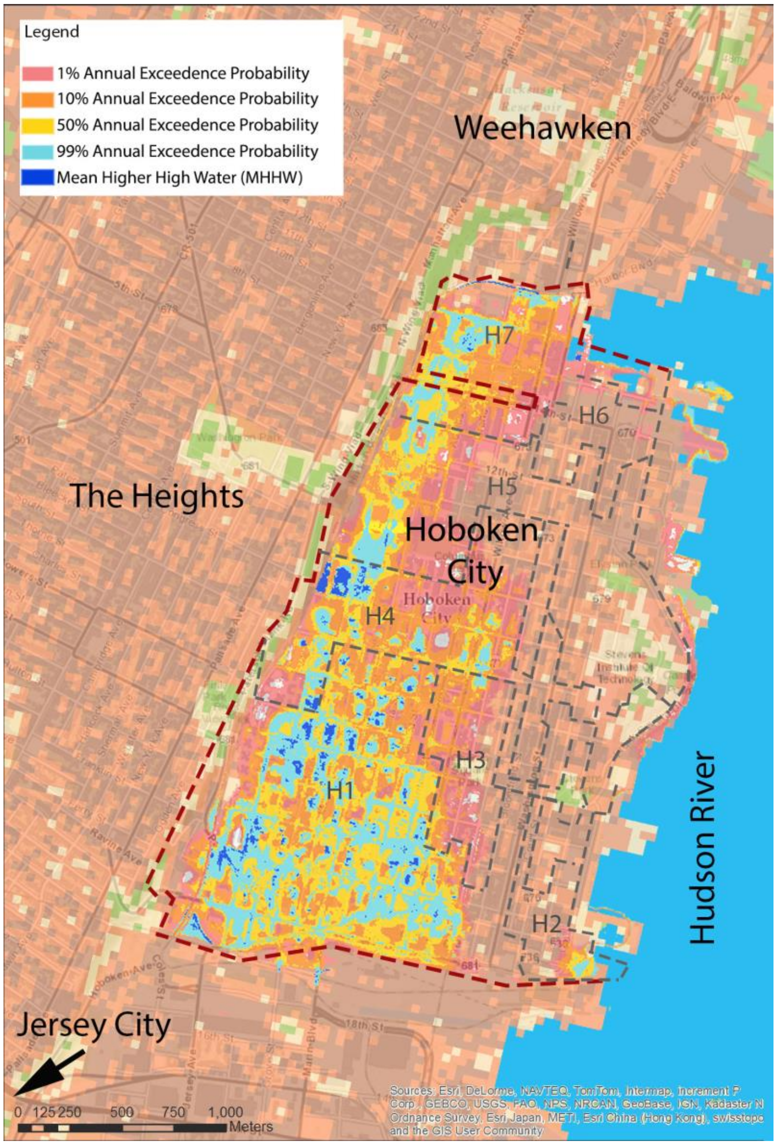


Figure 20 Hudson extreme water levels in Hoboken surface elevation (illustration by author; based on data tidesandcurrentsnoaa.gov)

2.6. Water Management and Urban Design

Adjustments to an existing water system though are way more complex and expensive than implementation in the design phase. Given growing urban populations, competition for water resources across all sectors will become fierce. Several frameworks have been developed in order to design urban resiliency strategies. These strategies vary from the testing of the urban design strategies, to stakeholder participation. Two frameworks that have been recently developed will be used as a guideline in this thesis: the Blue Green Dream (BGD) project and the Urban Climate Framework (UCF).

The Blue Green Dream project provides a framework to compose effective packages of blue-green measures from the large supply of available adaptation measures (Voskamp & van de Ven, 2014). The Blue Green Dream Adaptation Support Tool (AST) is an electronic design table (MapTable)-based application to support urban planners in finding site-specific blue-green adaptation measures for an existing urban environment. Appropriate adaptation measures can be selected based on required functions (increase vulnerability to flooding, drought and/or heat stress). Measures receive scores on the established site characteristics. A touch table can be used implement selected measures in the urban environment to directly visualize its effect on flooding, drought and heat stress. With the visual application, the Blue Green Dream AST aims to create understanding of integrating the multiple functions of blue-green measures into the urban planning and design process (Voskamp & van de Ven, 2014). The BGD tool will be applied to the project in paragraph 3.6.

The Urban Climate Framework (UCF) developed by Döpp, Hooimeijer, and Maas (2010), is a theoretical framework and a practical tool to get a grip on the urban complexity and climate change effects. The UCF approach is based on different system approaches and aims better understanding of the effects of climate change and the identification of robust strategies for existing urban environments. The framework is developed in the context of adaptive governance to integrate climate change in the complex processes of engineering, urban development, researchers, policy makers, designers and stakeholder groups (Döpp, Hooimeijer, & Maas, 2010). In paragraph 4.2, functional analysis, the UPC is applied to Hoboken.

2.7. Conclusions on urban water management in Hoboken

The aim for Hoboken is to understand the urban water system to reduce vulnerability to storm water floods and to create a more attractive city with a comprehensive flood mitigation plan. Both extreme precipitation and sea level rise are a growing threat. The most important effect of urbanization on the urban water cycle is its impact on rainfall runoff. Urbanized areas deal with increased runoff volumes, peak discharge, and frequency of floods, and decrease runoff time due to highly impermeable surfaces. Of the 816 acres (about 3,3 km^2) Hoboken covers, 265 acres are covered with buildings, 58 acres with of-street parking, 350 acres with infrastructure, and parks and vacant lands cover 100 acres.

Low elevation and high groundwater levels influence infiltration capacity and efficiency of the drainage system. Hoboken has shallow groundwater water tables especially in the lower parts of the city. It is uncertain how the groundwater tables relate to the water level of the river. Expected is that the groundwater does not receive much seepage water from the Hudson River.

Integrating storm water management and urban planning is important to create a sustainable living environment. Although models are of increasing importance to derive effective solutions to structural operational problems, technical measures alone are not sufficient. Several frameworks have been developed in order to design urban resiliency strategies. The Blue Green Dream project includes a framework to compose effective packages of blue-green measures from the large supply of available adaptation measures. The Urban Climate Framework is a theoretical framework and practical tool to get a grip on the urban complexity and climate change effects is developed. Both the Blue Green Dream Adaptation Support Tool and the Urban Climate Framework will be used in the coming chapters to analyse the existing urban (water) system.

Chapter 3 Blue-Green Measures

3.1. Adaptation to climate change in urban areas

Increasing urbanisation and growing awareness of climate change, impact on both humans and ecosystems, and put a worldwide pressure on improving water management and urban resilience (Fletcher, et al., 2014). In recent history, flooding was attempted to be prevented by "hard" infrastructural interventions, like separating combined sewers, expanding treatment capacity, expanding storage capacity in the sewer system or by improving the pipes system (American Rivers, ASIWPCA, NACWA, & et. al, 2008). Research on improved concepts for urban flood and water management showed the benefits of blue and green adaptation measures, which aim to recover the natural water cycle in urban environments by building with nature (van de Ven, 2013).

Blue-Green Measures is an overarching term for blue and green adaptation measures, highlighting the importance of combining storm water management, climate adaptation and multifunctional green space. Green measures refer to building with nature in the city. By utilizing soil and vegetation; the infiltration, retention and detention capacities can be enlarged (Voskamp & van de Ven, 2014). Examples of green measures are parks, urban forests, wetlands, green roofs and green walls. Blue measures refer to the creation of water storage possibilities in urban areas. Blue measures include for example water squares, blue roofs, and storage beneath parking garages. The main advantage of combining both blue and green measures is its multifunctional applicability to urban climate change mitigation and improving urban quality (Grant , 2010; Kazmierczak & Carter, 2010; Pötz & Bleuze, 2012; van de Ven, 2009). Figure 21 gives an example of the combination of both blue and green measures.

Figure 21 Example of a set of urban blue-green solutions in Singapore (source: Atelier Dreiseitl)

3.2. Benefits of blue-green measures

Blue green measures have gained attention for multiple benefits they provide in urban areas. Blue solutions benefit in particular problems related to flooding. Green solutions with vegetation improve the infiltration and buffering capacity, and provide shade and cooling by evaporation. Demurze et al (2014) developed a framework to categorize the physical benefits related to climate change mitigation and improvement of the physical environment of urban areas

- Flooding and peak flow mitigation
- Prevent drought
- Thermal comfort, reduced energy use
- Improved water quality
- CO_2 reduction
- Improved air quality

Not only physical benefits, but also social benefits are related to blue-green adaptation measures. During periods of heat stress, urban green spaces can alleviate thermal discomfort. They provide recreation benefits, could be used for food production, can be an opportunity to educate on climate change adaptation. Also may blue-green measures increase biodiversity, create more valuable land (up to 30% increased value), it provides biomass for energy production, and it creates opportunities for food production within cities, like urban (roof) farming. Ultimately, the appearance of green areas and water in the city provides a more pleasant living environment (Pötz & Bleuze, 2012; Foster, Lowe, & Winkelman, 2011; EPA, 2008; Breil, 2014). Green urban surroundings encourage people to go outside and be more active in terms of walking and cycling (Coombes, Jones, & Hillsdon, 2010). Neighbourhood green space enhances health by mitigating stressful life events (van den Berg, Hartig, & Staats, 2007). Opportunities to socialize in green areas may be particularly important for more vulnerable societal groups.

Drought stress is caused by reduced precipitation and increased evaporation due to higher temperatures. Periods of drought result in smaller stream flows, leading to water shortages (IPCC, 2013). Droughts in combination with low infiltration capacity can also lead to decreasing groundwater levels causing ground subsidence, especially in peat soil (van de Ven, 2011; Rotman, 2004). Damage to buildings and infrastructure is a common effect. Decreased groundwater levels may affect the water requirements of vegetation and can lead to rotten wood pilings in building constructions (Shoham, 2006; Leenaers, 2006). Storing water can deal with the temporal variation of water surplus and water shortage.

Blue-green measures improve the water quality by removing suspended solids, nutrients, hydrocarbons, and heavy metals (Demurze, et al., 2014). The efficiency of removal depends on the pollutant type, vegetation type, soil properties, fertilizer addition and climate (Demurze, et al., 2014). By reducing the urban air temperature, it benefits energy use and thermal comfort. The urban heat island (UHI) effect exists in dense urban areas due to more heat retention of buildings and large areas of concrete and asphalt, combined with less vegetation and water to provide cooling, (EPA, 2008; van de Ven, 2009). Impacts from the urban heat island range from heat related death, exhaustion and disease to comfort (f.e. lack of sleep) (IPCC, 2013; Helfand, 2012). Through adding trees, vegetation and open water to the urban streetscape, shade will be provided to buildings and the air will be cooled through evaporation. Green roofs often reflect more sunlight than conventional rooftops (Santamouris, 2014). They cool the air via evapotranspiration, and reduce energy demands via cooling and isolation (Demurze, et al., 2014; Santamouris, 2014).

Rapid urbanization has resulted in increased air pollution in major cities. This relates to one million premature deaths, and one million pre-native deaths each year (UNEP, 2012; Kura , Verma , Ajdari , & Iyer , 2013). Blue-green adaptation measures absorb pollutants. The amount of pollutants absorbed varies by vegetation (Demurze, et al., 2014). Also within grasses one type is more effective than the other, which can be an important consideration when speaking of green roofs Green walls are even more efficient (Demurze, et al., 2014).

The increase of CO_2 in the atmosphere is mainly caused by emission through human activities. CO_2 is naturally present in the atmosphere as part of the Earth's carbon cycle. CO_2 is consumed from the atmosphere by plants. Permafrost, forests and dead organic material (including peat and fossil fuels) contain high concentrations of CO_2. When it disappears by melting, cutting or burning, the CO_2 ends up in the atmosphere. Green adaptation measures contribute to CO_2 reduction as it directly removes CO_2 from the atmosphere via photosynthesis (by day) and respiration (by night).

3.3. Classification of adaptation measures

A long list of blue and green adaptation measures for urban areas has been developed in the past decades. In 'Appendix II Blue green measures', all adaptation measures that are suitable for Hoboken are illustrated. To make the available measures more accessible to use, they are classified based on three categories of distinction:

Retention or detention measures

The first category of distinction is how a measure deals with rainfall runoff. Therefor a differentiation between retention and detention measures is made. Retention measures can store and slowly infiltrate it into the ground. Retention measures have no connection to the sewer system. Infiltration retention measures directly infiltrate water and do typically not contain water. Storage retention measures are natural storage basins that are always filled with water and have a low infiltration capacity. Detention measures can store water during and right after a storm event and slowly release it to the sewer system. Both measures store (non-potable) rainwater that is disconnected from the sewer system.

Surface, subsurface or aboveground measures

The second category of distinction is location of the measure: on the surface, in the subsurface or above the ground. Surface measures on the surface and often contain vegetation and have big influence on the areas' liveability. Subsurface measures are beneath the ground, and are often constructed below existing buildings or recreational areas. Examples are storage below parking garages, storage in basements, or storage below sport fields (with impermeable cover). Green-and blue roofs, green facades and trees are examples of above ground measures. Green facades and trees can harvest rainwater to decrease peak rainfall runoff.

Private, street, neighbourhood or city scale

The third category of distinction is the scale in which the measures can be applied. Private scale measures decrease runoff on private or industrial lots. Measures are for example green and blue roofs, unpaved private gardens, and rainwater tanks. Block scale measures consider clusters of private or public lots, for example water squares, storm water flow-through planters, subsurface storage and permeable pavement. On district scale, effective measures include parks, urban agriculture, wetlands, retention-, and detention ponds. The connection of green and blue areas between blocks citywide will increase the individual effects of blue-green measures (Pötz & Bleuze, 2012).

The first two categories of distinction are summarized in Table 2. The distribution of the measures based on type of land use will be discussed in paragraph '4.2 Functional analysis of the area'.

Table 2 classification of adaptation measures

	Street level (Surface)	Subsurface	Above ground
Infiltration retention	Parks and urban forests; urban agriculture; Storm water flow-through planters; Bio retention garden; Bio retention swales; Permeable pavement; Storm water trees;	Subsurface storage with retention capacity;	Green facades; Trees; Green Roofs;
Storage retention	Urban wetland; Seasonal Storage and rainwater harvesting; Retention storage basins		Rainwater tanks;
Detention	Water square; Surface detention ponds;	Subsurface storage tanks;	Blue roofs;

3.4. Performance Indication of available blue-green measures

The adaptation performances for both physical benefits (flood mitigation and improvement of the physical environment) and social benefits of the adaptation measures are summarized in Table 3. The measures are colored light to dark based on their expected adaptation performance in Hoboken. The best performing adaptation measures are colored dark grey and the least performing white.

Table 3 Adaptation performance of blue-green measures available for Hoboken

	Physical benefits								Social benefits	
Measure	Flood mitigation		Improvement of the physical environment							
	Flood volume reduction	Peak flow reduction	Thermal comfort	Drought Reduction	Air quality	Water quality	Increase bio-diversity	Reduce noise	Aesthetic amenities	Recreation
Parks and urban forests	■	■	■	■	■	▨	■	■	■	■
Urban farms	■	■	■	▨	■	▨	▨	▨	▨	▨
Storm water flow-through planters	▨	▨	░	■	▨	■	░	▨	▨	░
Permeable pavement	▨	▨	░	▨	░	■	░	■	░	░
Green roofs	▨	■	■	░	▨	░	░	▨	▨	■
Blue roofs	▨	▨	□	□	□	□	□	□	□	□
Seasonal Storage	■	▨	░	■	░	▨	░	░	░	▨
Rainwater Harvest	▨	▨	□	░	░	░	░	░	░	░
Detention ponds or tanks	■	■	□	░	□	□	□	□	□	□
Green facades	░	░	■	░	▨	░	░	■	▨	░
Retention ponds	■	■	■	■	░	■	▨	░	▨	▨
Add green to street scape	▨	▨	■	▨	▨	░	░	░	▨	░
Artificial urban wetlands	■	■	■	■	▨	■	▨	▨	■	▨
Hollow Roads	□	■	□	□	□	□	□	□	□	□
Storm water trees	▨	▨	■	▨	■	▨	▨	▨	▨	░
Open channel water	■	■	░	░	░	░	░	░	▨	□
Bio retention swales	▨	▨	▨	▨	▨	■	▨	▨	▨	▨
Rain gardens	▨	■	▨	▨	▨	■	▨	░	■	░

3.5. Tools to integrate blue-green measures in urban drainage

There has been rapid growth in the use of terms capturing sustainable urban drainage (Fletcher, et al., 2014). There are no substantive differences in the content of these systems. An often-used Scandinavian term for blue-green networks is ‘Green Urban Infrastructure’ (GUI) (Naumann, et al., 2010; Pauleit, Liu, Ahern, & Kazmierczak, 2011). The term ‘Sustainable Urban Drainage Systems’ (SUDS) is commonly used in the United Kingdom and uses the concept of the sustainable drainage triangle (quantity, quality, habitat/amenity), developed by D’Arcy (1998). The Australian ‘Water-Sensitive Urban Design’ (WSUD) has the objective to “manage the water balance, maintain and enhance water quality, encourage water conservation and maintain water-related environmental and recreational opportunities” (Fletcher, et al., 2014). North America and New Zealand speak of ‘Low-Impact Developments’ (LID). LIDs are defined as an approach attempting to minimize the cost of storm water management by taking the “design with nature approach” (Fletcher, et al., 2014). North American ‘Best Management Practices’ (BMP), intent focuses on pollution prevention of the water system and includes both non-structural (operational or procedural practices) and structural (engineered or built infrastructure) attributes (Fletcher, et al., 2014). This wide range of approaches for sustainable urban drainage shows how blue-green measures have been widely accepted as an opportunity for integrated urban design.

3.6. The Blue-Green Dream Adaptation Support Tool

The Blue-Green Dream (BGD) paradigm is a new framework to better combine urban water management and green spaces in their existing ways of planning designing, constructing, operating and maintaining (BGD, 2013). It enhances the synergy of urban blue and green systems, in order to increase hydrological performance, adaptability and stakeholder acceptance and mitigate climate change. The BGD Adaptation Support Tool (AST) is a visual MapTable-based application. It consists of two main components: a ‘Rapid Evaluation Tool’ and a ‘Dynamic Evaluation Tool’ (Figure 22) (BGD, 2013). The AST in this research is used to select suitable adaptation measures for the Hoboken design strategies.

The rapid tool supports the cooperation between urban planners, engineers, ecologists and policy makers. It helps users to select a range of preferred measures. Ranking is based on site-specific conditions and their expected performance in terms of climate adaptation and multi functionality of land use (Voskamp & van de Ven, 2014). As a starting point from the map-table, a number of requirements need to be drawn. These include:

- The importance of multi-functionality of the land [scale 0-1]
- Scale level under consideration [building, street, neighbourhood, city]
- Area slope [sloping area, flat area on high ground, flat area on low ground]
- Soil type [sand, peat, clay, bedrock]
- Existing land use [buildings, paved surface, private green space, green space for recreational use and urban farming, green space with no recreational use, grey or green space for sports or playgrounds, open water]
- Surface characteristics [roof slope less than 35 degrees, flat roofs, no flat roofs/roof slope less than 35 degrees]
- Subsurface depth available with no constraints is available on average? [less than 0.6m, 0.6-1m,1-1.5m, more than 1.5m or less than 2 ft., 2-3.3ft., 3.3-4.9ft., more than 4.9ft.]
- Required system capacities; threshold capacity (prevention) and coping capacity (coping) [heat stress prevention, heat stress coping, drought prevention, drought coping, pluvial flood prevention, pluvial flood coping]

The tool includes 46 adaptation measures. Based on the size of every measure (f.e. area and depth of the measure), it's contribution to climate change mitigation (storage capacity, heat reduction (°C), peak flow reduction and drought reduction), water quality, biodiversity and economic benefits is calculated. The Rapid Evaluation Tool outcomes are the input for the 'Dynamic Evaluation Tool'. A dynamic hydrological model can provide improved performance estimates of the set of blue-green measures that is included in the design.

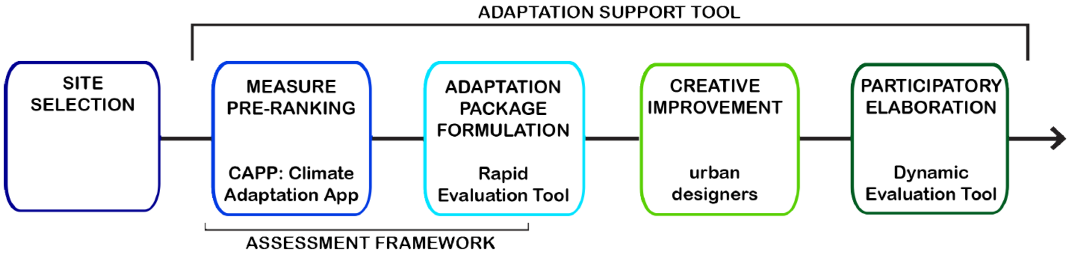


Figure 22 The BGD Adaptation Support Tool (BGD.com, 2014)

3.7. Blue-Green Implementation and policy

The cooperation between urban planners, water management engineers and architects provides opportunities, but also makes implementation more difficult. This relation has long been ignored, but in recent years its importance got recognized again. In the Netherlands, climate change and water management found its way into national policymaking and new planning and design concepts for urban development. A water assessment is obligatory for spatial planning and decision-making, so that water is implemented already early in the design process (Ministry of Infrastructure and the Environment, 2003). The basic principles of the Dutch Water Agreement, which intends to make use of water in a sustainable way, are signed up to the National Administrative Agreement on Water (Government of the Netherlands, Union of Water Boards, Interprovincial Agreement, & Association of Dutch Municipalities, Updated in 2008 and 2011).

Although many countries are adopting new national approaches to integrate water management and urban planning (paragraph **3.5. Tools to integrate blue-green measures in urban drainage**), the United States hasn't. Their federal water policy wasn't updated to deal with national and global challenges in climate change and urbanization since the 1970's (Christian-Smith & Gleick, 2012). In the United States, urban planning (or zoning) is controlled by local governments (i.e. counties, municipalities), but may be determined or limited by state or national planning authorities. The process of implementation, in which domains like governance, stakeholders, engineering, ecology, spatial planning, urban design and management are involved, influences the performance and success of adaptation measures at different locations.

3.8. Conclusions on Urban Blue Green measures

Blue-Green measures is an overarching term for adaptation measures that aim to solve urban and climatic challenges by re-building urban areas with nature. Plenty of adaptation measures have been developed to provide resiliency and adaptation to flood events. The multi functionality advantages also include drought and heat stress reduction, reduced energy use, CO_2 reduction, improved water quality, improved air quality, efficient use of limited space, and creating a better live-able city.

A wide range of approaches for sustainable urban drainage shows how blue-green measures have been widely accepted as an opportunity for integrated urban design. The Blue-Green

Dream (BGD) paradigm is a new framework to better combine urban water management and green spaces in their existing environment. The aim is to increase hydrological performance, adaptability and stakeholder acceptance and mitigate climate change. The BGD Adaptation Support Tool (AST) is a visual MapTable-based application, and used to select suitable adaptation measures for the Hoboken design strategies.

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2

Analysis of the water system

The analysis of the water system creates general understanding of the current water system behaviour. ‘Chapter 4 Water System Analysis Hoboken’ overviews historical research, provides a functional analysis, calculates the water assignment and selects suitable adaptation measures for the Hoboken design strategies. ‘Chapter 5 testing the Design Strategies’ includes the design of a dynamic hydrology-hydraulic water simulation model to test the effectiveness of the design strategies on storm water flood nuisance reduction.

Chapter 4 Water System Analysis Hoboken

The water system analysis provides a technical background to understand the urban storm water and ground water system in Hoboken. In a functional analysis, characteristics of Hoboken regarding subsurface, infrastructure, public space, buildings, metabolism and people are identified. The water assignment is calculated to give an approach of the required storage capacity of the water system. Based on area characteristics, the best fitting blue-green measures for the urban typology of Hoboken were selected.

4.1. Research to flooding in Hoboken

In the current situation, Hoboken has water in the streets once or twice per year (EmNet, 2013). Future regulations may require the North Hudson Sewerage Authority (NHSA), to reduce the flood frequency to an average of once every 4 years (T4 return period) (HobokenNJ, 2013). The preferred T10 drainage capacity (5.0 inch in 24h) even corresponds with a required T10 storage capacity (FHWA, 2001).

To identify bottlenecks in the system, a number of historical sewer system analyses have been carried out. In 2002, a detailed flood analysis was done by the NHSA for the south-western part of Hoboken (NHSA, 2002). The hydraulic and hydrological analysis was conducted using SWMM. To better understand the storm water flood problems, EmNet carried out a rough study of the hydraulics of the whole collection systems in 2011 (EmNet, 2011). In 2008, the NHSA decided to build four wet-weather pumps to alleviate most of the flooding in Hoboken. The first wet weather pump started operating in 2011. In 2013, the Hoboken Green Infrastructure Strategic Plan researched the possibilities for redevelopment and rehabilitation areas to provide large-scale opportunities to integrate green infrastructure (HobokenNJ, 2013). In that same year, EmNet carried out a study in order to examine the benefits of the in 2011-installed H1 wet weather pump (EmNet, 2013). The results from all previous studies are shortly summarized below in order to better understand the current drainage system and flooding situation in Hoboken.

The 2002 hydraulic analysis was conducted for the south-western, flood prone part of the city (H1 drainage area). CD2MHILL developed a sewer model in SWMM for the NHSA in 1966 (NHSA, 2002). This storm water model showed that during a 3-month storm, already severe flooding up to 1.5 feet occurred in the H1 drainage basin (NHSA, 2002). The area of southwest of Hoboken is vulnerable to flood till the point that emergency vehicles may not be able to get through. One of the recommendations from the report was therefor to increase road elevations up to the level of hydraulic grades. This would increase inflow of storm water into lower lying properties. Sump pumps were proposed to these properties to withstand 1-year storms (NHSA, 2002). Another long-term recommendation was to add sub-surface storage capacity in the south-western part with pumps to discharge the water back into the sewer system once the storm is over (NHSA, 2002). Both proposals have not been implemented yet.

Research by EmNet in 2011 let to better understanding of the historical flooding problems and bottlenecks in the city sewer before installation of the first wet weather pump in 2011 (EmNet, 2011). The three main goals were to determine the outfalls that overflowed during observed storm events, the impact of interconnections between drainage areas on floods, and the locations where additional means were needed to reduce vulnerability to flooding (EmNet, 2011). An extensive sewer monitoring system was installed to gather data throughout the system. The first conclusion of the report was that all of the detected floods during medium storms occurred in the H1 drainage area. The second conclusion was that southern regulators were unable to overflow during medium storm events (with a return period of less than five years), causing floods in the H1 drainage area. The third conclusion was that flooding was detected in the H1, H4, H5 and H7 drainage areas during large storm events (return periods of more than five years). The final result showed that the southern regulators were unable to overflow during large storm events (EmNet, 2011).

The in 2011 built H1 wet weather pump significantly improved the flooding situation, but was not able to solve the whole flooding problem. This was showed in research by EmNet in 2013 (EmNet, 2013). After installation of the pumping station with a 50 MGD design capacity (two pumps with each a capacity of 50 MGD or 93cfs or 1141m^3/hr)), floods were still detected in the H1, H4 and H5 drainage areas during large storm events (EmNet, 2013). In some cases flooding also occurred in the north western H7 basin. All of the detected medium storm events caused floods in the H1 drainage area. Interconnections between the sewer sheds were assumed to be an explanation for this (locations of interconnections were shown in figure 19). EmNet therefor studied several flood adaptation measures for Hoboken, including additional storage, wet weather pumps, and rainwater infiltration. The research found that the area characteristics of Hoboken caused many constraints for implementation of these types of measures. Storage is difficult due to high water tables in combination with low surface elevation. Above ground storage was discouraged due to high urban density. EmNet therefor proposed additional pumping in the H5 drainage area as being the most effective measure. This pump was required to prevent flooding in all but the largest observed storm event, if the additional capacity were 65 million gallons per day (EmNet, 2013). In August 2014, New Jersey's Governor Chris Christy approved an $11.7 million dollar loan for a second wet weather pumping station (Eisenberg, 2014). This station is to serve the H5 drainage area and includes a wet weather pump equipped with two 42MGD pumps, an electrical room, and a standby generator for in case of power outage (Eisenberg, 2014). Mayor Zimmer added that the city is still looking for ways to improve the storage capacity, which raised the idea to build a 10 million gallon storage tank in the northwest of the city (Eisenberg, 2014). This proposal is still to work out, but shows the willingness to progress in the redevelopment progress.

After Sandy, progress was made in terms of getting people prepared with emergency supplies in case another storm would hit the city. Hoboken residents were encouraged to subscribe to the National Weather Service (NWS) to receive alerts and warning information for extreme weather (HobokenNJ, 2013). In 2013, the Hoboken Quality of Life Commission (QLC) sent out a list of tips to prevent and deal with flooding in private homes and businesses (TheBoken, 2013). Examples of these measures include the installation of a small sump pumps (3,600 gallons per hour) and sand bags to create flood barriers around private properties. Also were residents encouraged to replace existing concrete in front of buildings by installing tree pits, place rain barrels to collect run off from roofs (with minimum volume 50 gallons), install a drywell, replace sidewalks and driveways with pervious pavement, or install green roofs (TheBoken, 2013). The Federal Emergency Management Agency (FEMA) has updated her preliminary flood maps for Hoboken (and multiple other areas) to provide the most accurate updated flood risk information (TheBoken, 2013).

4.2. Functional analysis of the area

To select appropriate blue-green measures for Hoboken, a functional analysis of the area was done using the six-layer approach (Maring & Hooimeijer, 2013). The approach aims to better integrate urban planning and subsoil characteristics and gives an overview of the opportunities and constraints in the area. Subsurface, infrastructure, public space, buildings, metabolism, and people are the six layers of the approach, visualized in Figure 23. The natural and technical boundary conditions of the different layers are illustrated for different themes (Maring & Hooimeijer, 2013). Urban development with understanding of the natural (subsurface) system will improve spatial quality, sustainability, and cost-effectiveness during maintenance (Maring & Hooimeijer, 2013).

Subsurface

The subsurface system, which includes subsoil, water, energy, and civil constructions, addresses a number of chances, obstacles, requirements and points of attention (Maring & Hooimeijer, 2013). The natural flow directions in Hoboken based on natural elevations is specified in Figure 24. The red dots show the outlet points of the natural watersheds. These are important indicators to uncover natural streams or to indicate water storage locations. The water systems have changed over time, from meandering tributaries to a piped sewer system. Flood prone zones are there for more spread out. The grid structure of the roads in Hoboken indicates the subsurface infrastructure (pipes and cables), which follows the same grid pattern.

Opportunities for blue-green measures in the subsurface:

The Hoboken soil has low infiltration capacity. Due to low elevation and high groundwater level, subsurface storage is almost impossible. Subsurface storage in elevated areas, where groundwater is no threat, could be a possibility below sports fields and buildings.

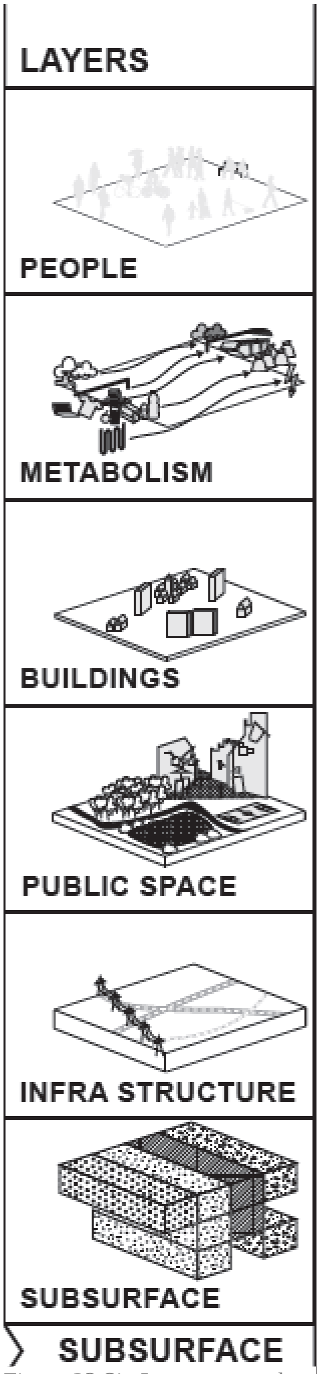


Figure 23 Six Layer approach (source: Maring & Hooimeijer, 2013)

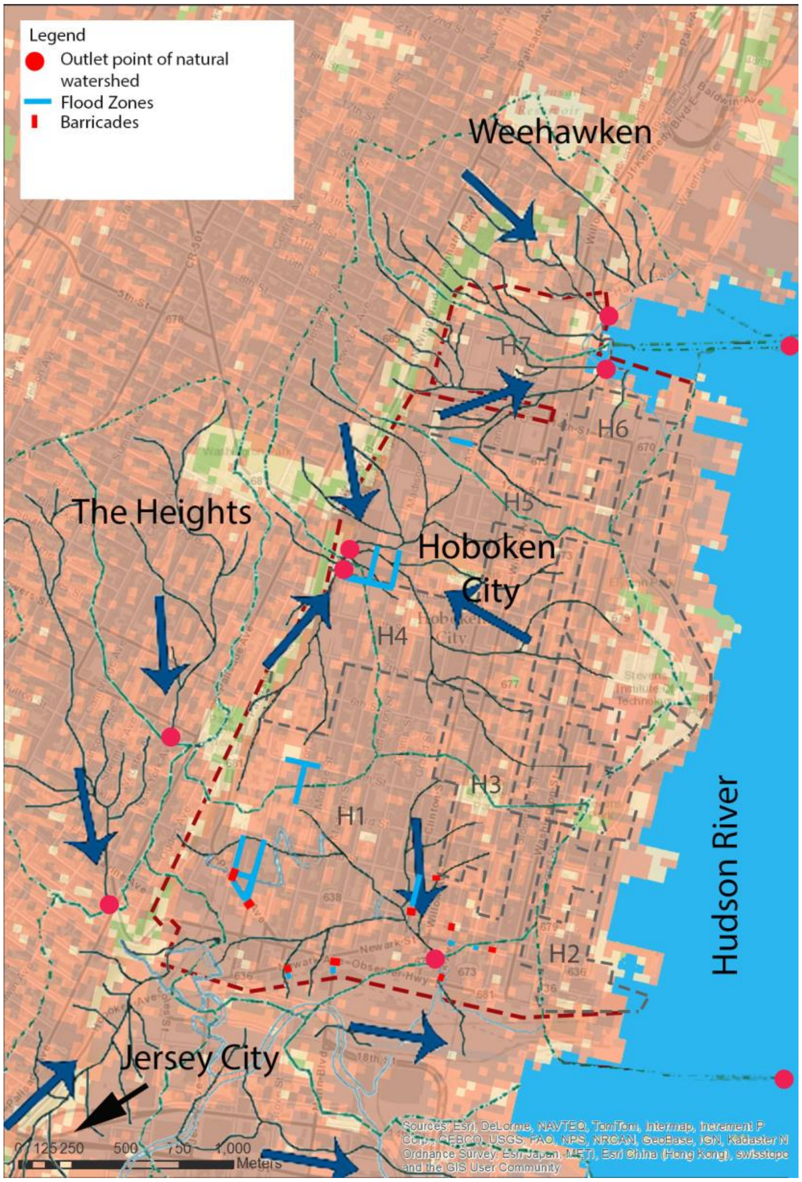


Figure 24 Natural storm water flow directions and storm flood zones
(Illustration by author; based on Bykowski, 2013 and City of Hoboken, 2010)

Infrastructure
Hoboken has the highest transportation use of any city in the United States (HobokenNJ, 2014). An overview of the Hoboken infrastructure is visualized in Figure 25. The New Jersey transit train surrounds the Hoboken infrastructure grid along the steep Palisade cliffs. The 14th Street Viaduct connects Hoboken to the Paterson Plank Road in the Jersey City Heights (Union City). Newark Street is the main road to enter Jersey City (Newark) from the south of Hoboken and Willow Avenue to enter Weehawken from the north of Hoboken. The Lincoln tunnel (Weehawken) and the Holland tunnel (downtown Jersey City), north and south of Hoboken, connect New Jersey to New York.

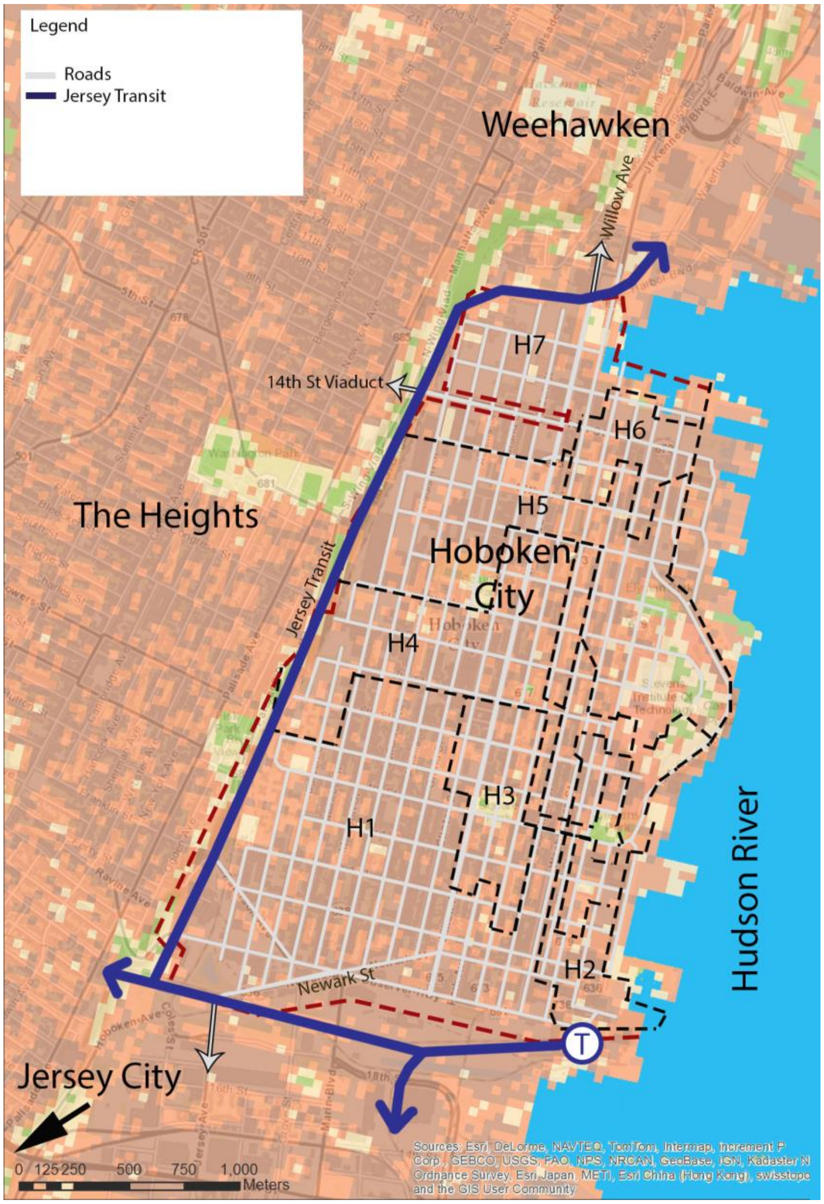


Figure 25 Infrastructure Hoboken (illustration by author)

The main roads in Hoboken, running from north to south, have a width up to 65 feet (20 meters, four driving lanes and two parking lanes). The smaller roads, in the east-western direction, have fewer lanes. Especially wide roads suffer from pedestrian safety problems due to high volumes and speed of traffic (City of Hoboken, 2010). This safety problem can be a unique opportunity to upgrade (segments) of these roads by applying infiltration measures and green areas. Also pavement with higher permeability then concrete, like Belgian block, can be applied to reduce vehicular speeds (Department of Transportation and Parking Hoboken, 2011). The major transportation hub is the Hoboken train station in the southeast of the City, which transports more than 60,000 people daily (NJtransit, 2014). This station serves PATH (Port Authority Trans Hudson), various NJT buses and private bus lines, New Jersey Transit (NJT) rail lines, the Metro-North Railroad line, and NY Waterway operated ferries (NJtransit, 2014).

Opportunities for blue-green measures in infrastructure:

Storm water flow-through planters, storm water infiltration trees, permeable pavement, and adding green to streetscape are opportunities for the wide roads in Hoboken. Especially the major north-south roads are suitable for infiltration measures.

Public space

Hoboken is known as a vibrant urban destination with a rich history, offering considerable cultural, recreational and commercial development (HobokenNJ, 2014). The original Hoboken street grid from the 19th century included four parks: Church Square Park, Columbus Park, Elysian Park and Stevens Park. Plenty of new parks have been constructed after, often designed in the existing grid. The beautiful waterfront of Hoboken, with great views over Manhattan (Figure 26 and Figure 27), contains plenty of open spaces and parks. The promenade along the riverbank is part of the Hudson River Waterfront Walkway, a state-mandated master plan to create an 18-mile urban linear park from the Bayonne Bridge to the George Washington Bridge, offering great views over the Lower Hudson (HobokenNJ, 2014).

Figure 26 Hoboken waterfront Park; left: view over Hoboken Terminal (source: EdC, 2011) right: view over Manhattan (Source: Hoboken Brownstone, 2014)

In 2004, a master plan for urban development was prepared with a great deal of public input (City of Hoboken, 2010). Parking and traffic were the main problems discussed in the report. Everyone who was involved agreed that the city needed more recreational acreage. The existing 30 acres of park in 2004 (equivalent to 0.78 acres per 1,000 population), were then proposed to be extended with an additional 60 acres (City of Hoboken, 2010). This included a complete waterfront walkway with parks and piers, new parks, ball fields and other recreation facilities in parts of the City with severe shortage of open space. Only 10 acres of this plan was realized. Currently, Hoboken has about 40 acres of open space, an average of 0.96 acres per 1,000 residents (HobokenNJ, 2014). This is still low compared to, for example, New York City, which has 2.5 acres per 1,000 residents (City of Hoboken, 2010). From the open space acreage of 40 acres, 22 acres are within the Hoboken sewer drainage basins (H1-H7), the other 18 acres are along the waterfront and drain storm water directly into the Hudson River.

Opportunities for blue-green measures in public space:

Parks, storage below sports fields, water squares, and green squares are measures suitable for the elevated areas. In the low-lying areas, like the green area along the Palisade Cliffs, it is almost impossible to infiltrate and store water in the subsurface. These areas though can be shaped with open water bodies or urban wetlands.

Figure 27 View from Hoboken over Manhattan (Picture made by author)

Buildings

Hoboken is listed 4th in the United Stated on urban density. 56 percent of its working residents use public transportation every day (Forbes, 2011). Buildings are mostly residential and low-rise (City of Hoboken, Hoboken , 2014). The most important public buildings are the Hoboken terminal station, the hospital, the police station, the EMT (Emergency Medical Technician) building, several schools and a number of fire stations. An overview of this vital infrastructure, together with flood prone locations, is specified in Figure 28.

Opportunities for blue-green measures on buildings:

Feasible opportunities are rainwater harvesting (tanks), green roofs and green facades (vegetated walls). These can be applied to large, public buildings, or private buildings. In case of private buildings, participation of residents and governmental subsidies are required.

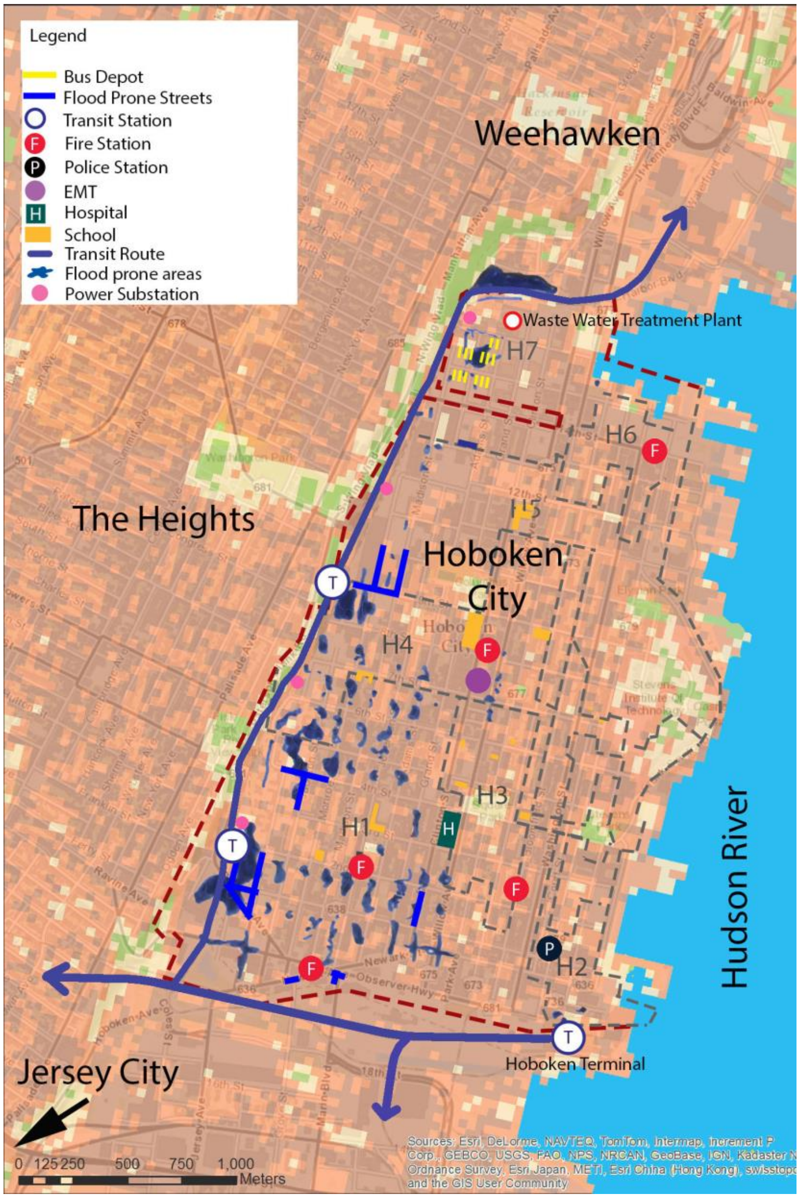


Figure 28 Vital infrastructure (illustration by author, based on HobokenNJ, 2013)

Metabolism

In 2014, Hoboken developed a program to increase urban sustainability (HobokenNJ, 2014). Goals within this program are to increase energy efficiency, minimize waste streams, encourage sustainable land use and development, mitigate greenhouse gas emissions, mitigate air quality impacts, stimulate sustainable job creation, engage Hoboken’s community in sustainable initiatives, and reduce vehicle miles traveled (VMT) by encouraging walking, cycling, mass transit and car sharing. Examples of current sustainability projects are waste recycling, a farmers market with fresh and locally grown products, and the planting of trees for climate change mitigation (HobokenNJ, 2014).

Opportunities for blue-green measures regarding metabolism:

Open space, fallow grounds and large flat roofs are suitable for urban agriculture. This can be applied in the form of community farms, commercial farms, Institutional farms, and community gardens, to produce locally grown fruits and vegetables. A network of waterways to connect water bodies can be applied to increase the storage capacity of individual measures in the system. Hollow roads and adding green to the streetscape can be used to create a blue-green network through the city.

People

Public participation in planning and decision-making is the norm in the United States (Bassett, 2011). Citizens, residents, and affected stakeholders desire and expect to be involved in public deliberations (Bassett, 2011). The Hoboken City Council design processes are extensively community-driven. Hoboken residents are regularly invited to open public meetings and stakeholder groups to discuss new proposals and designs for urban development (HobokenNJ, 2014).

Opportunities for blue-green measures regarding people:

With the participation of residents, opportunities can be created for urban farms and common gardens. Hoboken residents are very much involved with urban developments, especially when it accounts flood mitigation. Private and community initiatives, like rainwater harvesting in tanks, green roofs and green gardens can be supported by governmental grants and on large scale can significant mitigate flooding.

Summary of six-layer approach results

The six-layer approach gives an overview of appropriate blue-green measures for Hoboken, based on opportunities and constraints from both surface and subsurface layers. Table 4 summarizes the results of the six-layer approach for Hoboken as described above.

Table 4 Results of six-layer approach for Hoboken

Layer	Blue-green measures
Subsurface	Subsurface detention storage;
Infrastructure	Storm water flow-through planters; (storm water infiltration) trees; permeable pavement;
Public Space	Park; water/green square (with fountain); detention below sports fields; open water; Urban farming
Buildings	Rainwater harvest tanks; blue and green roofs; green facades; urban farming on rooftops
Metabolism	Network of waterways; network of green systems, hollow/inclining road; add green to streetscape
People	Common gardens

4.3. Urban water Assignment Hoboken

The relation between precipitation depth, storage, and storm water discharge is important to understand the behaviour of the drainage system. The water assignment isn't normative. It does not take detailed area characteristics, elevation profile and sewer layout into account and therefore cannot determine the locations where flooding occurs.

Storage and discharge are exchangeable (van de Ven, 2013). All water that cannot (temporarily) be stored needs to be discharged to prevent flooding and vice versa. The urban water assignment gives an overview of the required storage capacity of the drainage system for a sustainable future. The base of the technical assignment focuses on surface water, water quality and ground water (van de Ven, 2013). For that the urban water balance factors are included: precipitation, groundwater seepage and infiltration, retention and losses, storage capacity and discharge capacity. The overall discussion of the water assignment is described in this paragraph. Additional information is specified in Appendix IV Water Assignment calculation.

Return Period	Precipitation Depth [inch/24hr]
T1	2.72
T2	3.29
T5	4.20
T10	4.97
T25	6.11
T50	7.09
T100	8.16

Table 5 Return Periods based on DDF curves for 24-hours of precipitation (source: noaa.com)

The reoccurrence of rainfall events in Hoboken is expressed in return periods with Depth-Duration-Frequency (DDF) curves in Figure 29 (NOAA, 2014). The DDF curves include cumulative rainfall depths with return periods of 1, 2, 5, 10, 25, 50 and 100 years with five days durations. The 24-hour return periods of the precipitation depths associated to the DDF curves are summarized in Table 5.

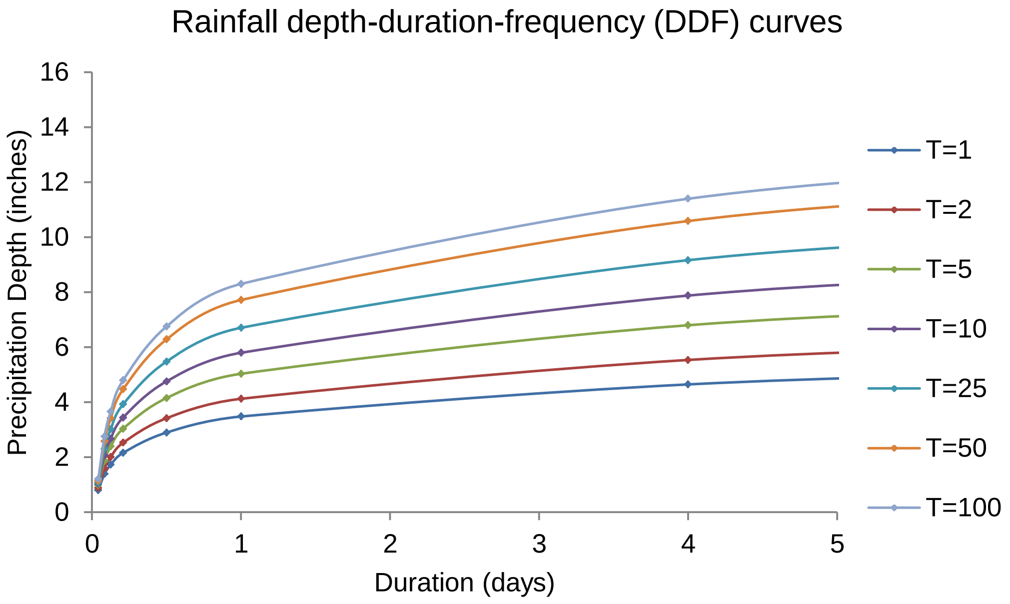


Figure 29 Rainfall Depth-Duration-Frequency-Curves for Hoboken (source: NOAA, 2014)

Since no open water exists, the total available storage capacity is only the sewer system capacity. Sewer storage values per sub basin were calculated from the sewer dimensions and given in Table 6. The assumption of full pipe storage is not typically valid, because the purpose of the pump station is to prevent the sewer pipes from filling up (EmNet, 2011). Normally, the pipes should only be half full to two thirds full at the peak of the storm event (EmNet, 2011). When EmNet determined the storage volume for the H1 drainage basin, they determined approximately 3.0MG was available (EmNet, 2011). This corresponds to the calculated storage amount in the table below.

Table 6 Volume of water that can be stored in the sewer (based on full pipe storage)

Sub basin	Sewer Storage [ft^3]	Sewer Storage [MG]	Average Sewer Storage [inch/acre]
H1	401,000	3.00	0.55
H2	33,000	0.25	0.35
H3	107,000	0.80	0.52
H4	240,000	1.79	0.69
H5	160,000	1.20	0.35
H6	12,000	0.09	0.12
H7	160,000	1.19	0.51
Total	**1,112,000**	**8.32**	**0.44**

The total pumping capacity of the system includes both the H1 wet weather pump (2.5 inch/day) and the discharge towards the wet weather treatment plant (1.2 inch/day). Figure 30 specifies DDF curves for T1, T2, T10 and T50 together with the pumping capacity. The water in the sewer below the pumping capacity line is discharged directly by the pumps. The amount of water between the DDF curve and the pumping curve needs to be stored (temporarily) to prevent flooding.

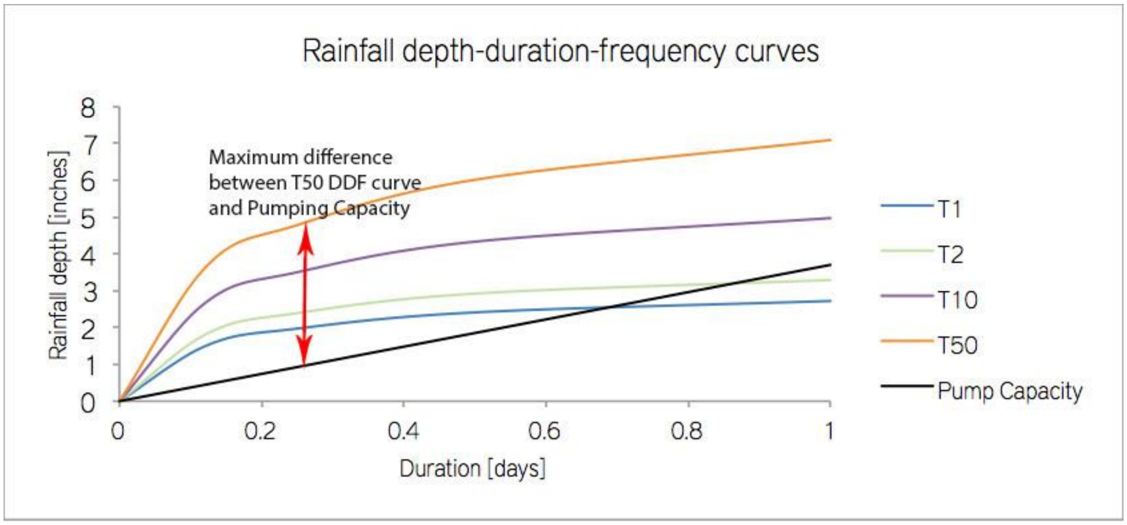


Figure 30 Hoboken wet weather pumping capacity and DDF curves

The relation between storage and discharge as an effect of the rainfall depth can be visualized in Storage-Discharge-Frequency (SDF) curves. The storage capacity was estimated by subtracting the discharge capacity of a wet weather pump (with varying capacity of 0 to 20 inch/day) from the rainfall depth. Storage Discharge Frequency Curves were made for storms with a return period of 1, 2, 10 and 50 years.

The maximum difference between precipitation and storage capacity for T1, and T2 storms was measures after three hours. The maximum difference for T10 and T50 was measures after six hours. The storage capacity is the average for the total drainage area. In the current situation, the storage is 0.5 inch per acre and the pumping capacity 3.7inch per acre per day. The calculated storage values are plotted against the discharge capacity for different return periods in Figure 31. Each point on the line represents the required storage volume for a certain discharge capacity or vice versa.

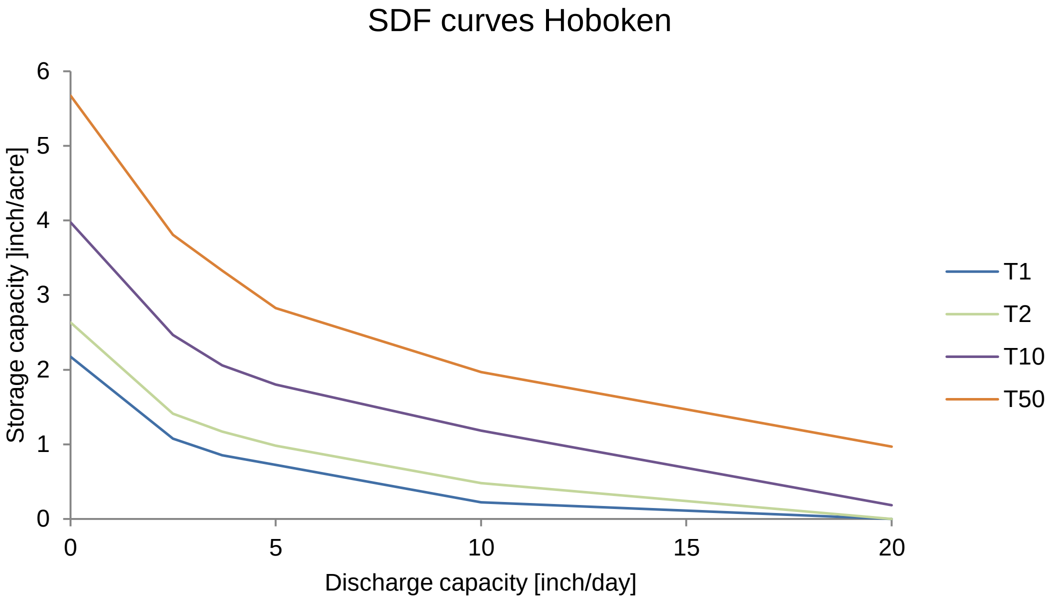


Figure 31 Storage Discharge Frequency (SDF) curves for Hoboken

The SDF curves show that for the current storage capacity in Hoboken of 0.5 inch per acre, the required discharge capacity is 7 inches per day for a T1 storm event. This is twice the current pumping capacity. As estimated by EmNet (2013), flooding indeed occurs about twice a year. With the same 2.5 inch per day pumping capacity, the system would require a lot more storage capacity for a T10 or T100 storm.

With the current pumping capacity, additional five-folded storage capacity is required to resist a T10 storm. With the current storage capacity of 0.5 inch/day, for a T10 storm, a pumping capacity of more than 15 inch per day would be required. Due to interconnections, the calculated volumes per sub basin may differ from the actual volumes. Table 7 summarizes the storage volume calculations with water depths from the SDF curve, based on the actual discharge capacity of 3.7 inch per acre (H1WWP and WWTP). The maximum difference between the precipitation depth and the discharge capacity is used to calculate the water assignment, as shown in Figure 30.

Table 7 Calculated Water Assignments

Return period storm event [year]	Rain depth [inch/ 24h]	Depth water assignment [inch]	Water assignment [cu.ft]	Water assignment [MG]
T1	2.72	0.85	2,265,000	16.9
T2	3.29	1.72	3,106,000	23.2
T10	4.96	2.06	5,458,000	40.9
T50	7.07	3.33	8,821,000	66.0

4.4. Historic Studies for Blue-Green measures in Hoboken

Historic studies have already been done to identify effective sets of blue-green measures for Hoboken. In November 2011, the U.S. Department of Housing and Urban Development (HUD) funded a regional plan to increase flood resiliency in Hoboken, This resulted in the Hoboken Green Infrastructure Strategic Plan. This plan focuses on developing of a framework for green infrastructure on both a city wide and district-by-district basis (HobokenNJ, 2013).

The Green Infrastructure Strategic Plan identifies the most cost-effective best management practices (BMPs) suitable for within the area characteristics (HobokenNJ, 2013). The proposed conceptual framework divides the city into three zones. The grey zone being the area along the riverside, with bedrock in the shallow subsoil, was designed for aboveground BMPs like rainwater harvesting and green roofs. The green zone, the mid-western part, was designed for vegetated BMPs, like rain gardens, swales and storm water trees. The blue zone, the area along the cliff, has the lowest elevations in the city and therefor chosen to store water (HobokenNJ, 2013).

The BMPs in the green infrastructure plan were rated on cost-effectiveness and suitability for the city (HobokenNJ, 2013). The proposed measures included urban wetlands, permeable pavement, storm water street trees, vegetated swales, rainwater detention measures, storage basins or ponds, rain gardens, storm water infiltration/flow-through planters, subsurface storage and green roofs. The most cost-effective BMPs indicated by storage volumes were: constructed wetlands ($1/cu.ft.), permeable pavement ($3/cu.ft.), storm water trees ($6/cu.ft.), swales ($10/cu.ft.), and rainwater harvest and reuse ($11/cu.ft.) (HobokenNJ, 2013). The Green Infrastructure Strategic Plan also quantified the amounts of rainwater to be captured using different measures. Sewer sheds H1, H4, H5 and H7 showed the biggest potential for stormwater storage using green infrastructures.

4.5. Selection of blue-green measures for Hoboken

Four sets of adaptation measures were established using four existing urban water management tools. Table 8 shows a summary of the list of most suitable blue-green measures for Hoboken based on those tools (list of all in Appendix II Blue green measures). The first column shows the measures that were emerged from the Green Infrastructure Strategic Plan (HobokenNJ, 2013). The second column shows the best fitting measures based on area characteristics and technical feasibility estimated by the Blue Green Dream AST (Deltares, 2014). The third column contains the best fitting urban blue green measures based on Urban Green-Blue Grids for sustainable and resilient cites (Pötz & Bleuze, 2012). The last column gives an overview of the most cost effective Best Management Practices for Hoboken as estimated in the Green Infrastructure Strategic Plan. The table is used as a guideline for the establishment of design strategies.

Table 8 Blue-green adaptation measures proposed by different tools

Green infrastructure Strategic Plan Hoboken	Blue Green Dream Rapid Evaluation Tool (best measures first)	Urban Green Blue Grids (focus on water quantity)	Most cost-effective BMPs
Storm water infiltrations planters	1. Adding shrubbery, grass and herbs to the streetscape	1.Green squares, parks and play fields	1. Constructed wetlands
Constructed Wetlands	2. Private green garden	2. Reduce paved surface	2. Permeable pavement
(bio)Swales	3. Urban Agriculture	3. Bio swales	3. Storm water trees
Storm water trees	4. Increase height difference between street level & ground floor level	4. Infiltration basins	4. Swales
Green Roofs	5. Raised curbs/hollow roads	5. Retention basins with green zones	5. Rainwater harvest and reuse
Subsurface Storage (f.e. parking garage, sports field)	6. Intensive/extensive green roofs	6. Seasonal storage	
Basins or Ponds	7. Systems for rainwater harvesting/rainwater tanks	7. Trees and green facades	
Permeable pavement	8. Water Roofs	8. Subsurface storage	
Rainwater harvest and Reuse	9. Green facades		
Rain gardens	10. Porous pavement		
	11. Parks and urban forests		
	12. Infiltration boxes		

4.5. Conclusions of the water system analysis

The water system analysis provides a technical background to understand the urban storm water system in Hoboken. Hoboken has water in the streets once or twice per year. Future regulations may require the North Hudson Sewerage Authority to reduce the flooding frequency to at least once per four years. The by the United States urban drainage design manual preferred T10 drainage capacity even corresponds with a required T10 storage capacity. Flood prone areas and bottlenecks in the sewer system were identified in a number of sewer system analyses that have been carried out.

The sewer system is gravity-based driven. Excess water is discharged into the Hudson River by 8 combined sewer overflows. During high water level, the valves to the river are closed to prevent the river water to flow into the sewer system. When heavy rainfall coincides with high tide, excess water backs up in the sewer, causing in particular the low-lying areas to flood. The H1 drainage basin in the southwest is the most flood prone area. The first wet weather pump, which pumps water in the Hudson River when the valves are closed, started operating in 2011. This pump alleviated the situation, but didn’t prevent the city from flooding. A loan was approved in 2014 to build a second wet weather station.

In a functional analysis, characteristics of Hoboken regarding subsurface, infrastructure, public space, buildings, metabolism and people were identified using the six-layer approach. With the approach, design opportunities and constraints for different layers were identified.

The water assignment was calculated to give an approach of the required storage capacity of the drainage system based on the current situation. Since no open water exists, the total available storage capacity of the system is only in the sewer pipes. This makes the storage capacity of the area 0.5 inch per acre. For a T1 storm event (2.72 inch.24h), the required pumping capacity would be 7 inches per day. This is almost twice the current pumping capacity of 3.7inch per acre per day (the wet weather pump and the waste water treatment plant combined). With the current pumping capacity, the required storage capacity is almost five times the current storage capacity for a T10 storm. This highlights the pressure on the current system and the importance of improving its performance.

Historic studies to identify blue-green measures for sustainable integrated water management solutions are used to compare four different sets of adaptation measures. The suitable measures presented in table 8 are used as a guideline for the establishment of design strategies for Hoboken.

Chapter 5 Testing the Design Strategies

To derive effective solutions to structural operational problems, models are of increasing importance. Especially now that the urban environment is becoming more and more complex, modelling tools are needed to describe and understand water related interactions. Models can be used to evaluate different strategies for urban water management at the planning level. In this chapter, a SWMM rainfall runoff model is designed that will be used to simulate the effects of different design strategies on the current urban water system.

5.1. Introduction to SWMM

SWMM is a dynamic rainfall runoff model to simulate single events or long-term series in primarily urban areas. SWMM can calculate flood volumes and peak flows from the sewer system, but it can also simulate water quality. SWMM was first developed in 1971 and since then has undergone several major upgrades; with the last update of the 5.0 version released in 2014. SWMM5 simulates a number of environmental components: the atmosphere (mainly precipitation), the land surface (the sub catchments), the groundwater (receives infiltration from the land surface), and the transport compartment (contains a network of pipes, channels, storage devices, regulators, pumps and treatment elements) (EPA, 2013).

The hydrological processes are applied to the model through the sub catchments. These have pervious and impervious surface. Pervious areas have losses due to infiltration. Impervious areas have losses due to depression (detention) storage. Infiltration is modeled in by the Horton infiltration method. Surface runoff is calculated by Manning’s equation. Flow routing in channels and pipes is simulated by the Saint Venant equation through the conservation of mass and momentum for unsteady flow. To produce the most theoretically accurate results, dynamic flow routing was used to solve the complete one-dimensional Saint Venant flow equations (EPA, 2013). The SWMM model was manually developed. Key hydraulic features of the model are summarized in Table 9.

Table 9 Key hydrological features of the SWMM model

Process	In SWMM
Spatial representation	User-defined Sub catchment areas
Rainfall	User supplied
Interception/evaporation	User supplied
Infiltration	Horton Method Green-Ampt method SCS Method
Overland flow	Non-linear reservoir
Drainage elements	Nodes (junction, storage, outfall) Links (conduits, pumps, regulators)
Conduit shapes	20 common shapes, irregular open channels, custom closed conduits
Flow routing	Steady flow Kinematic wave (non-linear form) Dynamic wave (semi implicit)
Flooding	Overflow/ponding
LID runoff reduction	User-assigned percent reduction

Low Impact Developments

To model the hydrologic performance of blue-green adaptation measures, SWMM 5 has recently been extended with Low Impact Developments or LIDs (defined in paragraph 3.5).

Seven types of blue- green measures can be applied to the model: permeable pavement, rain gardens, green roofs, street planters, rain barrels, infiltration trenches and vegetative swales (EPA, 2013). The types of SWMM LID compartments are surface, pavement, soil, storage, and under drain. The measures are integrated within the sub catchment and allow further refinement of the overflows, infiltration flow and evaporation. For all design strategies, LIDs were manually applied to the current situation (EPA, 2013).

5.2. Methodology

To quantify the contribution of the design strategies to the water assignment, a number of criteria and parameters are identified. The main objectives of the proposed design strategy are to (1) reduce flooding and to (2) increase urban quality. The following criteria are used as performance indicators for the efficiency of the design strategies:

a. Flood volume reduction during heavy rainfall events;
b. Reduce number of CSO's per year;
c. Reduce vulnerability of critical public buildings and infrastructure (f.e. Hoboken terminal, hospitals, wastewater treatment plant, electricity distribution locations)
d. Improvement of the urban quality of living

Based on the design criteria, four parameters to evaluate the contribution to flood mitigation and overflow reduction are:

1. What is the flood volume in the drainage area (internal outflow)? [MG per storm event]
2. What is the runoff per sub-basin? [MGD]
3. What is the total storm water storage per sub-basin (excluding sewer storage)? [MG]
4. Are critical facilities threatened by flooding nodes? [Name of building/service]

The four parameters to indicate the design criteria are answered using the modeling results in paragraph 6.2 Results of modelling blue-green urban design strategies.

5.3. Precipitation analysis

Urban water calculations are done using specific design storms for every return period. 24-hours design storms with return periods of 1, 2, 10 and 50 years were chosen for the input. The design storms are derived from actual storms based on 50 years of 60-minute precipitation data, provided by the NCDC at the New York City Central Park rain station (NCDC, 2014). A set of design storms is derived for the required return periods and durations. There was no increase in precipitation due to climate change taken into account (FHWA, 2001).

For hydrologic design purposes, rainfall distributions are determined from historical rainfall frequency data. There are four different types of rainfall distributions throughout the United States: Type IA, Type IB, Type II and Type III. These differ from each other in the moment of rainfall peak. Figure 32 shows the geographic boundaries for NRCS (Natural Resources Conservation Service) rainfall distribution. Hoboken located in the type III zone. In this type of distribution, approximately 50% of the 24-hr rainfall occurs between the 11th and the 13th hour.

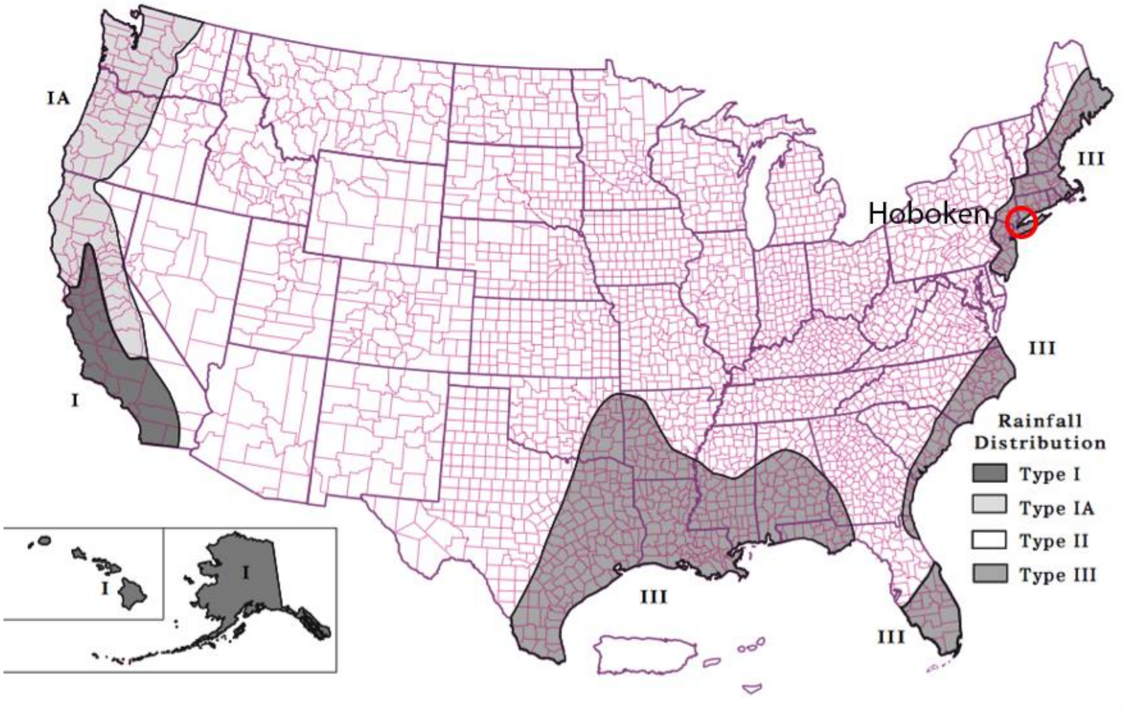
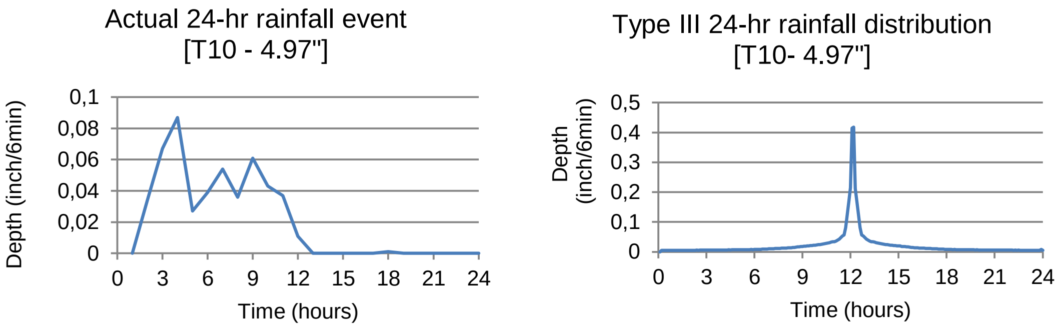


Figure 32 Rainfall distribution types throughout the United States (SCS hypothetical storm, 2014)

HydroCAD® (2013) was used to estimate the type III 24-hr rainfall distribution. The result for the 24-hr T10 storm (4.97 inch) is specified in the right graph in Figure 33. The precipitation peaks halfway. Design storms for the other return periods (1, 2 and 50 years), are added to Appendix III Precipitation analysis.


Actual 24-hr rainfall event [T10 - 4.97"]

Type III 24-hr rainfall distribution [T10- 4.97"]

Figure 33 Actual rainfall event and Type III rainfall distribution

5.4. Description of the SWMM model

The detailed model relies largely on publicly available spatial datasets. The map of the Hoboken sewer system (Appendix I Map of Hoboken sewer system (Boswell Engineering, 1995)) is used to identify sewer dimensions and pipe materials. Digital elevation models were utilized to estimate the elevation of manholes with the GIS methodology. The digital elevation model of Hoboken (3x3meters), provided by Esri DeLorme, was shown in Figure 9 (DeLorme, 2010). Literature values were also of importance where no spatial data was available. The process involved substantial manual work, which sped up by the routines established in the study. To evaluate the parameterization results, the SWMM application was run using an hourly data series of meteorological observations covering a one-year time span. To test the sewer's performance at critical moments, the CSOs are supposed to be closed due to high tide.

Sub catchment parameterization

From GIS data and literature review, the wide range of parameters to model sub catchments SWMM was obtained. Each sub catchment was manually assigned and connected to an outlet junction (manhole) in the drainage network. The sub catchments were shaped rectangular based on the drainage grid and conduits. The sub catchments were not based on the natural flow direction. This resulted in 178 sub catchments with an average of 4.1 acres (1.7 hectares). The sub catchments were named corresponding the drainage basin (H1 to H7). The runoff from both the pervious and impervious fraction of a sub catchment was connected to one junction. All pipes redirect the water, gravity based, to the outfalls along the riverside.

Sub catchment characteristics are crucial to calculate rainfall runoff. SWMM's sensitive parameters for the process of surface water runoff are: the width of the overland flow path (feet), the percentage in pervious area (%) and the depth of depression storage in impervious areas (inch) (Moglen, 2013). The sub catchment widths are calculated by dividing the sub catchment area (A) by the sub catchment's longest overland flow path length (L). Mean impermeability values were calculated for all sub basins (see also table 19 in appendix IV). Manning's roughness coefficient (n) was used to compute overland flow rates. Values vary typically between 0.012 for smooth asphalt and 0.8 for dense wooded areas (Rossman, 2010). For impervious areas, manning's roughness coefficient was set to a value of 0.015 for smooth asphalt (Rossman, 2010). For pervious areas, n was estimated 0.2, based on standard values from the SWMM user's manual (Rossman, 2010). The Horton model was selected to calculate infiltration rates. Infiltration depends on the soil type. Since no data about the city's subsoil is available, some assumptions were made. The depth of the depression storage was estimated 0.06 inches for impervious, and 0.15 inches for pervious surfaces, assuming a clay-loam soil (Rossman, 2010). Since no flow measurements were available for this study, calibration was not possible. Verification of the model is addressed in paragraph 5.5.

Storm water system parameterization

All manholes and pipes were drawn manually. The invert elevations of manholes were derived from the GIS digital elevation data. The depths of the manholes were based on conduit depths. The eight outfalls have their outflow to the Hudson River. The elevation of the outfalls is estimated 1 foot above NAVD88. The pipelines grid was based on the Appendix I Map of Hoboken sewer system. Values of Manning's n were estimated based on pipe materials. Pipe materials are brass, brick, concrete, clay and wood. Their roughness ranges from 0.011 and 0.015. Desired slopes were based on roughness to ensure the minimum water velocity of 3.0 feet per second in full flowing storm drains (US Department of Transportation, 2009). Velocities higher than 10 feet per second were to be avoided (US Department of Transportation, 2009). Slopes range from 0.0004 feet/feet for pipes with large diameters to 0.0015 for pipes with smaller diameters (US Department of Transportation, 2009). Slope requirements may cause deep lying pipes in the ground. Proper sewer depths depend on the water table, elevation of the surface, subsurface structure and the depth of the frost line below grade (EPA, 2002). A sewer should lie at least 1.0 foot deep (US Department of Transportation, 2009). Under a road, the cover on the sewer pipe should be maintained at 3.0 feet where possible (US Department of Transportation, 2009). Forced main pipes and interceptors, driven by the 5th street and 11th street lifting stations, discharge dry weather flow to the wastewater treatment plant. The dry weather system was not added to the storm water management model. The H1wet weather pump, with a maximum pumping capacity of 50 MGD (78.7 CFS), was integrated in the design to discharge water into the Hudson River when the valves cannot open to gravity drain water at high tide.

5.5. Model calibration and verification

The model was calibrated for two real storm events and four 24-hours design storms and was verified by running the running the complete 1-year data series. Verification was done with statistics afterwards. Data available from the North Hudson Sewerage Authority was used as calibration data (EmNet, 2013; EmNet, 2011). For the short rain event simulations, the outlet valves were assumed being closed because of high tide. In the 1-year simulations, the outlets were modeled with open valves to allow surplus water to overflow. Most storm water flood prone areas were in the low-lying H1 drainage basin in the southwestern part of the city. For verification, the long-term time series from 01/01/2010 until 12/31/2010 was used based on 1-hour interval data from New York City central park rain station. A concise illustration of the calibration and verification of the model is specified below, with extended information in appendix V Model calibration and verification.

1-year data series

For the 2010 precipitation data series, the SWMM model calculations of the CSO overflows is presented in Table 10 below (expressed in Million Gallons). No river tide variations were implemented in the model. Therefor in the long-term simulation, the outflow valves were always open to the Hudson River. Flash flooding appeared in higher elevated areas, which is not likely. Flooding in the simulation occurred between September 30th and October 1st. During those days, 3.53 inch of precipitation fell in the city. The maximum precipitation in one hour was 0.84 inch. No flood volume data of those dates of even the year 2010 is available. Incorrect overflow volumes appeared in elevated areas with little to no chance on flash flooding. Calibration concludes by adjusting various SWMM parameters, like enlarging and deepening manholes.

Table 10 Outfall volumes for 1-year data series

Outfall node	**Total Volume (MG)**
Outlet0	9.9
Outlet1	198.4
Outlet2	0.0
Outlet3	84.4.1
Outlet4	102.3
Outlet5	60.8
Outlet6	19.8
Outlet7	69.0
TOTAL CSO	**544.6**

Real storm events

The analysis by EmNet (2013) of the two storm events in 2013 is quantified in

Table 11Table 12, together with the calculated SWMM flood volumes. In both the 8th May and 2nd June SWMM calculations, the calculated flood volumes are somewhat lower than the EmNet calculations, but are in the same order of magnitude.

Table 11 Description of Storm events resulting in Flooding during EmNet analysis period (source: EmNet, 2013)

Storm	Total Rainfall (inch)	Duration (hours)	EmNet H1 peak Flood Volume (MG)	SWMM H1 peak Flood Volume (MG)
May 8, 2013	2.44	11	4.2	3.1
Jun 2-3, 2013	1.22	19	1	0.4

24-hour design storms

Design storm floods with return periods 1, 2 10 and 50 years, are simulated in the SWMM model with no CSO overflow. Differences between calculated and simulated volumes range between 20 to 30 percent. Values are expressed in Table 12 below. The deviations form the real measured areas are assumed to be reasonable for this research due to lack of available data.

Table 12 SWMM model calculations for 24-hours design storm with different return period

Storm	Total Rainfall (inch)	Water assignment Required storage volume (MG)	SWMM H1 peak Flood Volume (MG)
1-year storm	2.72	12.2	8.6
2-year storm	3.29	18.5	13.6
10-year storm	4.97	44.9	29.7
50-year storm	7.09	77.9	52.7

The calibrated model predicted the observed outputs with differences up to 30 percent. A sensitivity analysis on the node elevations and their maximum depth showed the importance of reliable manhole depth and conduit depth. Since no information was available, assumptions were made on these variables. Detailed manhole depth, pipe depth and pipe slope information in the model can provide more reliable output results. Especially since the whole system is gravity driven and thus depends on the capacity and flow velocity of sewer pipes. In-detail modeling of a large and complex urban area is time-consuming process that would provide highly detailed input. Storm water models of a lowered spatial resolution would thus appear valuable if only their ability to provide realistic results could be proved. This SWMM5 model provides a tool that can be used for updating and improving the model.

5.6. Conclusions of testing the design strategies

To derive meaningful conclusions from the design strategy effects on rainfall runoff, the Hoboken urban water system is modelled in SWMM. SWMM computes runoff quantity and quality from primarily urban areas. The model gives understanding of the hydraulic functioning of the existing and proposed water system to meet future principles. Precipitation data is provided by the National Climatic Data Centre (NCDC) from 50 years of climatological data. Design storms for return periods of 1, 2, 10 and 50 years are used for the urban water calculations.

The map of the Hoboken sewer system (Appendix I Map of Hoboken sewer system (Boswell Engineering, 1995)) is used for the layout of the system and to identify sewer dimensions and pipe materials. Low Impact Development controls (i.e. green roofs, permeable pavement, bio swales), are implemented in the sub catchment characteristics for all design strategies. Digital elevation models were used to estimate the elevation of manholes with the GIS methodology. The digital elevation model of Hoboken (3x3meters), provided by Esri DeLorme, was shown in Figure 9 (DeLorme, 2010). Literature values were also of importance where no spatial data was available. The process involved substantial manual work, which sped up by the routines established in the study. To test the sewer's performance at critical moments, the CSOs are supposed to be closed due to high tide.

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3

Urban Water Design

The urban water design aims to integrate urban water and urban planning. In ‘Chapter 6 Urban Design Strategies’, five design strategies are worked out based on functional and technical characteristics of the area. The mitigation performance of every design strategy regarding the water assignment is tested on the basis of a Storm Water Management Model (SWMM). This leads to the selection of one best performing design strategy. The overall findings from the research are discussed in ‘Chapter 7 Discussion and recommendations’. Subsequently, ‘Chapter 8 Conclusion’ will provide answers to the main research question and to the sub-questions.

Chapter 6 Urban Design Strategies

Growing awareness of the potentials of water systems and vegetated areas integrated in the urban landscape has made designers, architects and planners work together to create a more attractive and climate resilient city. Suitable blue-green adaptation measures are based on the outcomes of the functional analysis. The quantitative effects of the design strategies are tested in the storm water management model.

6.1. Strategies for design and planning solutions

Five design strategies were developed for different combinations of blue-green adaptation measures. Table 13 overviews the appropriate blue-green measures for Hoboken. These are classified for different types of existing urban development based on the six-layer approach. The mitigation performance of every design strategy regarding the water assignment is tested on the basis of a Storm Water Management Model (SWMM). The five strategies are elaborated from combinations of (1) subsurface measures, (2) measures to be applied to infrastructure, (3) measures to be applied to public open spaces, (4) measures to be applied to private space and buildings, and (5) a combination of all measures by creating a network of blue and green measures.

Table 13 Suitable blue-green measures for different types of development in Hoboken

	Infiltration retention	Detention	Storage retention
Subsurface		Subsurface storage beneath public space;	
Infrastructure	Permeable pavement; Storm water infiltration planters; (storm water infiltration) trees;		
Public grey	Rain gardens; (storm water infiltration) trees	Water square; Subsurface detention;	Retention ponds;
Public green	Park; urban agriculture; bio retention swales	Rainwater harvest cistern;	Seasonal storage; Retention ponds; Urban wetland
Private space	Add green to private space	Rainwater harvest tanks;	Private retention ponds;
Buildings (above ground)		Blue roofs; green roofs; Green facades;	
Network	Add green to streetscape	Hollow/inclining roads;	

Strategies

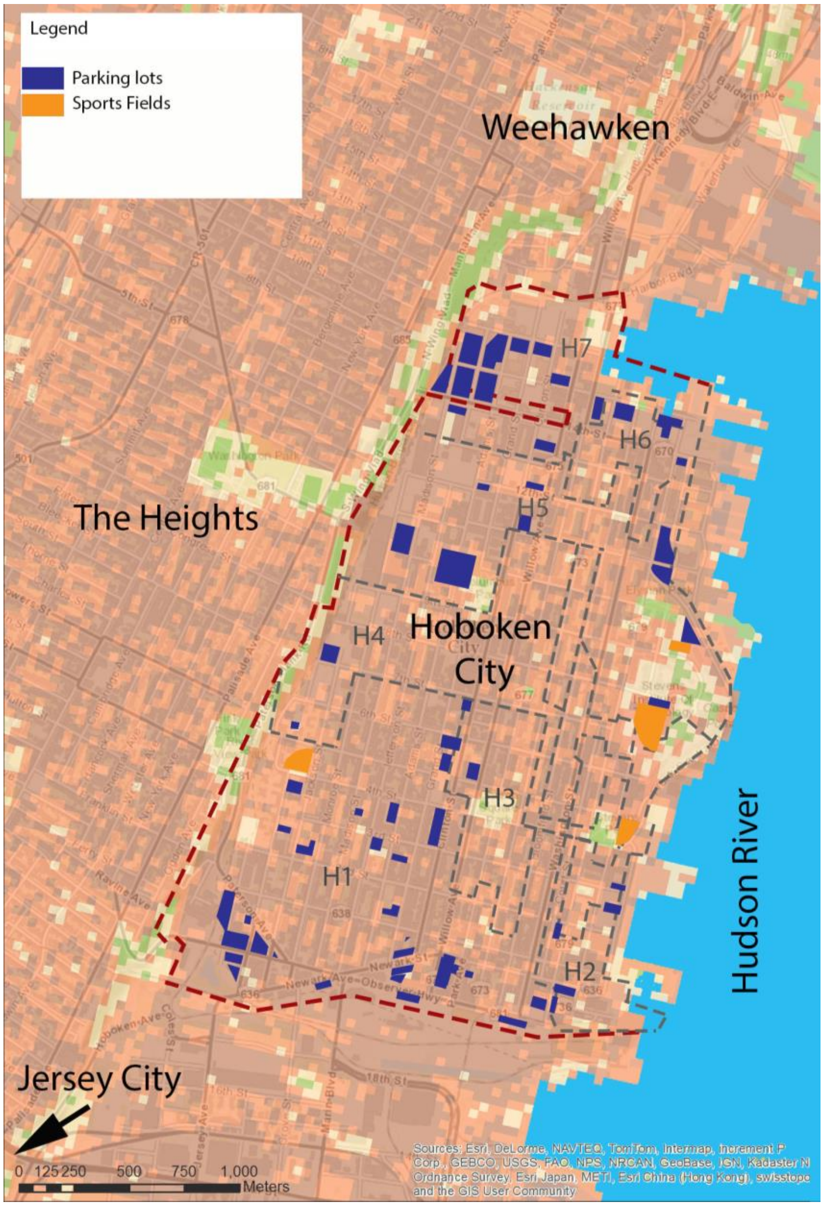
Five design strategies are developed, applied to different layers in the urban system. Both the current situation and the five design strategies are simulated in SWMM. Rainfall events with 24-hour duration and return periods of 1,2, 10, and 50 years served as input when simulating the design strategies. The strategies are explained below and additional information is added to Appendix VI Design Strategies.

0. Current situation

In the current situation, almost 90% of the area has impervious surface. Rainwater is discharged into the Hudson River during low tide, or pumped by the H1 wet weather pump at high tide. Design storms with return periods of 1, 2, 10 and 50 years were simulated to compute flash flood volumes and critical buildings in flash-flood prone areas.

1. Improve current situation with application of subsurface adaptation measures

For the first strategy, subsurface adaptation measures were applied. With a functional analysis of the existing urban environment, the storage possibilities beneath parking lots and sports fields is determined. Storage below buildings and parking garages was not taken into account due to the intention of using the existing urban development. Lack of knowledge about the existing cultivation makes it impossible to include storage below buildings in the analysis. Two deep storage basins will be placed: one beneath the sports field in the south west of the city (H1 basin), and one beneath the parking a bit more to the north (H4 basin). Both basins will have acreage of 0.52 acres (23,000 square feet) and a depth of 16 feet, which means they can each store 2,65 million gallons of water. The remaining sports fields and parking lots will be equipped with shallow storage facilities. With a total sports fields acreage of 3.8 acres, combined with 20 acres of parking lots, the total storage provided based on an average effective storage 2 inch (State University, 2009) is 1.3 million gallons of water (274,250 cubic feet). The design layout of the first strategy with the distribution of subsurface adaptation measures is specified in Figure 34 below.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 34 Strategy 1: application of subsurface adaptation measures

2. Improve current situation with application of infrastructural adaptation measures

The second strategy includes the current drainage system with the application of surface adaptation measures. With a functional analysis, areas suitable for permeable pavement (at flat parking lots and sidewalks), storm water infiltration planters and trees along major roads, and adding green to the streetscape are identified. In low-lying areas, permeable pavement cannot be applied due to high groundwater levels, unless subsurface (groundwater) drainage is installed. No permeable pavement will be applied in the H1, H4 and H7 drainage areas. In total 9.2 acres of pervious paving will be placed on parking lots in the other drainage basins. The major roads in Hoboken, being Willow Avenue, Jefferson Street and Washington Street, have wide sidewalks up to 25 feet wide. Cross sections of these streets are given in Figure 35.

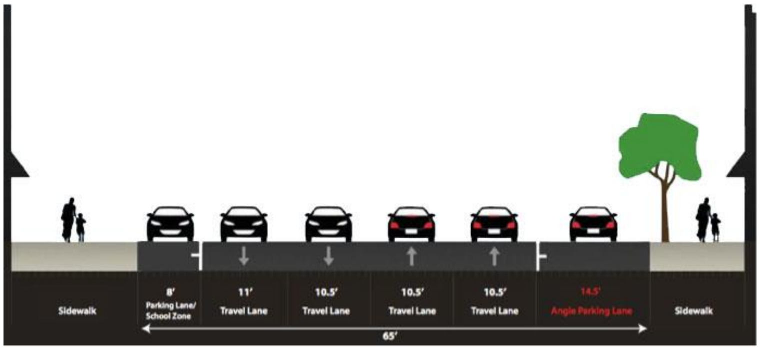


Figure 35 Willow Avenue Cross Section - 11th St to 13th St (source: HobokenNJ, 2014)

The existing pavement will be replaced with permeable pavement in the three major roads. For Washington Street, the major road, also storm water flow-through planters and storm water trees will be added. The total acreage of permeable sidewalks, based on an average sidewalk width of 15 feet, and the length of each street 7000 feet, the estimated acreage of permeable pavement is 14.5 acres. The width of the green planters is 5 feet. Adding green planters and storm water trees along Washington Street on both sides of the road, the total area is estimated 1.6 acres. The design layout of the second strategy with the distribution of parking lots and the main roads is shown in Figure 36 below.

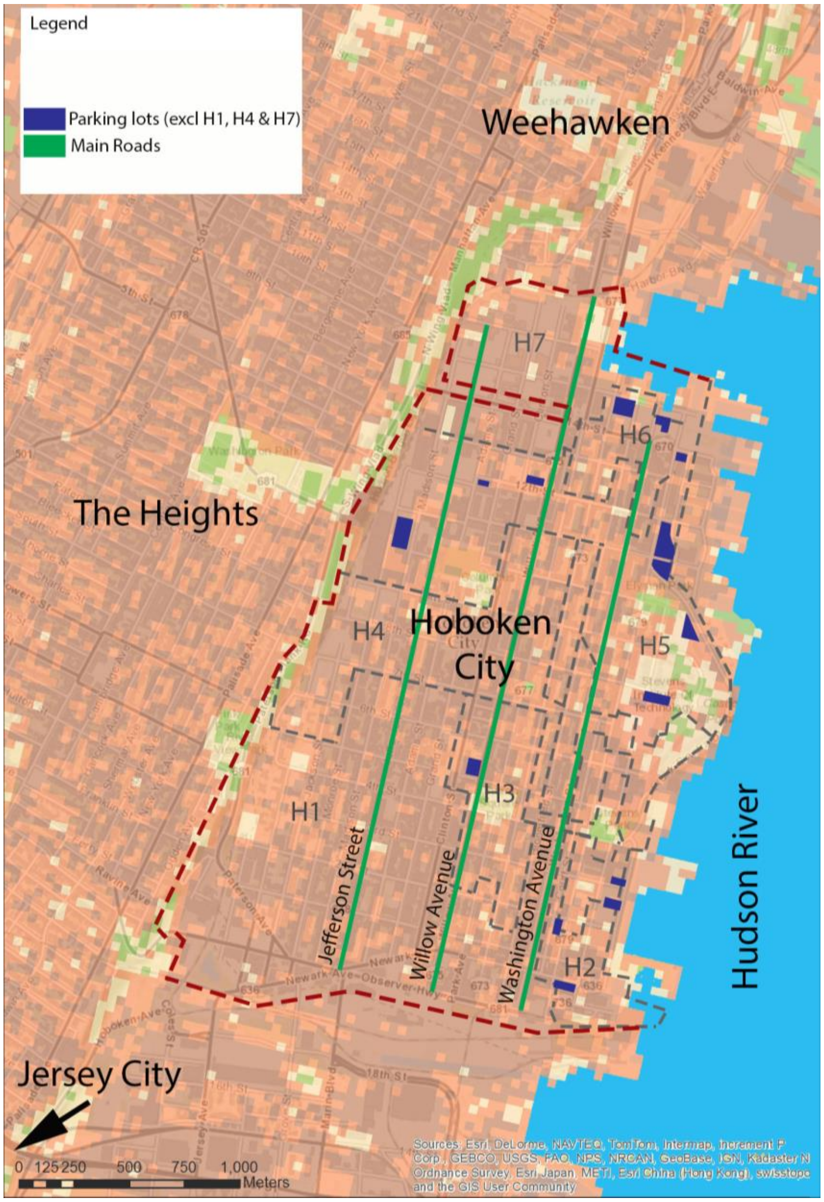


Figure 36 Strategy 2: application of infrastructural adaptation measures

3. Improve current situation with application of adaptation measures on public space

The third strategy includes the current drainage system with the application of blue-green adaptation measures to open public space. With a functional analysis of the existing urban environment, undeveloped public areas suitable to rain gardens, storm water trees and flow-through planters, water squares, detention below sport fields, parks, retention ponds (in new/existing green space), urban agriculture, bio retention swales, rainwater harvest cistern and seasonal storage are identified. Total undeveloped is 26.2, but not all suitable for infiltration. Since open space suitable for infiltration is scarce, not all measures can be implemented. Preferred therefor are the ones with relative high flood mitigation effects with the highest green addition to the area. The design for adaptation measures on public space contains the following: a water square in H4 (0.8 acres) which can store up to 0.4 MG (60,000 cubic feet); urban farming in H5 (6.4 acres); parks at undeveloped sites in basin H7 and H5 (4.8 acres), bio retention gardens in H2, H6 and H4 (1.5 acres), urban wetland H1 (5.0 acres) and a rain garden in the higher parts of H1 (0.2 acres). One fourth of the wetland site is wetland surface area, with a total storage capacity of 0.6 MG. The design layout of the third strategy with the distribution of undeveloped sites suitable for blue-green measures is specified in Figure 37 below.

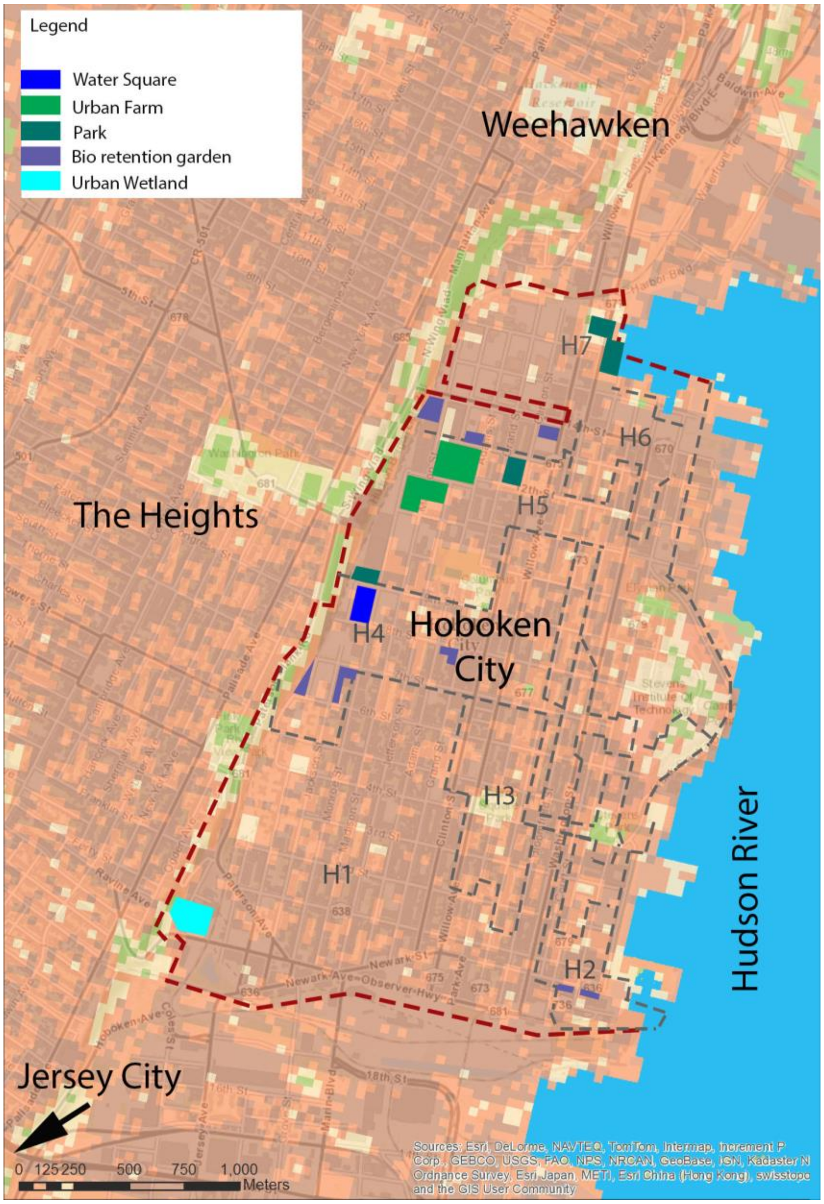


Figure 37 Strategy 3: application of adaptation measures on public space

4. Improve current situation with application of adaptation measures on private space and buildings

The fourth strategy includes the current drainage system with the application of blue-green adaptation measures to all open public space. With a functional analysis of the existing urban environment, buildings suitable to place green roofs are analysed. In total 83 acres of (public and private) roofs are flat and suitable to place green roofs. All buildings that are not suitable for green roofs are assumed to receive rainwater harvest tanks. Different types of rainwater harvest tanks exist. Examples are cisterns on roofs and tanks next to buildings. These tanks are assumed 17 cubic feet (500 litres). The storage tanks are modelled as a fixed volume storage basin for the whole sub catchment. The average of the 178 sub catchments is 4 acres. This means that 16,000 rainwater harvest tanks are required to 2.1 million gallons of water, based on 2 inches of precipitation. Additionally green facades can be placed, but are not taken into account for the water assignment calculation in SWMM. The design layout of the fourth strategy with the distribution of roofs suitable for blue-green measures is shown in Figure 38 below.

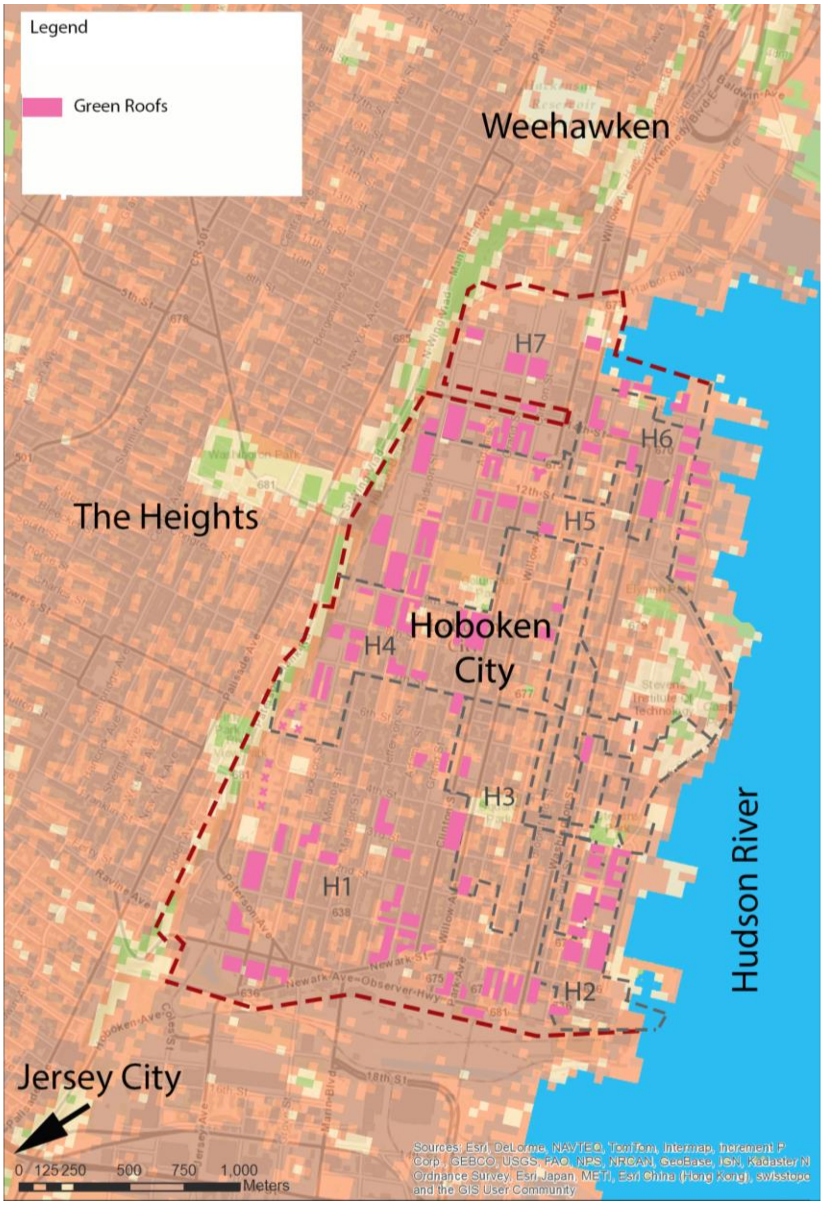
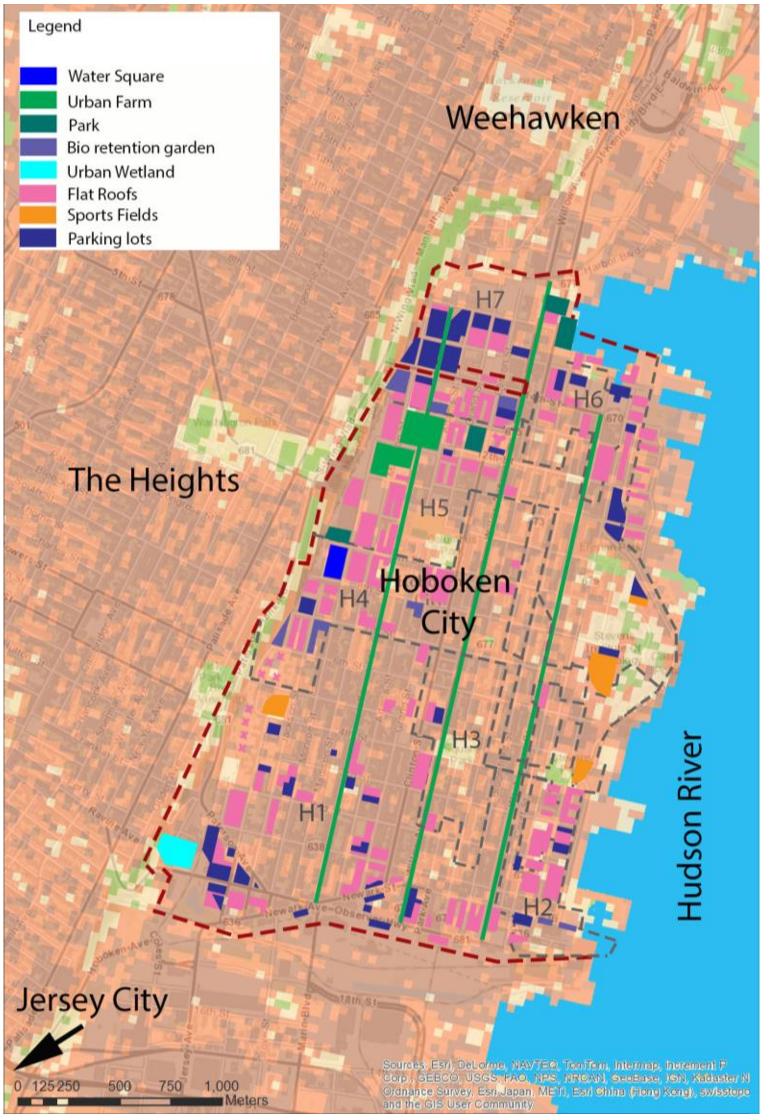


Figure 38 Strategy 4: application of adaptation measures on private space buildings

5. Combine proposed measures in an urban blue-green network

The fifth strategy combines all proposed blue-green adaptation measures into a city wide blue-green network. By applying additional green in the streetscape and hollow roads to discharge storm water, green areas and open water bodies in the city centre are connected to the surrounding green belt. Hollow roads in this situation transport storm water from higher areas in the west of Hoboken towards the green belt and other storage facilities. In total, 4.8 MG storage is created, 31.7 acres of permeable surface that infiltrates storm water and 83 acres of green roofs to infiltrate and delay water before it discharges into the sewer system. The total increase of green surface city-wide with the application of pervious surface and green roofs is 16%. The design layout of the fifth strategy with the combination of the three previous strategies is specified in Figure 39 below.



Sources: Esri, DeLorme, NAVTEQ, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure 39 Strategy 5: proposed measures to construct an urban blue-green network

6.2. Results of modelling blue-green urban design strategies

The mitigation performance of every design strategy regarding the water assignment is tested on the basis of a Storm Water Management Model (SWMM). The T10 design storm results for all strategies are discussed extensively in this chapter. **Appendix VII Simulation Results** contains tables with results from the T1, T2 and T50 deign storms. The effectiveness of the strategies is evaluated based on the four parameters appointed in the methodology.

These four parameters were (1) the flood volume per drainage area, (2) the runoff per sub-basin, (3) the storm water storage per sub-basin and (4) the critical facilities threatened by flash floods.

1. What is the flood volume in the drainage area (internal outflow)?

The results from the Hoboken flood volume calculations in the whole area for every design storm is given in Table 14. The flood volumes for the current situation (strategy 0) are much smaller than calculated in the water assignment. This difference varies from twenty percent (T50) to almost fifty percent (T1).

Table 14 Internal flood volume calculations

Return period storm event [year]	Rain depth [inch/ 24h]	Water assignment [MG]	Strat. 0 [MG]	Strat. 1 [MG]	Strat. 2 [MG]	Strat. 3 [MG]	Strat. 4 [MG]	Strat. 5 [MG]
T1	2.72	16.9	8.6	4.4	7.8	8.6	6.3	2.9
T2	3.29	23.2	13.6	7.7	12.6	13.5	10.7	5.3
T10	4.96	40.9	29.7	20.2	27.0	29.7	24.9	15.1
T50	7.07	66.0	52.7	37.5	49.2	52.6	45.6	29.7

The water assignment is a useful instrument to quickly make rough approximations of flood volumes and provides reliable values regarding the order of magnitude. The dynamic model generates continuous simulation of received precipitation, which is generated into runoff through pipes, storage devices, treatment devices, pumps and regulators. The dynamic model is therefore assumed to provide the most reliable results.

The effects of implementation of blue-green measures on the Hoboken sewer system are shown in Table 15. Flood volumes per sub basin are given for the T10 design storm. Volumes are expressed in million gallons per 24-hours storm event. Basin H1 deals with relatively most flooding per acre, which is indeed most reliable. Flood volumes reduce 10 to 50 percent with the application of blue-green measures. When applying citywide (strategy 5), the effects are the greatest, with 50% on average.

Table 15 Flood volumes per sub basin for a T10 storm event

Sub basin	Strat.0Volume [MG]	Strat.1Volume [MG]	Strat.2Volume [MG]	Strat.3Volume [MG]	Strat.4Volume [MG]	Strat.5Volume [MG]
H1	11.90	7.80	11.37	11.88	10.42	6.37
H2	0.01	0.0	0.0	0.01	0.0	0.0
H3	3.47	3.00	3.31	3.47	2.98	2.46
H4	4.91	3.08	4.69	4.91	4.09	2.19
H5	2.38	0.91	2.17	2.38	1.76	0.54
H6	2.74	2.19	2.55	2.71	2.42	1.78
H7	4.33	3.21	3.86	4.33	3.26	1.68
TOTAL	**29.7**	**20.2**	**27.0**	**29.7**	**24.9**	**15.1**

To visualize the Hoboken floods, Olympic swimming pools are used as volume indicators. A standard Olympic swimming pool is 50 meters long (164 feet), 25 meters wide and 2 meters deep (6.6 feet). The total volume of such a pool is 2500m3 or 1.5MG. Figure 40, Figure 41 and Figure 42 visualize the flood volumes after T10 design storms for all strategies, expressed in the number of swimming pools per sub-basin, for all design strategies.

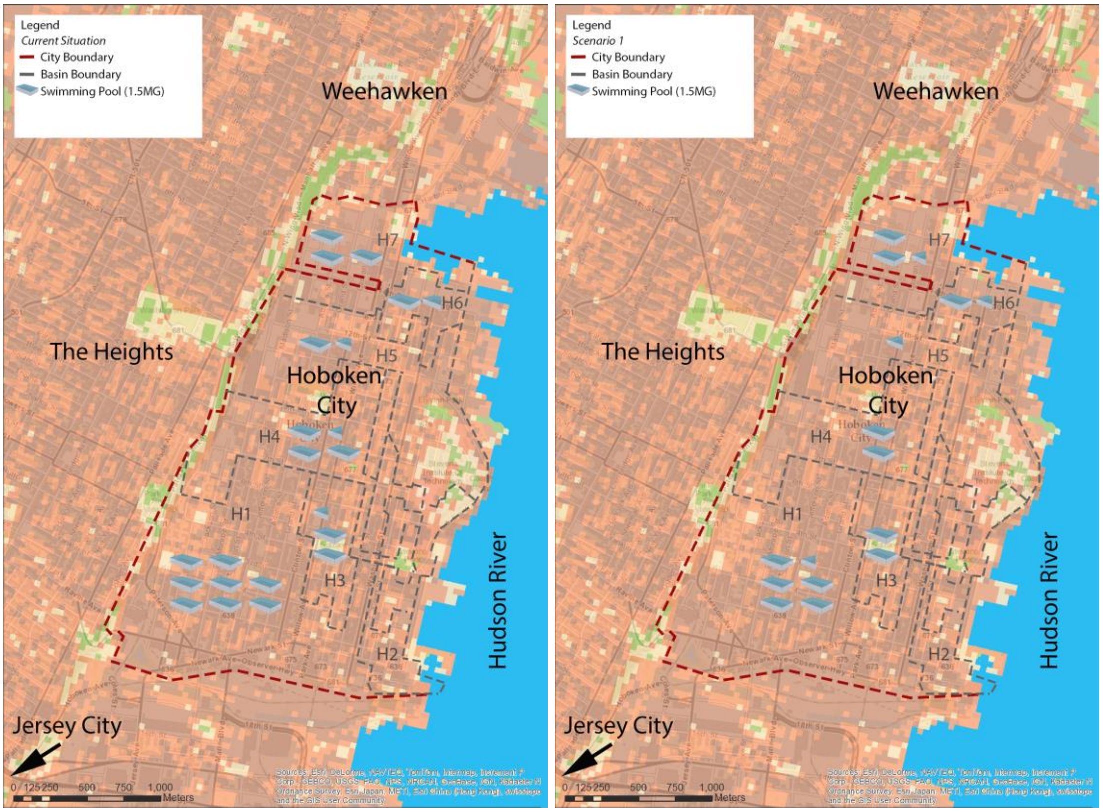


Figure 40 Flood volumes per sub basin for T10 design storms in the current situation (left) and strategy 1 (right)

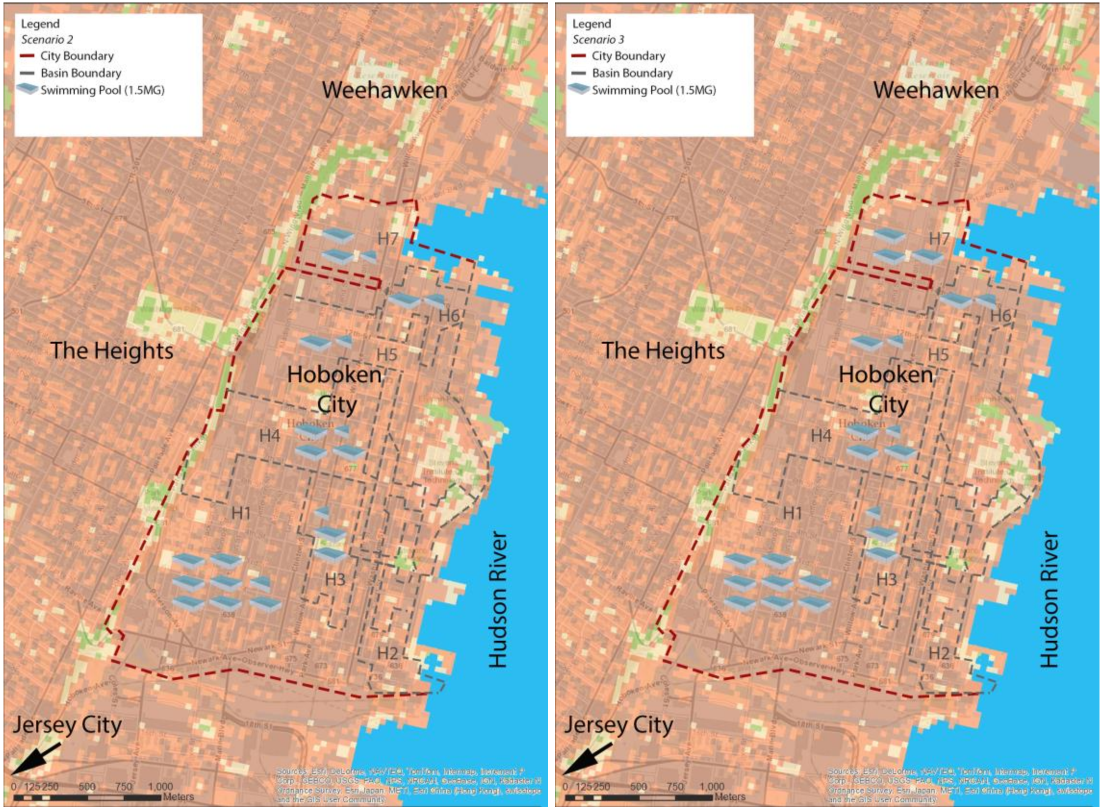


Figure 41 Flood volumes per sub basin for T10 design storms in strategy 2 (left) and strategy 3 (right)

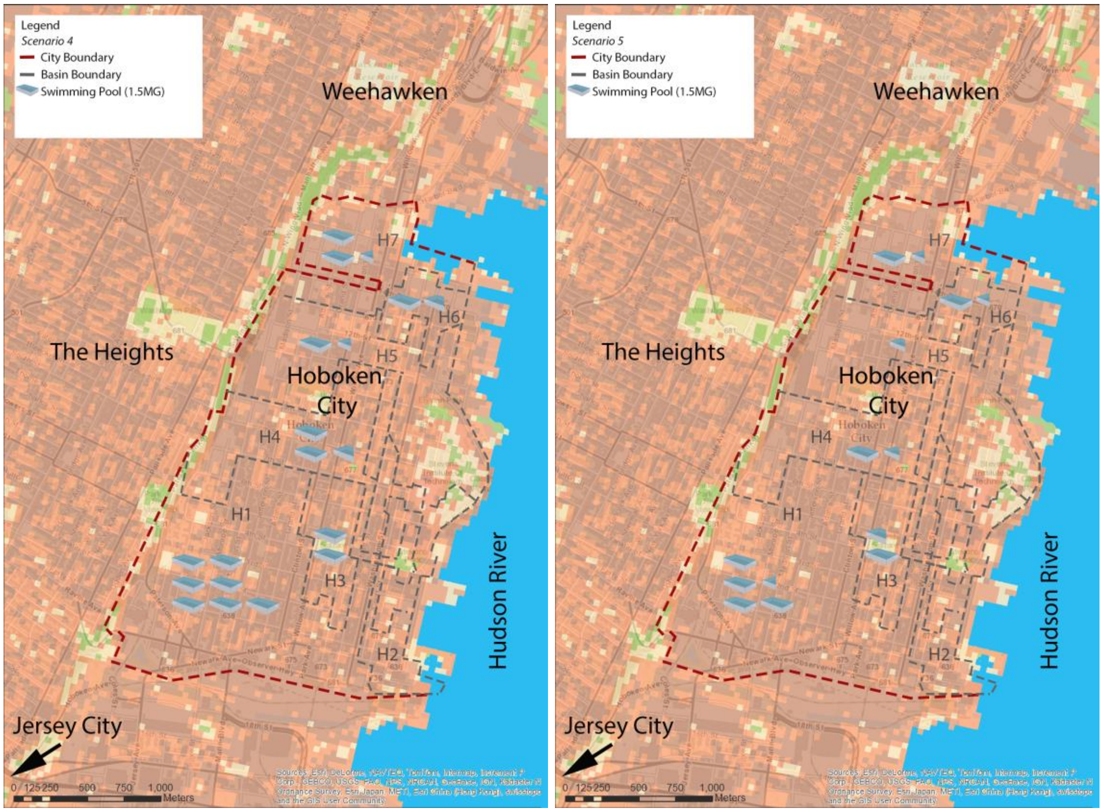


Figure 42 Flood volumes per sub basin for T10 design storms in strategy 4 (left) and strategy 5 (right)

2. What is the runoff per sub-basin?

The runoff per sub-basin indicates the rainfall discharge through a system of pipes, channels, storage and treatment devices, pumps, and regulators. Runoff will reduce when more water infiltrates in the soil. The sub catchment runoff calculations for T10 design storms are given in Table 16. The bottom row shows the percentage of runoff from the total storm water volume falling on the city surface. The calculated runoff reduction varies from 60 percent in strategy 1 to almost 50 percent in strategy 5. The measures differ in rainfall runoff between the current situation and after the implementation of citywide retention and detention measures is almost 10 percent.

	Total Volume Storm water [MG]	Strategy 0 [MG]	Strategy 1 [MG]	Strategy 2 [MG]	Strategy 3 [MG]	Strategy 4 [MG]	Strategy 5 [MG]
H1	35.4	22.3	22.3	21.7	22.3	20.7	20.1
H2	4.0	2.4	2.4	2.2	2.4	2.1	2.0
H3	9.2	5.4	5.4	5.2	5.4	5.0	4.8
H4	14.4	9.3	9.3	9.2	9.3	8.4	8.2
H5	21.4	11.0	11.0	10.5	10.3	9.7	9.3
H6	3.8	2.5	2.5	2.3	2.5	2.2	2.0
H7	10.9	7.0	7.0	6.3	6.7	6.1	5.4
TOTAL	**99.1**	**59.9**	**59.9**	**57.5**	**58.9**	**54.2**	**51.8**
PERCENT	**100**	**60.4**	**60.4**	**58.0**	**59.4**	**54.6**	**52.2**

Table 16 Rainfall Runoff (MG per 24 hours) per sub basin for T10 design storm

3. What is the total storm water storage per sub-basin?

Additional water storage can effectively decrease peak rainfall runoff during a storm event. The results from the storm water storage calculations for T10 design storms are given in Table 17. Not only large subsurface systems provide significant water storage. Also (small) rain gardens along streets have a noticeable impact on the urban water system in flood reduction. The additional storage in strategy 1 decreases the flood volume with respect to the current situation with more than 30 percent (from 29.7 to 20.2 MG). Stored water alleviates the pressure on the drainage system and can also be reused for non-potable purposes.

Table 17 Storm water storage for T10 design storm

	Strategy 0 [MG]	Strategy 1 [MG]	Strategy 2 [MG]	Strategy 3 [MG]	Strategy 4 [MG]	Strategy 5 [MG]
Storm water Storage (MG)	0.0	9.5	0.0	0.7	0.0	9.0

4. Are flooded nodes threatening public buildings or services?

To identify critical areas, the sub basins are divided into smaller units. These units are analysed on flood volumes to find out what services and buildings may be put at risk due to flooding. In Figure 43, the distribution of the smaller units within the sub basins is drawn.

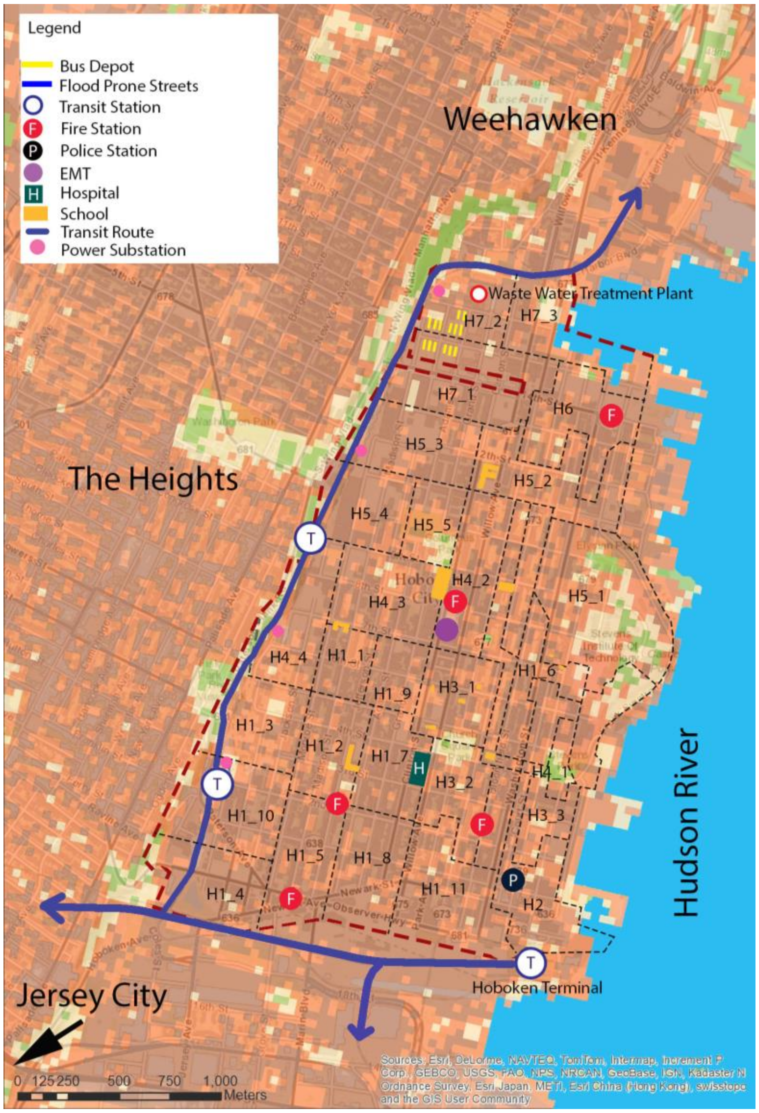


Figure 43 Distribution of critical drainage areas (illustration by author)

Basin units containing schools, the hospital, the EMT building (Emergency Medical Technician), transit stations, police station and power stations, are shown in table 18. Floods are threatening all but units H1_2, H1_7 and H2. Design strategies 1 and 5 prevent flooding in unit H5_3. The hospital is situated in an area (H1_7) where floods are uncommon. Only strategy 5 prevents basin H6, with a fire station, from flooding.

Unit H1_5 is an area dealing with relatively much flooding. One vulnerable building in that basin is the fire station. Second most flood volume is measured in unit H3_2. This area locates another fire station. Critical buildings in these areas, the two fire stations, should have additional protection measures for when it comes to flooding. Bain units that are not listed in table 18 are not flood prone in T10 storm events.

Table 18 Flood volumes of units containing critical infrastructure

	Strat.0 [MG]	Strat.1 [MG]	Strat.2 [MG]	Strat.3 [MG]	Strat.4 [MG]	Strat.5 [MG]
H1_2	0	0	0	0	0	0
H1_5	4.1	5.2	2.9	4.1	3.6	2.7
H1_7	0	0	0	0	0	0
H1_10	0.6	0.6	0.6	0.6	0.5	0.4
H2	0	0	0	0	0	0
H3_2	2.1	3.3	2.0	2.1	1.8	2.1
H4_2	0.5	0.6	0.5	0.5	0.4	0.2
H4_4	0.8	0.3	0.8	0.8	0.5	0.1
H5_3	0.2	0	0.2	0.2	0.2	0
H6	2.2	5.0	0.1	0.1	0.1	0
H7_2	0.5	0.8	0.4	0.5	0.3	0.2

6.3. Selection of an urban design strategy for Hoboken

For Hoboken, both flood reduction and improvement of the urban quality are important. Flood volume reduction during heavy rainfall events, the reduction of CSO's per year, vulnerability reduction of critical public buildings and infrastructure, and Improvement of the urban quality were identified as design criteria. To quantify the contribution of the design strategies to the water assignment, a number of criteria and parameters are identified. The criteria for design performance are (a) flood volume reduction during heavy rainfall events, (b) CSO reduction, (c) vulnerability reduction of critical public buildings and infrastructure (f.e. Hoboken terminal, hospitals, wastewater treatment plant, electricity distribution locations), and (d) improvement the urban quality of living. Four parameters to evaluate the to evaluate the contribution to flood mitigation and overflow reduction are (1) the flood volume in the drainage area (internal outflow), (2) the runoff per sub-basin, (3) the total storm water storage per sub-basin (excluding sewer storage), (4) critical facilities threatened by flash floods.

All strategies contribute to flood volume reduction and creating urban quality, but not all strategies are as effective. Strategy 1 can store about 10% of the total flood volume. It has the least contribution to urban quality, since only subsurface storage, and no vegetated measures were used. Strategy 2 on the other hand, has a very broad effect on the green experience of the city. It includes the greening of three major roads. Strategy 3 uses undeveloped space to create a green network throughout the city. It has the least effect on total flood reduction of all strategies, but uses space that would otherwise lie fallow. In strategy 4, green roofs are applied on all suitable buildings throughout the city. This has a positive effect on both flood reduction, reduction of the urban heat island effect, and air quality. When the roofs are large enough, they can even function as a roof garden, roof restaurant or private kitchen garden. Strategy 5 ultimately, combines all design strategies into a citywide system of blue-green measures.

The integration of water systems and vegetated areas makes the city most habitable and resilient in spite of climate change. Modeling showed that Hoboken benefits most from design strategy 5 in terms of quantitative flood reduction. This design strategy also has the most additional green through a citywide network of vegetated measures. This citywide system of flood prevention measures provides a pleasant, physical appearance.

This visible way of dealing with what happened during Sandy creates a positive vibe over the negative memories. By taking away the reluctance towards flood defense systems in a soft way, the city creates faith in an integrated approach for urban water design. The design of citywide measures proposed in strategy 5 is therefore the most sustainable urban water management solution for Hoboken.

6.4. Urban Design Strategy for Hoboken

The proposed spatial typology of design strategy 5 is elaborated in this paragraph in a number of illustrations. Green roofs, permeable pavement, bio-retention gardens, storage basins, an urban farm, urban wetlands and water squares are included in the adaptation design. Through the urban grid system, vegetated areas are connected to create a pleasant experience throughout the city.

Figure 44 shows an impression of the new identity the combination of measures provides on citywide scale. The riverbeds in the east and the areas at the bottom of the cliff, are surrounding the city with a green belt. The green belt along the cliffs serves for both storage and infiltration of water. The three major roads with trees and plants create green veins through the heart of the city. In every part between the major roads parks, urban farms or wetlands can be found. A solid footpath or bicycle lane can be applied along the city borders to create an uninterrupted route.

Figure 44 New identity of Hoboken with blue-green network

The riverside detail in Figure 45 illustrates of the effects of green roofs on the city face from above. Green roofs reduce the urban heat island effect by preventing pavement and buildings to collect solar heat. Green roofs also improve air quality, they relieve the sewer system by storing water, and create pleasant areas for recreation.

Figure 45 Impression of riverside

Figure 46 shows the results of adjustments for Washington Street with infiltration lanes and (storm water) trees. These measures will also be applied to Willow avenue en Jefferson Street. Green strips with separate sidewalks from the roads. The green strips contain bio-retention gardens and infiltration basins. Sidewalks are made of permeable paving. In Figure 47, a detailed illustration is given of the bio-retention garden in 1st Street.

Figure 46 Impression of Washington street with infiltration lanes and trees

Figure 47 Impression of bio retention garden 1st street

Figure 48 illustrates an urban farm, realized on the undeveloped area in the northwest of Hoboken. Crops can grow here and, if desired, it can also provide grass to feed livestock. Urban farms can be a pleasant place for people to come together and produce food in a fair and local way. The urban farm is next to the palisade cliffs, so that a walk along the green belt can be interrupted with a visit to the urban farm.

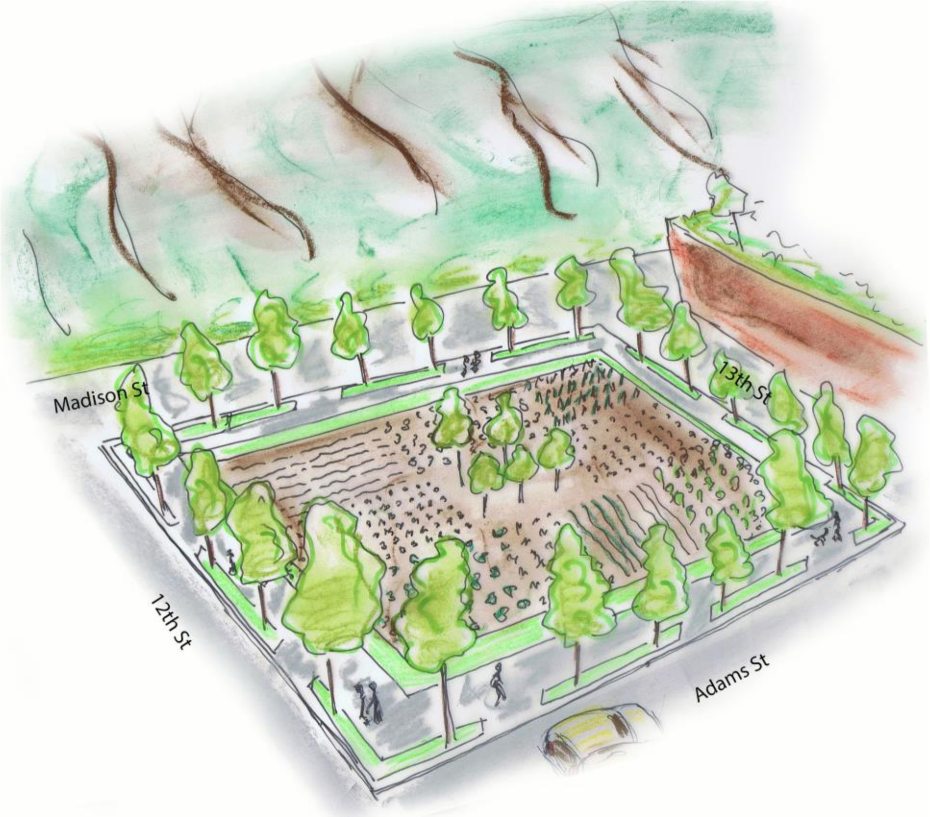


Figure 48 Impression of urban Farming

The construction of a water square in the western central part of the city is visualized in Figure 49. When no rainwater needs to be stored, the water square can function as a recreational area. It can for example be used as a basketball field.

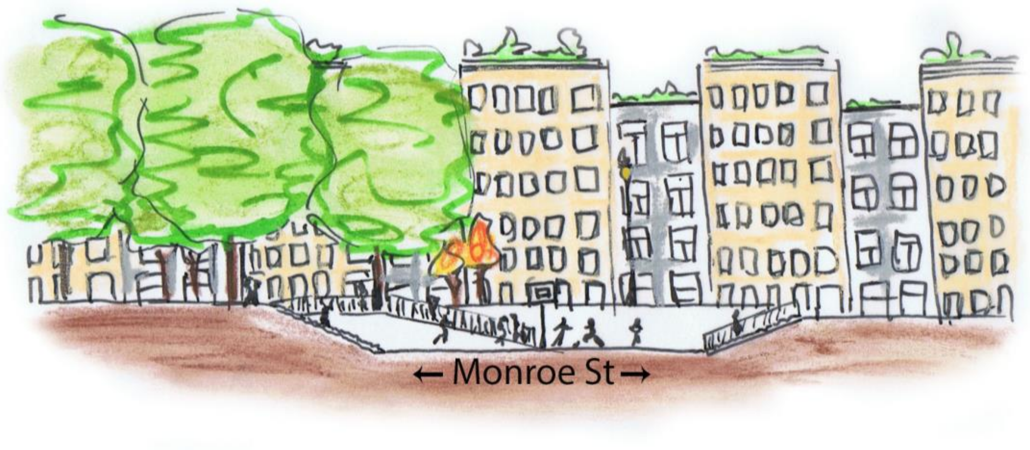


Figure 49 Impression of water square

6.5. Conclusions of Urban Design Strategies

Growing awareness of the potentials of water systems and vegetated areas integrated in the urban landscape has made designers, architects and planners work together to create a more attractive and climate resilient city. Five design strategies were developed for different combinations of blue-green and grey adaptation measures. The five strategies are elaborated from combinations of (1) subsurface measures, (2) measures that can be applied to infrastructure, (3) measures that can be applied to public open spaces, (4) measures that can be applied to private space and buildings, and (5) a combination of all measures by creating a network of blue and green measures.

The mitigation performance of every design strategy regarding the water assignment is tested on the basis of a Storm Water Management Model (SWMM). Strategy modeling showed that Hoboken benefits most from design strategy 5 in quantitative flood reduction and creating a citywide network of vegetated measures. The proposed urban water management design based on design strategy 5 includes a citywide system containing green roofs, permeable pavement, bio-retention gardens, storage basins, an urban farm, urban wetlands and water squares are included in the design. Through the urban grid system, green parts are connected to create a pleasant experience throughout the city.

Chapter 7 Discussion and Recommendations

This chapter discusses the results and difficulties within the research project. The discussion results in suggestions for future research and follow-up studies.

7.1. Effectiveness of design towards flood reduction

The most important aspect of the discussion is the effectiveness of the proposed design strategy. Modelling simulations showed that design strategy 5 had the largest impact on flood volume reduction. The impact appeared to be significantly higher than in strategies with only one type of adaptation measure. The model is not considered to be truly reliable. Therefor the quantitative results from the simulations are not to be taken as true values, but as an indication. Outcomes are compared on a relative basis. The outcome of the study enables to underpin the added value of different blue-green adaptation measure. The flood volume reduction values are seen as qualitative indicators.

It is suggested to conduct a more reliable storm water management model. Additional information is needed on mainly sewer dimensions. In particular the slope and depth of pipes, the size and depths of manhole and the dimensions and operation of structures (weirs, outlets, storage) are data of great value for rainfall runoff modelling. Second suggestion is to conduct field measurements of flooding and runoff values to check the reliability of the model.

7.2. Effectiveness of design towards urban quality

Important is also to consider the added value of the proposed spatial typology towards the urban quality. Principles of urbanism serve as a basis for suitable adaptation measures. The underlying grid is therefor used to create a system of connected measurements. Trustworthiness and usability of the design depends on its acceptation by the inhabitants. No quantitative indicators were used to identify additional value towards air quality, urban heat island effects, and physical improvements of the urban layout. Only the proven multifunctional effects of blue and green measures were used as guidance. The functional analysis has exposed the layers of the city to redesign districts in an interactive design. Towards the urban design, the elaboration of more detailed visualizations and visual 3D elaborated strategies may be helpful to make stakeholder experience the proposed design.

7.3. Difficulties of modeling urban water systems

The application of an urban water management model on an urban system gives a well performance indication of the water system, but also comes with a number of challenges. Parameterization of heterogeneous sub catchments of low spatial resolution turned out to be challenging and inaccurate. Not only is it time consuming, the limitations of available data, both climatologic, environmental and sewer system data, ask for clear assumptions and boundary conditions. No clear procedures have been presented in literature on how to choose certain parameter values in an aggregated SWMM approach without calibration. A combination of GIS methods and literature values was used for the purpose, but the results were found partly inaccurate with respect to calibrated values. To reliably use the results in modeling, either calibration should be performed or the model sensitivity for the most hard-to-define parameters such as flow width or depression storage should be proved minor. Detailed elevation information, shapes of streets, permeability of pavement types, and information on impermeability of private gardens all influence rainfall runoff. Implementation of the modeling results in detailed GIS data layers (i.e. water depths) might provide most of this information. The variability of many external factors is influencing the model. The water level of the Hudson River and the runoff from surrounding areas into the Hoboken drainage basins, are of great importance for the reliability of the model. It is not impossible to take these limitations away. Nevertheless, considerations have to be made in what is required and what not in the time and means available regarding the goals to be achieved.

7.4. Recommendations for Future work

For future work, a number of suggestions can be presented towards the reliability and effectiveness of this study. A number of improvements were already suggested in the previous paragraphs. Besides filling up data gaps in the current model, a follow up study regarding the costs and support of the proposed design is meaningful. The suggested design strategy 5 is the most extensive urban design is the most extensive one and therefor also the most costly. Historical research on blue-green measures resulted in implementation costs indications. These results need to be revised for the proposed design and with up to date financial taxes. Support for the design is needed when it comes to realization. Inhabitants, businesses, landowners, the NJ transit and the governance are important stakeholders. Based on the outcome of this research, the improvement of the storm water management model is of biggest interest.

Chapter 8 Conclusion

The overarching aim of this research project was to establish a sustainable urban water management design for Hoboken City to improve resiliency towards flash flooding and to improve urban quality. This was achieved by carrying out a functional analysis of the area and a technical analysis of the sewer system. Recommendations were made for soft and natural spatial solutions (i.e. blue-green measures). The base of the design is the existing urban environment.

The main goals of the urban design were to reduce flash floods and combined sewer overflows, and to increase urban quality. Urban quality was indicated by air quality, additional public green- and recreational space, decreasing the urban heat island effects and increase infiltration capacity to prevent subsidence. The following research question was the guidance for the research: *'What system of blue-green adaptation measures is most beneficial for Hoboken in terms of flood reduction and improve the quality of the living environment?'* In order to answer the research question, four sub research questions were drafted:

1. 'What are the key issues of climate change for vulnerability to flooding in Hoboken?'
2. 'What adaptation measures are available to increase urban resiliency to flooding in Hoboken?'
3. 'How can hydro dynamical modelling be used to come to smart solutions for urban design?'
4. 'How can water management be effectively integrated in urban planning and design?'

In the next paragraphs, each research question is answered, leading to an overarching answer regarding the main research question.

8.1. What are the key issues of increased vulnerability towards flooding in Hoboken?

In this thesis, vulnerability is defined as "the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability therefore implies not only exposure to hazard factors but also the capacity to recover from their effect" (Srinivas, 2007). The threatening effects of climate change (longer and more intense periods of rainfall, higher temperatures and longer periods of drought), rising sea water levels, and the increasing risks of tropical storms, makes Hoboken additionally vulnerable to flooding.

Hoboken suffers both flash flooding overwhelming the sewer system and storm surge. Not only more extreme precipitation, but also sea level rise is a growing threat. High urban density, combined with the expected climate change effects, is threatening the current urban water management system. Increased precipitation, higher temperatures and longer periods of drought are the key elements of the impact of climate change on urban areas. The aim is to understand the urban water system to reduce vulnerability to floods, and to create a more attractive city with a comprehensive flood mitigation plan. A combined set of blue-green measures with grey infrastructure is proposed to provide a more sustainable way of runoff routing that leads to an improved storm water drainage system in Hoboken.

Low elevation and high groundwater levels influence infiltration capacity and efficiency of the drainage system. The former marshland, covering 450 of the total 730 acres of Hoboken, has a clay, mud and peat soil (20 to 100 feet deep) (Ward, 1878). High runoff potential and very low infiltration rates come together with this. The combined sewer system lies in the infrastructure grid. Many of the original wooden sewers from the 1800s are still present. The storm water drainage system is fully gravity-based. Outlets with valves to the Hudson River carry excess water from the combined sewer trunk lines directly into the river during storms. When heavy rainfall coincides with high tide, excess water backs up in the sewer, causing in particular the low-lying areas to flood. The H1 drainage basin in the southwest is the most flood prone area.

The first wet weather pump, which pumps water in the Hudson River when the valves are closed, started operating in 2011. This pump alleviated the situation, but didn’t prevent the city from flooding. In the current situation, Hoboken has water in the streets once or twice per year. Future regulations may require the North Hudson Sewerage Authority, to reduce the flooding frequency to at least once per four years.

8.2. What adaptation measures are available to increase urban resiliency to flooding in Hoboken?

Flooding does not only have to be countered by increasing discharge- and increasing storage capacity. Blue and green measures have the advantage to solve urban and climatic challenges in a natural way. They provide resiliency and adaptation to flood events, drought and heat stress. With storage on roofs and in basements, buildings can delay rainfall discharge. The shape and material of roads can provide additional storage and infiltration capacity. Green in the urban landscape increases infiltration capacity, but also benefits urban energy consumption, air quality, CO2 reduction, urban heat island, common liveability, habitat improvement and public education. Advantages of blue and green measures include efficient use of limited space in creating a better live-able and safer city.

For the selection of suitable blue-green measures in Hoboken, a wide range of sustainable urban drainage approaches are analysed. The main focus was on the Blue Green Dream Adaptation support tool. This tool supports the cooperation between urban planners, engineers, ecologists and policy makers by providing a visual map-based tool. It ranks preferred measures, based on site-specific conditions and their expected performance in terms of climate adaptation and multi functionality of land use.

The cooperation between urban planners, water management engineers and architects provides opportunities, but also makes implementation more difficult. Although many countries are adopting new national approaches to integrate water management and urban planning, the United States hasn’t. The process of implementation, in which domains like governance, stakeholders, engineering, ecology, spatial planning, urban design and management are involved, influences the performance and success of adaptation measures at different locations.

In terms of the required storage and drainage capacity, the water assignment for Hoboken is calculated. This technical assignment provides a rough measure of the required delay and storage capacity in urban areas for given rain events that exceed the existing storage and pumping capacity (van de Ven, 2013). With a basic hydrological model, the storage is determined on the basis of 100 years of precipitation data. The water assignment isn’t normative. It does not take detailed area characteristics, elevation profile and sewer layout into account and therefore cannot determine the locations where flooding occurs.

With statistics afterwards, the storage volumes for 1, 2, 10 and 50 years design storms is determined. The table below shows the water assignment for these storm events. The volumes of water in the water assignment show the pressure on the current drainage system. During a T1 storm event, the required storage capacity is already twice the available sewer storage of 8.3 MG. For a T10 the excessive volume is 40.9 MG, corresponding to 62 Olympic swimming pools spread over the city. Based on the current storage capacity of 0.5 inch/day, SDF curves show that for a T10 storm, a pumping capacity of more than 15 inch per day would be needed. Due to interconnections, the calculated volumes per sub basin may differ from the actual volumes.

Return period storm event [year]	Rain depth [inch/ 24h]	Depth water assignment [inch]	Water assignment [cu.ft]	Water assignment [MG]
T1	2.72	0.85	2,265,000	16.9
T2	3.29	1.72	3,106,000	23.2
T10	4.96	2.06	5,458,000	40.9
T50	7.07	3.33	8,821,000	66.0

Future regulations may require the North Hudson Sewerage Authority (NHSA), to reduce the flooding frequency on average once every 4 years or a T4 return period (HobokenNJ, 2013). The preferred T10 drainage capacity (5.0 inch in 24h) as set out in the US urban drainage design manual even corresponds with a required T10 storage capacity.

A number of blue-green adaptation measures have been selected for Hoboken based on site suitability. The six-layer approach, which integrates urban planning and subsoil characteristics, gives an overview of the opportunities and constraints for blue and green measures in the area. Well-fitting measures appeared to be subsurface detention storage in the higher elevated areas, storm water flow-through planters, (storm water infiltration) trees and permeable pavement in infrastructure. In public space, parks, water squares, green squares, detention below sports fields, open water and urban farming would fit well. The buildings in Hoboken found to be suitable for rainwater harvest tanks, blue- and green roofs, green facades and urban farming on rooftops. To maximize blue-green benefits, a citywide network of waterways, green areas, green streets and common gardens is proposed.

Five design strategies were developed with combinations of blue-green measures, applied to different layers in the urban system. The first (1) design strategy improves the current situation with the application of subsurface adaptation measures. With a functional analysis, storage possibilities beneath parking lots and sports fields are determined. Two deep storage basins will are proposed. The remaining sports fields and parking lots will be equipped with shallow storage facilities. The second (2) design strategy improves the current situation with the application of infrastructural adaptation measures. This includes surface measures like permeable pavement, storm water infiltration planters and trees along major roads, and green in the streetscape. The third (3) design strategy applies adaptation measures on public space. Undeveloped public areas suitable to rain gardens, storm water trees and flow-through planters, water squares, detention below sport fields, parks, retention ponds (in new/existing green space), urban agriculture, bio retention swales, rainwater harvest cistern and seasonal storage are here for identified. For the fourth (4) design scenario, adaptation measures were applied on private space and buildings. Buildings suitable to place green roofs in the area are analysed. The fifth (5) strategy in the end, combines all proposed measures by in an urban blue-green network. Additional green is applied to the public space. Hollow roads discharge storm water towards open water bodies and green in the streetscape connects green area and open water in the city centre to green belt.

8.3. How can hydro dynamical modelling be used to come to smart solutions for urban design?

To derive effective solutions to structural operational problems, models are of increasing importance. The Storm Water Management Model (SWMM) computes runoff quantity and quality from primarily urban areas, and gives understanding of the hydraulic functioning of the existing and proposed water system to meet future principles. Design storms for every return period are done for the urban water calculations. These design storms were derived from 50 years of 60-minute precipitation data provided by the National Climatic Data Centre (NCDC) at the NY Central Park rain station (NCDC, 2014).

SWMM is built up from a manually modeled network of sub catchments, sewer pipes, manholes, outfalls and pumps. The five design scenarios were added to the basic model by Low Impact Development controls (i.e. green roofs, permeable pavement, bio swales). To quantify the contribution of the design strategies to the water assignment, a number of criteria and parameters are identified. The criteria for design performance are (a) flood volume reduction during heavy rainfall events, (b) CSO reduction, (c) vulnerability reduction of critical public buildings and infrastructure (f.e. Hoboken terminal, hospitals, wastewater treatment plant, electricity distribution locations), and (d) improvement the urban quality of living. Four parameters to evaluate the to evaluate the contribution to flood mitigation and overflow reduction are (1) the flood volume in the drainage area (internal outflow), (2) the runoff per sub-basin, (3) the total storm water storage per sub-basin (excluding sewer storage), (4) critical facilities threatened by flash floods.

All strategies showed contribution to flood volume reduction and creating urban quality, but not all strategies were as effective. Strategy 1 can store about 10% of the total flood volume. It has the least contribution to urban quality, since only subsurface storage, and no vegetated measures were used. Strategy 2 on the other hand, has a very broad effect on the green experience of the city. It includes the greening of three major roads. Strategy 3 uses undeveloped space to create a green network throughout the city. It has the least effect on total flood reduction of all strategies, but uses space that would otherwise lie fallow. In strategy 4, green roofs are applied on all suitable buildings throughout the city. This had a positive effect on both flood reduction, reduction of the urban heat island effect, and air quality. When the roofs are large enough, they can even function as a roof garden, roof restaurant or private kitchen garden. Strategy 5 ultimately, combines all design strategies into a citywide system of blue-green measures. Modeling showed that Hoboken benefits most from design strategy 5 in terms of quantitative flood reduction. This design strategy also has the most additional green through a citywide network of vegetated measures. This citywide system of flood prevention measures provides a pleasant, physical appearance.

8.4. How can water management be effectively integrated in urban planning and design?’

The integration of water systems and vegetated areas makes cities more habitable and resilient in spite of climate change. This visible way of dealing with what happened during Sandy creates a positive vibe over the negative memories. By taking away the reluctance towards flood defense systems in a soft way, the city creates faith in an integrated approach for urban water design. The design of citywide measures proposed in strategy 5 is therefore the most sustainable urban water management solution for Hoboken.

The proposed spatial typology is elaborated in a number of illustrations in paragraph 6.4. Through the urban grid system, vegetated areas are connected to create a new identity of the city. The riverbeds in the east and the areas at the bottom of the cliff, are surrounding the city with a green belt. The green belt along the cliffs serves for both storage and infiltration of water. The three major roads with trees and plants create green veins through the heart of the city. In every part between the major roads parks, urban farms or wetlands can be found. A solid footpath or bicycle lane can be applied along the city borders to create an uninterrupted route.

Strategy 5 is the most comprehensive one and therefor the most complex and challenging one to implement. The suggested urban design is the most extensive one and therefor also the most expensive. Historical research on blue-green measures resulted in implementation costs indications. These results need to be revised for the proposed design and with up to date financial taxes. Support for the design is needed when it comes to realization. Inhabitants, businesses, landowners, the NJ transit and the governance are important stakeholders. However the benefits to the livability of Hoboken and the sustainable social and economic development of Hoboken require this investment.

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Appendices

Appendix I Map of Hoboken sewer system

Figure 50 City of Hoboken Sewer Atlas 1995 (Source: North Hudson Sewerage Authority)

Appendix II Blue green measures

Parks and urban forests

By decreasing the total acreage of paved surfaces, parks and urban forests (Figure 51) increase the infiltration capacity of the soil and therefor have a big impact on flooding mitigation. Additionally, parks increase the quality of urban living by reducing the urban heat island effects, improving air quality and creating a more beautiful environment with more recreational area. Parks don't have to require a lot of space and are easy to maintain. If needed, open water can be created for additional storage. The geomorphology of the soil is an important factor for infiltration capacity, meaning that parks and urban forests only function well on rainfall reduction when the soil drains well. Also groundwater levels need to be relatively deep so that infiltration doesn't create a critical rise of the groundwater table (Fryd, et al., 2013; Pötz & Bleuze, 2012).

Figure 51 Left: New Orleans City Park (Source: tripadvisor.com) and right: Houtan Park, Shanghai (source: policyinnovations.org)

Urban farms

Urban farms (Figure 52) provide increased infiltration capacity of the soil, together with benefits such as recreation, food production, and organic agricultural management. Urban farms can fulfil various roles, such as stock breading and fruit and vegetables growth, which can be combined with patients care or for educational purposes (Pötz & Bleuze, 2012). Urban farms require some space, but if available they suit well in high dense inner-city areas (Pötz & Bleuze, 2012).

Figure 52 urban farms in Philadelphia (left, source: ediblegeography.com) and Boston (source: inhabitat.com)

Storm water infiltration or flow-through planters

Planters are small, vegetated reservoirs to collect and filter storm water runoff. Infiltration planters (Figure 53, left) collect storm water on top of the soils and allow it to flow through vegetation, soil, and gravel. The soil in the planter filters sediment and pollutions as the water infiltrates down through the planter. Flow-through planters (Figure 53, right) store water temporarily on a waterproof layer and include an overflow and a subsurface drainage system to discharge the water (City of Sandy, 2004)

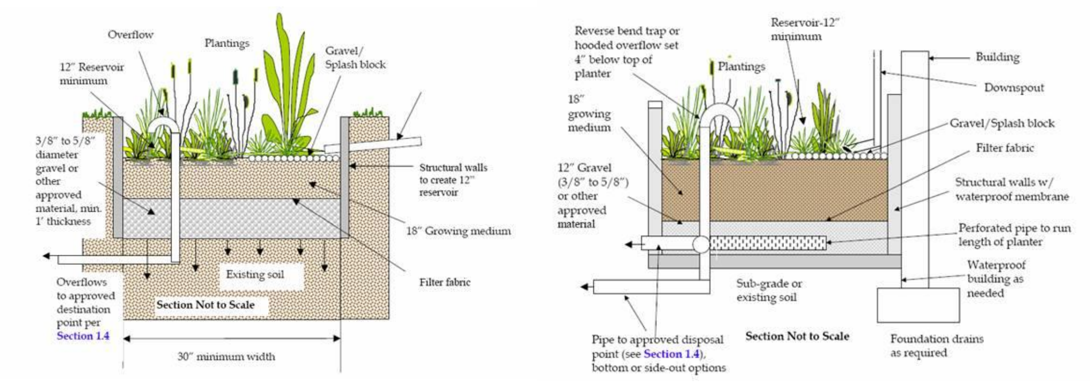

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Figure 53 Infiltration planter (left) and flow-through planter (source: ci.sandy.or.us)

Infiltration planters can be applied on poorly drained sites with contaminated soils. They are ideal to apply on space-limited sites. Besides the reduction and delay of storm water runoff, infiltration planters have a positive effect on water quality and air temperature due to vegetation. It also increases attractiveness of the area. Storm water infiltration planters can be deep or shallow, depending on the wanted buffering capacity. Depending on their size, they can receive disconnected rainwater from surrounding areas. Infiltration measures are low in construction costs since no drain has to be constructed. The maintenance of the plants is often required (Environmental Services City of Portland, 2006). Examples of infiltration planters are given in Figure 54 and Figure 55.

Figure 54 Storm water infiltration/flow-through planter San Francisco (source: spur.org)

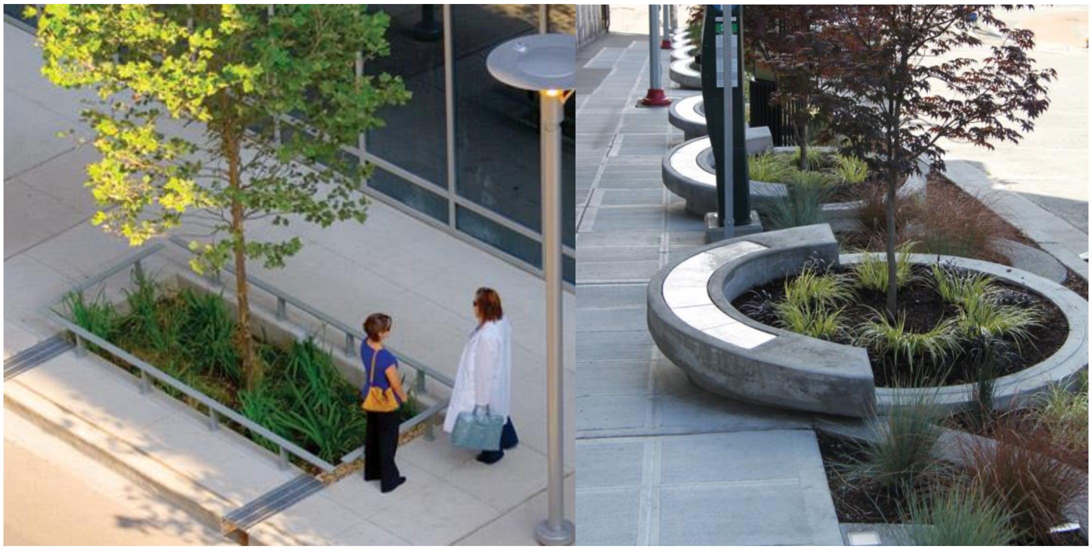


Figure 55 Storm water Infiltration/flow through Planters in Illinois (left) and Seattle (source: spur.org)

Permeable pavement

Permeable pavement (Figure 56) can substitute concrete or tiling to allow storm water to pass through and infiltrate in the soil. Permeable pavement is placed on top of a porous surface layer and an underlying aggregate layer. This bottom layer allows temporary storage before the water infiltrates into the soil. Sometimes the permeable paving contains an aggregate layer with a subsurface pipes to discharge storm water to the sewer system (which makes is then a detention measure). Permeable pavements may be constructed from pervious concrete, porous asphalt, permeable interlocking pavers and several other materials (Pelzer & Tam, 2013)

Permeable pavement can be applied on parking lots, low-traffic streets, driveways, bike paths, patios, plazas and sidewalks. The advantages are the reduction of the storm water runoff volume (up to 70-90% (Foster, Lowe, & Winkelman, 2011)). Also it improved water quality by reducing pollutants in the water. When adding vegetation, it also helps reducing the urban heat island effects. A study in Los Angeles showed that increasing pavement reflectivity by 10-30% could produce a 0.8°C decrease in average temperature, which results to estimated savings of $90 million per year based on less energy use and reduced ozone levels (Foster, Lowe, & Winkelman, 2011). Disadvantages are that it is limited to paved areas with little traffic, it can only be applied on slopes less than 5 percent (Pelzer & Tam, 2013), and it is more difficult to construct on sites with compacted soils like in cities.

Figure 56 Permeable Pavement Vancouver (source: blur.org)

Green roofs and blue roofs

Green roofs (Figure 57 and Figure 58) are vegetated green areas on roofs that can retain or detain water from precipitation. Blue roofs (Figure 57) store water on top of roofs without vegetation. Green roods are composed of multiple layers including a waterproof membrane, subsurface drainage pipes, suitable soils and special selected plants. Green roofs can be applied different types of roofs on both small and large scale. There are two types of green roofs: extensive and intensive. Extensive roofs have a thin system planted with only (drought tolerant) plants and grasses. Intensive roods are deeper and can contain trees, complete gardens with terraces, and roof farms.

Blue and green roofs suit best on flat roofs, but grass can also be placed on sloping areas (less than 20 degrees). Commercial, private, multifamily and industrial buildings are all suitable for blue or green roofs. Both new and existing roofs can be rebuilt to green or blue ones. Green and blue roofs affect in particular the runoff from small storms and can reduce runoff up to 50%. (Hall, 2010). This reduction depends on the type of (green) roof (layers and depth) and vegetation density. The life cycle of green roofs has been estimated to be 40% higher than a conventional roof in terms of storm-water management; electricity costs reductions and air quality benefits. Green roofs provide additional isolation and noise reduction to buildings and it reduces urban heat island effects. The energy savings from green roofs can be a15-45% on annual energy consumption. This is mainly because of its cooling capacity in summer (Foster, Lowe, & Winkelman, 2011). Green roofs, at last, increase biodiversity and habitat and provide aesthetic amenities. Disadvantages are the limits of roof slope, the additional structural support that may be needed to bear increased weight and the maintenance of the vegetation (Pelzer & Tam, 2013). Compared to other green measures it is quite expensive. Green roofs have the difficulty that they often need to be constructed on private space. Grants can be given to stimulate the construction of green roofs.

Figure 57 Left: Green roof, Vancouver (Source: nationalgeographic.com) and blue roof (water roof) (source: reducerunoff.org)

Figure 58 Left: Green roofs in Stuttgart and right: New York City (source: nationalgeographic.com)

Seasonal Storage and Rainwater Harvesting

Seasonal storage basins store water in periods of excessive rainfall, which can be used in periods of drought. Seasonal storage can be provided by vegetated ponds, but also by (subsurface) storage tanks or on rooftops (ClimateAPP, 2014). Storage in a large basin needs a stable site or flat area. They are a good alternative at sites with little infiltration possibility. Seasonal storage basins are low in maintenance.

Rainwater can be harvested in small rainwater tanks (like in private gardens) or in large rainwater cisterns in for example parks. Public rainwater harvest cisterns can efficiently store large volumes of water, like the one in Cumberland Park, Nashville (Figure 59, right). This cistern can store 133,700 cubic feet of storm water per year to reuse for irrigation (Pelzer & Tam, 2013). Private rainwater tanks (Figure 59, left) collect rainwater from impervious areas during peak flows. Rainwater tanks are often known as rain barrels (US) or rain butts (UK) and typically store water from rooftops via rain gutters. The stored water can be used for watering gardens, agriculture, flushing toilets, washing cars, and other non-potable purposes. Private rain barrels can yield 83 cubic feet of water from a 1inch storm event on a 1,000square feet roof (WVWA, 2013). To function properly, both large and small rainwater harvest tanks must be empty prior to a rainfall event.

Figure 59 Private rainwater tank (left) and Cumberland Park, Nashville (source: musiccityblog.wordpress.com)

Detention ponds or tanks

Detention tanks or ponds (Figure 60) can be surface or subsurface structures to harvest rainwater during peak flows and slowly release those flows in the sewer. When no rainfall occurs, the tanks are typically empty (Boer, Jorritsma, & Peijpe, 2010). Detention tanks are usually constructed out of concrete. Perforated subsurface retention systems that release stored storm water to infiltrate into the subsoil are recommended only for areas with well drained soils and where the water table is low enough to permit recharge.

Subsurface storage tanks can be placed below for example parking lots, sport fields, playgrounds, buildings or parking garages. Subsurface storage below parking lots, playgrounds and sport fields are covered with pervious pavement or other material. Both the infiltration water and water from surrounding areas can be stored in these pipes or boxes. Tanks underneath buildings can be used to store rainwater stored captured from the rooftops or along the sides of the building. A storage tank below a parking garage cannot be built below an existing one and therefore the whole garage has to be newly constructed. The tanks can efficiently store a large volume of water. The storage below the parking lot in the picture below in Illinois can hold 33,300 cubic feet of storm water and is constructed beneath a 27,500 square feet parking lot with permeable pavement. The storage below the parking garage in Rotterdam can store 353,000 cubic feet (10,000m3 or 2.64MG) in a 23,000 square feet basin (paulderuiter.nl, 2013). Storage tanks are effective at sites where no storm water infiltration is possible or where the soil is contaminated. A disadvantage of subsurface tanks is the high costs (Illinois storage tank $1.3million, Rotterdam storage $9.1 million (Pötz & Bleuze, 2012)). Also they are difficult to maintain and have no multifunctional benefits for the environment.

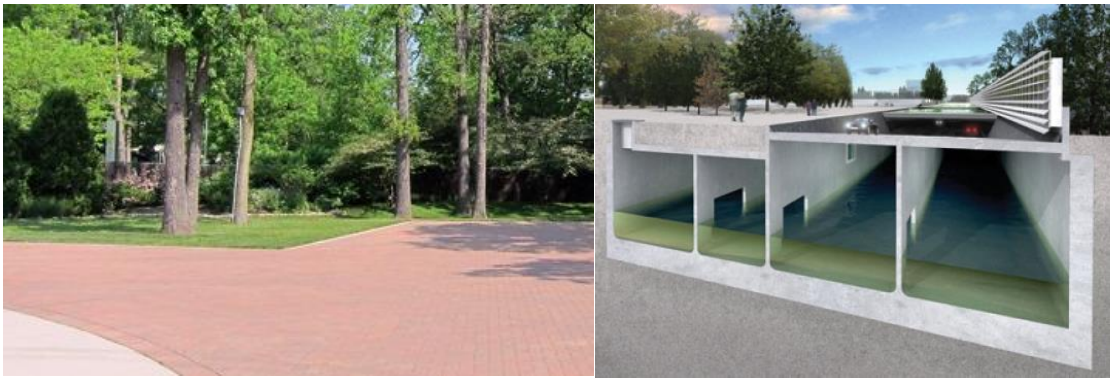


Figure 60 Left: Parking lot on top of storage tank, Illinois (Source: la foundation) and right: storage beneath parking garage, Rotterdam (source: Nooijer, 2011)

Open detention ponds are surface structures that fill with water during and right after a (heavy) rainfall. Detention ponds can either be close to water bodies (to store flooding water temporarily) or in inner-city areas as (green) water squares. The Benthem square in Rotterdam (Figure 61) is most of the year dry and only fills during heavy rainfall. The square can store up to 60,000 cubic feet (0.4 MG) in different layers in the square (Boer, Jorritsma, & Peijpe, 2010). In dry periods it can be used as a recreational square for sports, play and hangout. The square only fills with rainwater from the surrounding environment during extreme rainfall. Water squares are generally used in densely built up areas with little space left.

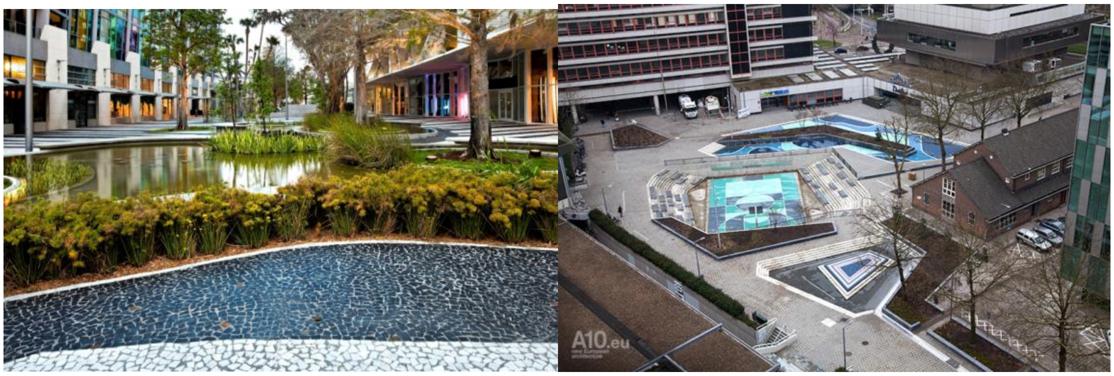


Figure 61 Left: Lincoln Road, Miami Beach (source: huffingtonpost.com) and right: Benthem watersquare, Rotterdam (source: de Urbanisten, 2013)

Green facades

Green facades (Figure 62), vertical vegetation against the wall of a building, have a minimal impact on rainfall runoff, but have a lot of additional benefits. It can reduce the interior surface temperatures by as much as 10°C, it reduces sound reflection, it reduces air pollution and through shading, green walls can lower temperatures in summer and reduce energy costs by 23 percent (Loh, 2008).

Figure 62 Left: vertical garden, CaixaForum Madrid (source: blogspot.com) and right: green façade (source: MMA architecture)

Retention ponds

Retention ponds or retention basins (Figure 63, Figure 64) are open water bodies that are used to store storm water runoff and prevent downstream erosion and improve water quality. Retention ponds are artificial lakes that are permanently filled with water and vary in water level depending on receiving waters. Retention ponds differ from infiltration ponds, which are designed to direct storm water to the groundwater through permeable soils. They also differ from detention ponds that are typically empty and only sill with water during or after a storm event.

The advantages of retention ponds are rainfall runoff reduction, water quality improvement, it creates biodiversity and it benefits the aesthetic value or the area.

Figure 63 Urban retention ponds (source: left, ASCE’s, right, landscapeonline.com)

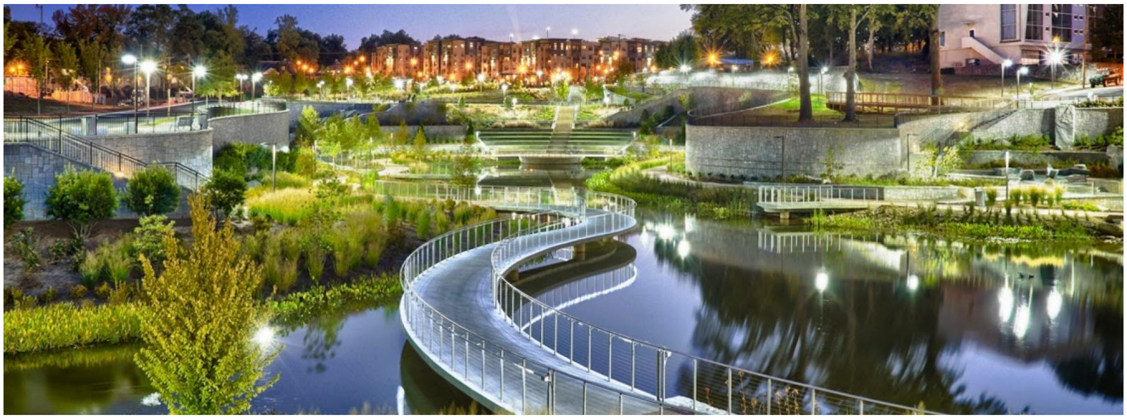


Figure 64 Historic Fourth Ward Park Atlanta (source: beltline.net)

Add green to the streetscape and open (private) space

Green can be added to the streetscape and (private) open space in the form of vegetation, grass, or shrubbery (Figure 65). This decreases the permeability so that more water can infiltrate in the ground. When water infiltrates in the soil, it removes pollutants, which increases water quality and replenishing of the groundwater. Also vegetation benefits heat reduction, biodiversity, and air quality (Pötz & Bleuze, 2012). Green in the streetscape does not have a big impact on the rainfall runoff, but has many other advantages towards the quality of urban life and is easy and cheap to implement on a large variety of sites.

Figure 65 Left: green square, Sydney (source: cityofsydney.nsw.gov.au) and right: urban green (source: urbangreen-space.co.uk)

Artificial urban wetlands

Urban wetlands (Figure 66) are man-made overflow areas for rivers. They are designed to reduce, detain and treat storm water runoff. Constructed wetlands have many functions corresponding to natural wetlands, like flood control, improving water quality and the growing of wetland plants, and they simulate natural wetland ecosystems.

Wetlands must be applied on relatively flat areas (less than 2 percent grade). They can be applied to various sizes site conditions and budgets. Wetlands can receive water form upstream slopes. Besides the great addition to rainfall runoff reduction, urban wetlands improve water quality, heat reduction, biodiversity, air quality, and they benefit the socio economic value of the area (Pötz & Bleuze, 2012). Urban wetlands can also been constructed in combination with a wastewater treatment plant. When both are combined, the costs will decrease from $10.00 per gallon to $5.00 per gallon, due to reduced advanced treatment costs (Hilke, 2013). Urban wetlands are, due to limited space in the city, not suitable to place next to the riverside. Disadvantages are that urban wetlands are relatively space consuming and therefor high in costs. Also it requires periodic maintenance to vegetation and to remove debris (Pelzer & Tam, 2013).

Figure 66 Qunli Wetland Park (source: turenscape.com)

Hollow roads

Increasing the height difference between street level and ground floor level can provide storage and drainage capacity of storm water (Figure 67). The road needs to be on a slope to direct the water flow to a gutter, water body, or an infiltration field (ClimateAPP, 2014). Raised sidewalks/curbs can even increase storage capacity. The roads can still be accessible by traffic when it rains, but can cause some nuisance due to splashing water. Accessibility for disabled can be a problem due to the slope (ClimateAPP, 2014).

Figure 67 Hollow Road (source: Atelier Dreiseitl)

Storm water trees

Storm water trees are placed next to roads and can be combined with subsurface trenches (Figure 68). Storm water runoff flows into the highly permeable storm water tree trenches, which are connected underground. When storage capacity is exceeded, the storm water overflows into a bypass (Philadelphia Water Department, 2014). Planting trees on streets, squares and parking lots also creates shade. Evaporation will have a cooling effect. Studies have shown the net economic benefits of urban trees range from $30-90 per tree per year. This includes storm water benefits (average $0.66/cubic foot of storage), carbon storage (700 million tons storage in urban trees in 2005) and the cooling savings when trees canopy over a house (annual heating savings of 2-8%). Also studies have found that residential property values increase up to 37% with the presence of trees and vegetation on the property (Foster, Lowe, & Winkelman, 2011). Hoboken has already many streets lined with trees. More trees would create more shade and evaporation, but also less sunshine to penetrate into the streets.

Figure 68 Left: storm water trees Ohio (Source: continuingeducation.construction.com) and right: impression of storm water trees with subsurface chamber (Source: waterworld.com)

Open channel water

Open channel water, for example in ditches, channels, or streams (Figure 69), can be the construction of a new, or uncovering and restoring the natural water behavior of a historical water. This can improve rainfall runoff; it increases storage and enhances local neighborhoods. Since it is often very hard to uncover historic creeks in urban dense areas, they can also be applied through existing low-lying open space. When applied on natural soil, open water has as an additional benefit that infiltration and groundwater recharge is increased. Also is improves biodiversity and provides aesthetic benefits. A disadvantage of open water streams is the high installation and maintenance costs, and requires much space, which often includes land acquisition.

Figure 69 Left: Thornton Creek, Seattle (Source: spur.org) and right: Seoul (Source: kennislink.nl)

Bio retention swales

Bio retention swales are ditches with vegetation, made of porous soil (Figure 70). Below the visible layer, a layer with large empty spaces (infiltration boxes, gravel, etc.) is constructed. Disconnected rainwater from the environment can be discharged into the bio swale. Water from the swale flows to the sewer system through an infiltration drain/pipe in the third layer. When the water level rises above a certain level it will enter the drain via an overflow (Pötz & Bleuze, 2012). Bio swales can help enhance biodiversity and an improved living environment.

Figure 70 Bio retention swales (Source: both the University of Washington)

Rain gardens

Rain gardens or bio retention cells (Figure 71) collect rainwater runoff from impervious areas like roofs, parking lots and walkways, and hold it in a (often) vegetated, depressed area to infiltrate in the soil. Rain gardens and bio retention cells can be connected to the sewer systems through an overflow (that makes it then a detention measure), but are usually sized to infiltrate the collected storm water runoff into the ground (Pelzer & Tam, 2013). (Bio) retention swales

Rainwater gardens are suitable for residential yards, offices and commercial storefronts, parks, right-of-ways and parking lots. Advantages are that they are relatively easy to install, can be applied on a wide range of scales. Assessment of bio retention areas and rain gardens has shown a peak flow reduction of at least 96.5% for small to medium sized storm events (Demurze, et al., 2014). Besides rainfall runoff reduction it improves air and water quality. Also they are aesthetically pleasing for residents (Pelzer & Tam, 2013). A disadvantage is that it requires relatively flat site.

Figure 71 Rain garden in Malmo, Sweden (source: nerdyplanner.blogspot.com)

Appendix III Precipitation analysis

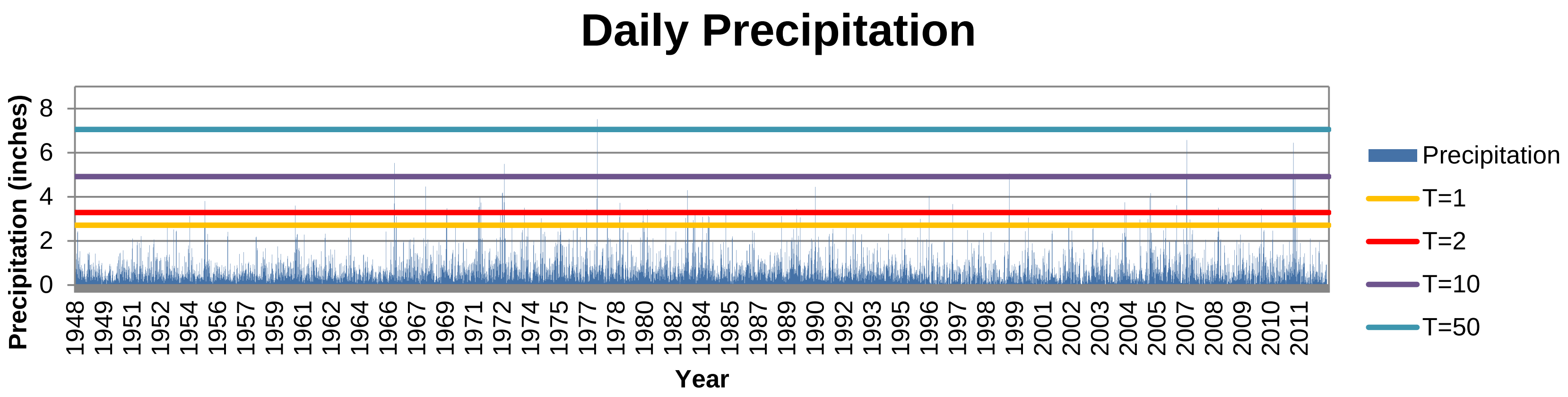


Figure 72 Daily precipitation in Hoboken (source: NOAA, 2014)

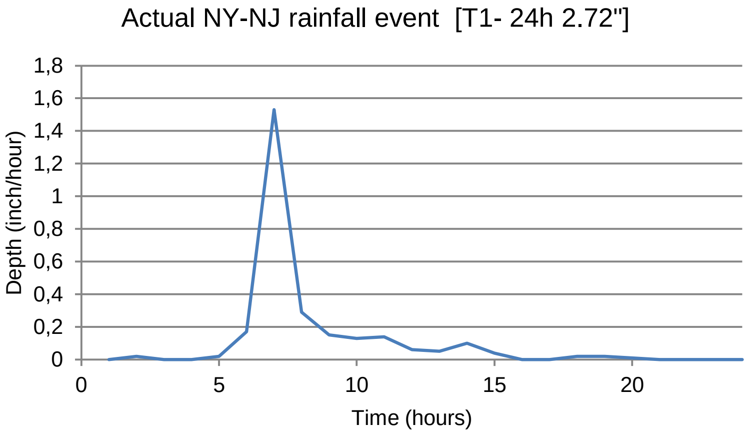


Figure 73 Actual T1 rainfall event NY-NJ

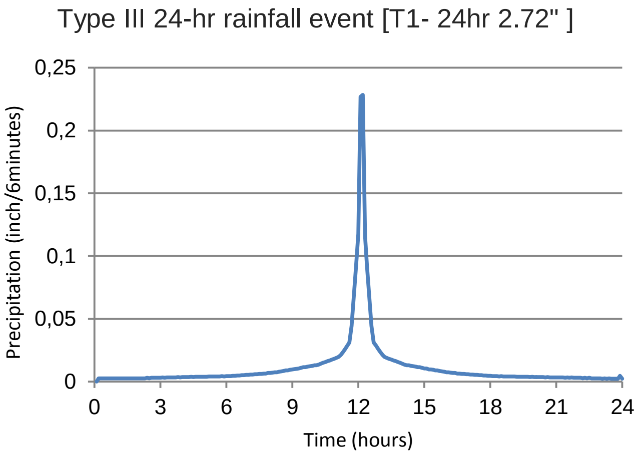


Figure 74 Type III rainfall event for T1

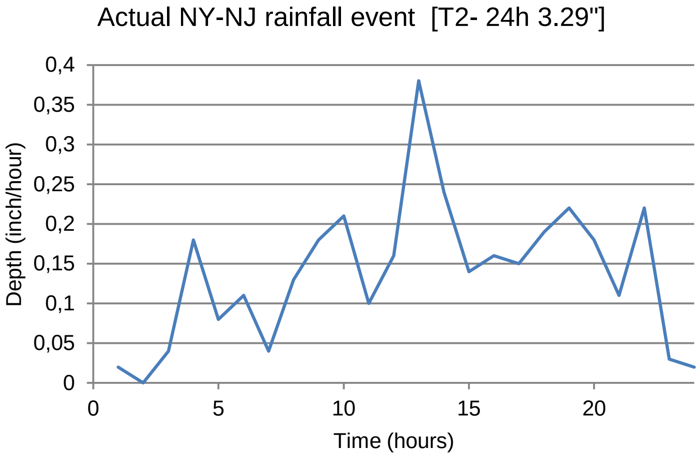


Figure 75 Actual T2 rainfall event NY-NJ

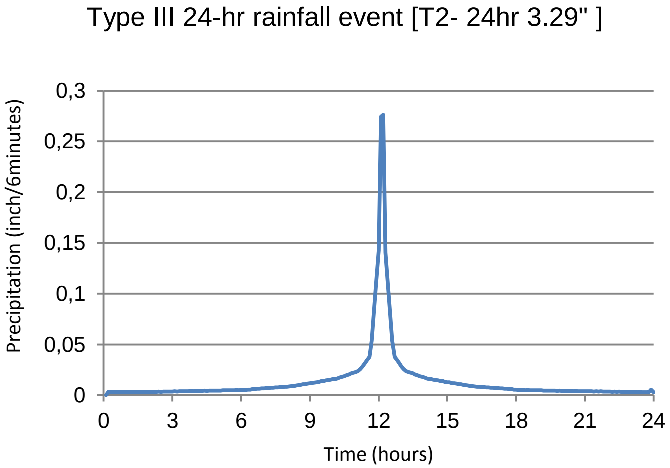


Figure 76 Type III rainfall event for T2

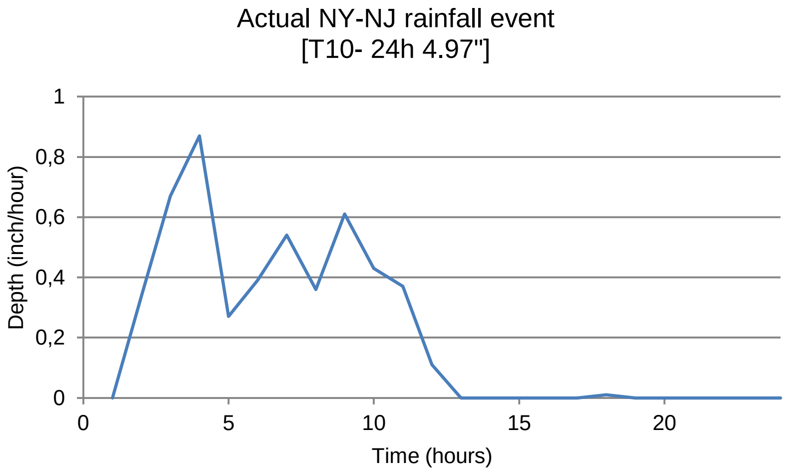

Actual NY-NJ rainfall event [T10- 24h 4.97"]

Figure 77 Actual T10 rainfall event NY-NJ

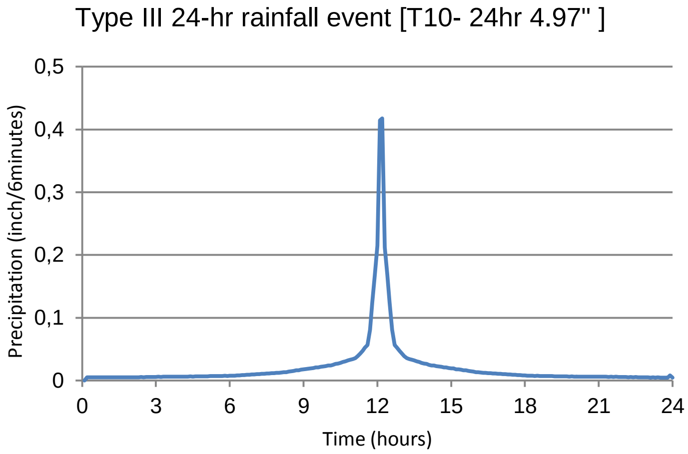
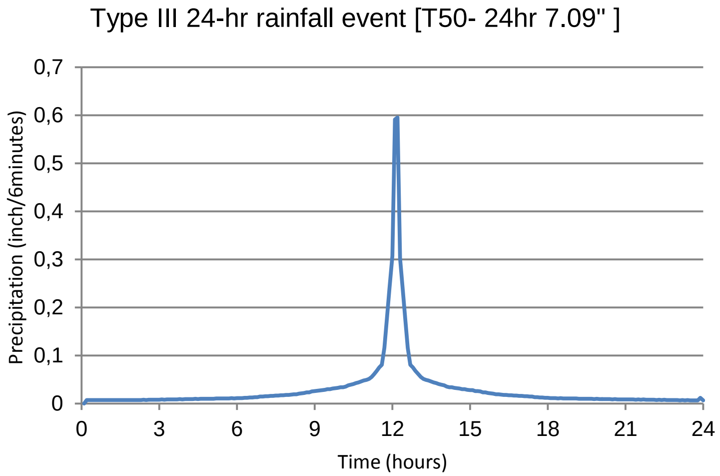

Type III 24-hr rainfall event [T10- 24hr 4.97"]

Figure 78 Type III rainfall event for T10


Type III 24-hr rainfall event [T50- 24hr 7.09"]

Actual T50 rainfall event not available

Figure 79 Type III rainfall event for T50

Appendix IV Water Assignment calculation

Table 19 Summary of area distribution (source: NLDC, 2006)

	Total surface [acre]	**Open water [acre]**	**Impermeable surface [acre]**	**Permeable surface [acre]**	**Impermeable [%]**
H1	263	0	220	43	84
H2	30	0	23	7	77
H3	68	0	52	16	76
H4	107	0	85	22	79
H5	159	0	115	44	72
H6	28	0	23	5	82
H7	81	0	62	19	77
Total	**736**	**0**	**581**	**155**	**79**

Table 20 area characteristics that influence rainfall runoff

Basin	**Area [acre]**	**Sewer storage [inch/ac]**	**Rainfall runoff [%]**	**Pumping capacity [inch/(ac*day)]**
H1	264	0.55	83.8	2.5
H2	30	0.35	75.7	2.5
H3	68	0.52	76.0	2.5
H4	107	0.69	79.7	2.5
H5	153	0.35	77.3	2.5
H6	28	0.12	82.9	2.5
H7	80	0.51	74.7	2.5
Total basin	730	0.44	78.9	2.5

Table 21 Potential water storage in sewer system

Sub basin	Sewer Storage [ft^3]	Sewer Storage [MG]	Sewer Storage [inch/acre]
H1	400,694	3.00	0.55
H2	33,377	0.25	0.35
H3	106,663	0.80	0.52
H4	239,563	1.79	0.69
H5	160,322	1.20	0.35
H6	11,578	0.09	0.12
H7	159,570	1.19	0.51
Total	**1,111,768**	**8.32**	**0.44**

Table 22 Water Assignment calculations

					T1 = 2.72		T2= 3.29		T10= 4.96		T50 =7.07	
Basin	**Area [acre]**	**Sewer storage [in/ac]**	**Rainfall runoff [%]**	**Pump cap. [in/(ac* d)]**	**Volume [acre*ft]**	**Depth [in/acre]**	**Volume [acre*ft]**	**Depth [in/acre]**	**Volume [acre*ft]**	**Depth [in/acre]**	**Volume [ac*feet]**	**Depth [in/acre]**
H1	264	0.55	83.8	2.5	15.5	0.71	23.0	1.05	53.7	2.45	92.4	4.22
H2	30	0.35	75.7	2.5	1.6	0.62	2.3	0.92	5.5	2.18	9.5	3.78
H3	68	0.52	76.0	2.5	3.0	0.53	4.4	0.84	12.0	2.12	21.2	3.74
H4	107	0.69	79.7	2.5	4.5	0.50	7.4	0.82	19.2	2.16	34.3	3.84
H5	153	0.35	77.3	2.5	7.0	0.53	10.7	0.81	26.7	2.02	47.0	3.54
H6	28	0.12	82.9	2.5	2.3	0.99	3.1	1.33	6.4	2.73	10.5	4.49
H7	80	0.51	74.7	2.5	3.6	0.53	5.6	0.83	14.2	2.11	25.1	3.72
Total basin	**730**	**0.44**	**78.9**	**2.5**	**37.5**	**0.61**	**56.8**	**0.93**	**137.7**	**2.24**	**239.9**	**3.91**

Appendix V Model calibration and verification

Table 23 Flooded nodes and flood volumes calibration 1-year data series

Node	Total Volume (MG)	Maximum Flood Rate (CFS)	Subbasin
J5	0.06	14.0	H5_4
J70	0.08	3.8	H6
J71	0.20	11.1	H6
J149	0.06	7.4	H7_1
J153	0.07	8.7	H7_1
J160	0.22	4.2	H5_1
J177	0.12	18.4	H3_1
J190	0.07	6.0	H1_10
J194	0.45	56.9	H1_11
J205	0.02	1.4	H1_6
J206	0.14	17.7	H1_6
TOTAL FLOODING	**1.63**		

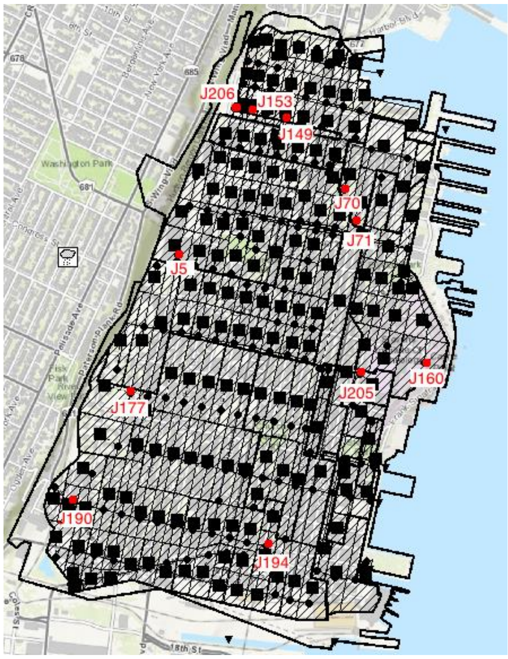


Figure 80 Overflowing nodes 1-year precipitation data series

Appendix VI Design Strategies

Table 24 Area characteristics

Basin	Area [acre]	Percent impervious [%]	Impervious area [acre]	Pervious area [acre]	Parks [acre]	Parking [acre]	Flat Roofs [acre]	Undeveloped land [acre]
H1_1	17.4	86.3	15	2.4	0.0	0.0	2.2	0.0
H1_2	19.9	85.5	17	2.9	0.2	1.2	0.3	0.0
H1_3	24.2	76.0	18.4	5.8	1.9	0.8	0.7	0.0
H1_4	19.0	85.7	16.2	2.8	0.3	4.1	2.7	0.0
H1_5	24.9	86.3	21.5	3.4	0.1	0.0	0.3	0.2
H1_6	28.6	81.1	23.2	5.4	0.0	0.0	0.0	0.0
H1_7	20.6	86.3	17.8	2.8	0.0	1.4	1.7	0.0
H1_8	25.1	85.8	21.5	3.6	0.5	2.6	4.5	0.0
H1_9	17.3	83.2	14.4	2.9	0.0	0.3	2.2	0.0
H1_10	27.7	82.8	22.9	4.8	0.1	2.9	5.2	0.0
H1_11	38.9	83.2	32.4	6.5	0.4	3.9	4.8	0.0
Total H1	**263.5**	**83.8**	**220.2**	**43.3**	**3.5**	**17.0**	**24.4**	**0.2**
H2	30.0	75.7	22.7	7.3	0.0	3.9	4.4	0.0
Total H2	**30.0**	**75.7**	**22.7**	**7.3**	**0.0**	**3.9**	**4.4**	**0.0**
H3_1	38.6	78.1	30.1	8.5	1.7	1.0	1.1	0.0
H3_2	20.0	73.4	14.7	5.3	1.7	0.0	1.8	0.0
H3_3	9.5	76.6	7.3	2.2	0.2	0.5	4.1	0.0
Total H3	**68.2**	**76.0**	**52.1**	**16.0**	**3.6**	**1.4**	**7.0**	**0.0**
H4_1	23.0	74.6	17.1	5.9	2.	0.0	1.9	0.0
H4_2	24.7	78.7	19.4	5.3	1.4	0.0	1.0	0.0
H4_3	30.1	81.2	24.5	5.6	0.0	0.0	4.8	0.8
H4_4	28.9	84.2	24.4	4.5	0.3	1.2	5.7	3.6
Total H4	**106.7**	**79.7**	**85.4**	**21.3**	**3.7**	**1.2**	**13.4**	**4.4**
H5_1	45.5	53.6	24.4	21.1	2.8	1.9	0.0	0.0
H5_2	32.2	81.5	26.3	5.9	0.0	2.4	3.8	0.0
H5_3	38.0	88.3	33.5	4.5	0.0	0.4	5.8	8.3
H5_4	20.4	87.8	17.9	2.5	0.8	1.9	6.7	1.5
H5_5	17.3	75.2	13.0	4.3	5.4	0.0	0.0	0.0
Total H5	**153.4**	**77.3**	**115.1**	**38.3**	**9.1**	**6.6**	**16.4**	**9.8**
H6	28.2	82.9	23.4	4.8	0.3	3.4	4.4	0.0
Total H6	**28.2**	**82.9**	**23.4**	**4.8**	**0.3**	**3.4**	**4.4**	**0.0**
H7_1	35.3	88.8	31.4	3.9	0.0	5.7	7.3	3.0
H7_2	24.0	82.2	19.8	4.2	0.0	3.4	2.1	0.0
H7_3	20.3	53.1	10.8	9.5	2.0	1.7	4.5	3.4

Total H7	**79.7**	**74.7**	**62.0**	**17.7**	**2.0**	**10.9**	**13.9**	**6.4**
Total basin	**729.6**	**78.9**	**580.9**	**148.7**	**22.1**	**44.4**	**83.8**	**20.8**


Figure 81 Washington Street (source: Google street view)


Figure 82 Willow Avenue (source: Google street view)

Figure 83 Jefferson Street (source: google street view)

Appendix VII Simulation Results

Table 25 Design criteria results for T1 design storm

	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Flood Volume (MG)	8.6	6.0	7.8	8.0	6.3	4.0
Stormwater Storage (MG)	0.0	2.8	0.0	0.5	0	2.7

Table 26 Design criteria results for T2 design storm

	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Flood Volume (MG)	13.6	10.6	12.6	12.9	10.7	7.0
Stormwater Storage (MG)	0.0	2.9	0.0	0.6	0.0	2.8

Table 27 Design criteria results for T50 design storm

	Strategy 0	Strategy 1	Strategy 2	Strategy 3	Strategy 4	Strategy 5
Flood Volume (MG)	52.7	49.6	49.8	51.5	45.6	39.8
Stormwater Storage (MG)	0	1.6	0	0.3	0.0	3.3

Table 28 Rainfall runoff per sub basin for T1 design storm

	Total Volume Stormwater [MG]	Strategy 0 [MG]	Strategy 1 [MG]	Strategy 2 [MG]	Strategy 3 [MG]	Strategy 4 [MG]	Strategy 5 [MG]
H1	35.4	11.2	11.2	10.8	11.2	10.4	10.1
H2	4.0	1.2	1.2	1.1	1.2	1.1	1.0
H3	9.2	2.7	2.7	2.6	2.7	2.5	2.4
H4	14.4	4.6	4.6	4.5	4.6	4.1	4.1
H5	21.4	5.5	5.5	5.3	5.2	4.9	4.7
H6	3.8	1.2	1.2	1.1	1.2	1.1	1.0
H7	10.9	3.5	3.5	3.2	3.4	3.0	2.7
TOTAL	**99.1**	**29.9**	**29.9**	**28.7**	**29.4**	**27.1**	**25.8**

Table 29 Rainfall runoff per sub basin for T2

	Total Volume Stormwater [MG]	Strategy 0 [MG]	Strategy 1 [MG]	Strategy 2 [MG]	Strategy 3 [MG]	Strategy 4 [MG]	Strategy 5 [MG]
H1	35.4	13.9	13.9	13.5	13.9	12.9	12.5
H2	4.0	1.5	1.5	1.4	1.4	1.3	1.2
H3	9.2	3.3	3.3	3.2	3.3	3.1	3.0
H4	14.4	5.8	5.8	5.7	5.8	5.2	5.1
H5	21.4	6.8	6.8	6.6	6.4	6.1	5.8
H6	3.8	1.5	1.5	1.4	1.5	1.4	1.2
H7	10.9	4.4	4.4	4.0	4.2	3.8	3.4
TOTAL	**99.1**	**37.2**	**37.2**	**35.7**	**36.5**	**33.7**	**32.2**

Table 30 Rainfall Runoff per sub basin for T50 design storm

	Total Volume Stormwater [MG]	Strategy 0 [MG]	Strategy 1 [MG]	Strategy 2 [MG]	Strategy 3 [MG]	Strategy 4 [MG]	Strategy 5 [MG]
H1	35.4	33.5	33.5	32.6	33.4	31.2	30.2
H2	4.0	3.6	3.6	3.4	3.6	3.2	3.0
H3	9.2	8.2	8.2	7.9	8.2	7.6	7.3
H4	14.4	14.0	14.0	13.6	14.0	12.6	12.3
H5	21.4	16.7	16.7	16.0	15.7	14.9	14.2
H6	3.8	3.7	3.7	3.5	3.7	3.3	3.0
H7	10.9	10.5	10.5	9.6	10.2	9.2	8.3
TOTAL	**99.1**	**90.1**	**90.1**	**86.5**	**88.7**	**81.1**	**78.1**

Table 31 Flood volume per drainage basin for T1 design storm

Return period T1	Strat.0Volume [MG]	Strat.1Volume [MG]	Strat.2Volume [MG]	Strat.3Volume [MG]	Strat.4Volume [MG]	Strat.5Volume [MG]
H1	3.89	2.12	3.63	3.89	3.09	1.49
H2	0.0	0.0	0.0	0.0	0.0	0.0
H3	1.01	0.87	0.95	1.01	0.78	0.60
H4	1.22	0.26	1.08	1.22	0.78	0.03
H5	0.22	0.04	0.19	0.22	0.12	0.02
H6	1.30	1.01	1.20	1.28	1.13	0.79
H7	0.96	0.15	0.75	1.22	0.43	0.0

Table 32 Flood volume per drainage basin for T1 design storm

Return period T2	Strat.0Volume [MG]	Strat.1Volume [MG]	Strat.2Volume [MG]	Strat.3Volume [MG]	Strat.4Volume [MG]	Strat.5Volume [MG]
H1	5.78	3.47	5.49	5.78	4.89	2.64
H2	0.0	0.0	0.0	0.0	0.0	0.0
H3	1.62	1.37	1.52	1.62	1.21	1.05
H4	2.13	0.71	1.98	2.13	1.57	0.39
H5	0.64	0.12	0.54	0.65	0.34	0.05
H6	1.33	1.30	1.53	1.63	1.44	1.03
H7	2.07	0.73	1.50	1.74	1.13	0.13

Table 33 Flood volume per drainage basin for T1 design storm

Return period T50	Strat.0Volume [MG]	Strat.1Volume [MG]	Strat.2Volume [MG]	Strat.3Volume [MG]	Strat.4Volume [MG]	Strat.5Volume [MG]
H1	20.68	14.12	19.84	20.67	18.57	11.73
H2	0.17	0.09	0.14	0.17	0.09	0.05
H3	6.06	5.31	5.80	6.05	5.33	1.40
H4	8.67	5.74	8.32	8.66	7.51	4.65
H5	4.94	2.67	4.63	4.94	4.00	1.77
H6	4.18	3.35	3.88	4.13	3.79	2.82
H7	7.99	6.19	7.21	7.99	7.17	4.29