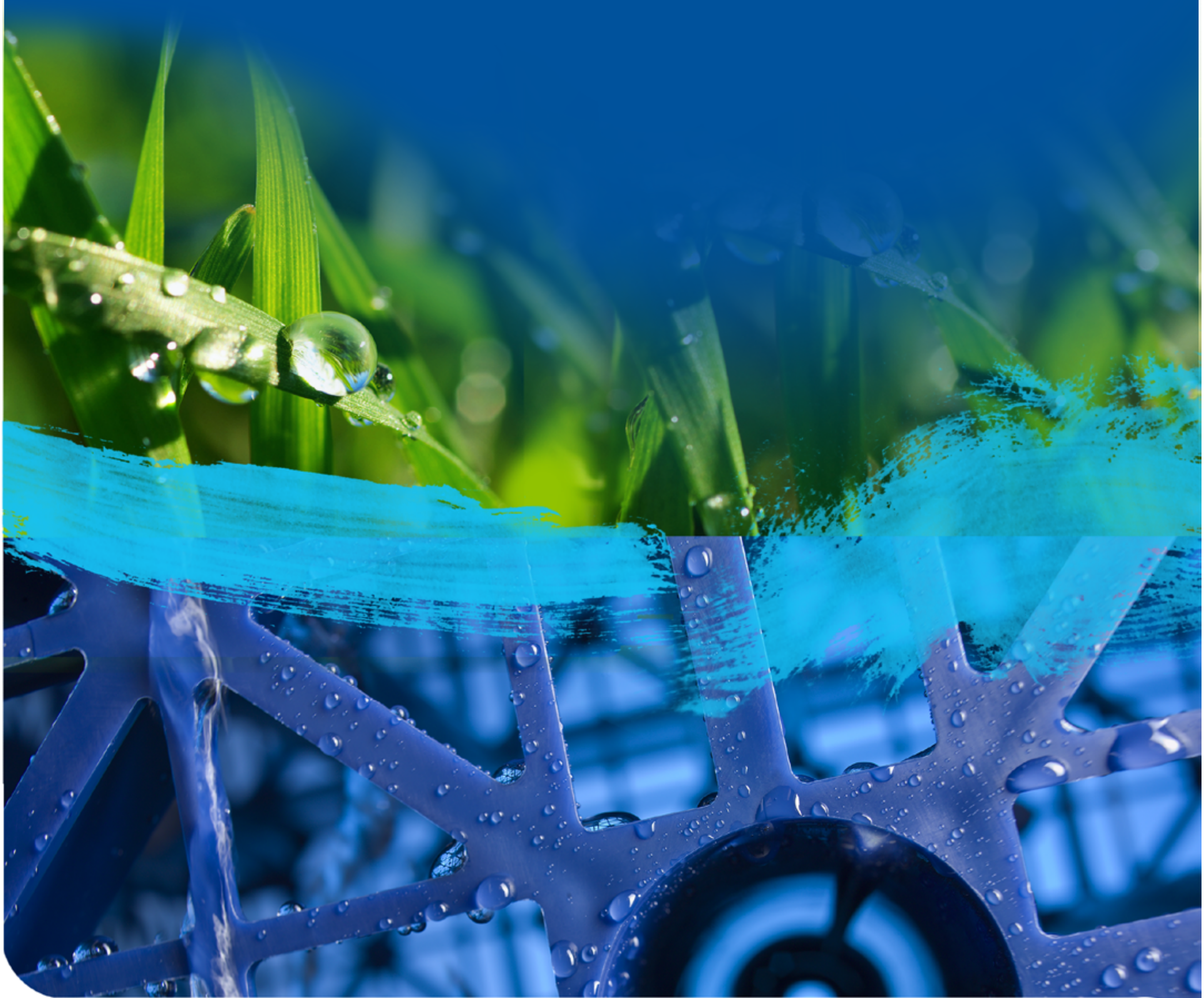
MASTER THESIS

STORM WATER MANAGEMENT SOLUTIONS TO IMPROVE URBAN CLIMATE RESILIENCE

a capillary water system



Evelyn van de Bildt
Industrial Design Engineering
December 2018

wavin
CONNECT TO BETTER

UNIVERSITY OF TWENTE.

STORM WATER MANAGEMENT SOLUTIONS TO IMPROVE URBAN CLIMATE RESILIENCE

a capillary water system

Author

Evelyn van de Bildt BSc.
Industrial Design Engineering
Human Technology Relations
e.m.vandebildt@student.utwente.nl

Graduation committee

Prof. dr. ir. M.C. van der Voort
Human Centred Design
Faculty of Engineering Technology
University of Twente

Dr. Ir. J. Vinke-de Kruijf
Construction Management and Engineering
Faculty of Engineering Technology
Univeristy of Twente

R.J. den Haan MSc.
Design, Production and Management
Faculty of Engineering Technology
University of Twente

Ir. G.J. van Dijk
European Product Manager
Storm Water Management
Wavin Group Zwolle

CONNECT TO BETTER

UNIVERSITY OF TWENTE.

PREFACE

This master thesis serves as a foundation to conclude my master's degree Industrial Design Engineering at the University of Twente. Over the past eight months, I have worked in collaboration with Wavin Zwolle on this research topic.

The assignment was initiated by Geertjo van Dijk at Wavin, wherefore I would like to give my gratitude to him for giving me this opportunity and support throughout the research. At the University of Twente, my supervisor Robert-Jan den Haan deserves a special thank for his guidance, feedback and the inspiration for setting up this research.

In addition, I would like to thank all employees of Wavin Zwolle for providing an educational and enjoyable workplace in the phase of my research, as well as everyone involved at Wavin T&I in Dedemsvaart. At T&I, I want to thank Alwin Huisjes for helping me out during my laboratory tests. In addition to this, a thanks goes to Arjen van der Ziel at Wavin, the Netherlands in Hardenberg for setting aside some of his valuable time for interviews and showing the production hall. Finally, I would like to thank all interviewees for their useful input.

Evelyn van de Bildt
Enschede, December 2018

CONTENTS

GLOSSARY

Attenuation	a solution to provide below ground buffering and to release water slowly
Climate resilience	the capacity of a system, such as a city, to prepare for, respond to, and recover from damage associated with climate change to keep human and nature activity
Climate mitigation	the action designed to reduce human impact on climate change
Detention	the buffering of water over a period of time, but eventually discharge a controlled amount of water, sometimes called "dry pond"
Rainwater harvesting	the collection, filtering, and storage of rainwater to replace water in non-potable applications, such as toilets, washing machines, and irrigation systems to reduce water consumption
Retention	the buffering of water in a permanent pool with vegetation in its design, sometimes called "wet pond"
Runoff	the flow of water that occurs when excess storm water flows over the surface
Storm water	the surface runoff from rain events that enter the drainage system
Urban area	the inner city and the surrounding area with high population density and built-up surfaces
Urban heat island	an urban area that is significantly warmer than its surrounding areas due to human activity

ABBREVIATIONS

DT	Drainage and Transport
EEA	European Environment Agency
IT	Infiltration and Transport
MCH	Maximum capillary height
NAS	National Climate Adaptation Strategies
PA	Polyamide
PE	Polyetheen
PP	Polypropyleen
PUR	Polyurethaan
PVC	Polyvinyl chloride
PVD	Pre-fabricated Vertical Drains
SuDS	Sustainable Drainage Systems
SWM	Storm Water Management
TRIZ	Theory of Inventive Problem Solving
TRL	Technology Readiness Levels
T&I	Technology & Innovation
UHI	Urban Heat Island
WHC	Water holding capacity
WAP	Water absorption pattern

SUMMARY

The urban water cycle is becoming increasingly unbalanced due to the growing urbanization and climate change. Every year, heavy rainfall and flooding events are increasing in both frequency and intensity. Combined with the rapid urbanization, this causes some serious challenges for many cities in Europe. As rainfall becomes more intense, the surface runoff can exceed the capacity of drainage and sewer systems. Furthermore, as cities have a large amount of impermeable surfaces, such as pavement, the percentage of rainfall absorbed by the soil is very low. The cities' challenge is to manage storm water of impervious surface in urban areas, and to address sewer overflow problems. However, the increasing urbanization, on-going density, and paving of ground surfaces result not only in water related challenges but also contribute to higher temperatures and longer periods of drought in cities.

Urban water management needs to be improved to make urban areas climate resilient. Public space can play an important role in coping with the extreme rainfall. This space can serve as temporary water storage, while the precipitation can be discharged over a longer period of time. However, space in an urban area is limited and therefore valuable. This research aims to contribute to storm water management solutions for climate-resilient cities in order to support Wavin in developing and implementing above ground solutions.

Highly urbanized areas are significantly warmer than the surrounding area. This is mainly due to the fact that paved surfaces and buildings absorb heat and diminish the evaporation from the ground and plants. Municipalities are conducting stress tests to map out the consequences of climate change in terms of urban flooding, heat waves, and drought. From the information collected during interviews, it can be concluded that adaptation plans and projects focus less on mitigating higher temperatures than on water management. Moreover, a market research was carried out that summarized broad-scaled effective above ground solutions. This, too, showed that existing solutions mainly consist of water related solutions.

Current trends and existing solutions to climate change adaptation were compared using a game technique. The results showed that future solutions have to focus on multifunctional solutions to: 1) achieve the water challenges; 2) mitigate the effect of higher temperatures; and 3) provide added value. Therefore, this research seeks to bridge the gap between the indication of vulnerable locations and the customer's search for multifunctional water systems.

To align the findings to Wavin's capabilities, this research suggests the incorporation of lower green areas to reduce surface temperatures through evaporative cooling as a potential solution. Calculations to measure the cooling effect show that the availability of rainwater has become a limiting factor in cities. To develop and implement evaporative cooling, water needs to be saved for longer periods of drought.

This results in an innovative technique, so called capillary irrigation, that uses a minimal amount of water. The technique enables constant transport of water from a below ground storage tank to the vegetation root zone which provides day-to-day evaporation to locally decrease air temperature. Capillary action is based on transporting water upward through absorbent material without the assistance of pumps. This fits the customer requirement to minimize maintenance. Several materials were tested to present the feasibility of the final concept. During the refinement of the final concept, it was concluded that it is important to create a very fine structure to improve the capillary action. Finally, recommendations are put forward to implement and develop the capillary water system in order to make cities more resilient to a warmer climate.

1. INTRODUCTION

This chapter provides an introduction to the master thesis and clarifies the research topic. It introduces the company Wavin and its motives for research. After this, the outline of the thesis is presented.

1.1 Background study of Storm Water Management

Climate change is altering rainfall patterns across Europe and across the globe (Lambley, 2017). Every year, heavy rain and flooding events are increasing in both frequency and intensity. The rapidly growing urban populations cause some serious challenges for many cities. Currently, 55% of the global population is living in urban areas and is expected to increase to 66% by 2050 (United Nations, 2014). These developments can increase the risk of local flooding, heat stress and drought in cities.

As rainfall becomes more intense, the surface runoff can exceed the capacity of drainage and sewer systems. When the system becomes overwhelmed, water flows into the streets and may cause damage to nearby buildings and homes. The sewers are not (yet) designed for heavy rainfall. Besides, urban areas are vulnerable to extreme rainfall due to a large percentage of impermeable surfaces (e.g. roads and roofs). This means that the percentage of rainfall absorbed by the soil is very low. The cities' challenge is to manage storm water of impervious surface in urban areas, and to address sewer overflow problems. However, the increasing urbanization, on-going density, and paving of ground surfaces affect not only the water related challenges but also contribute to higher temperatures and heat stress in cities (Theeuwes, 2015).

Given these trends, water management needs to be improved to make urban areas more resilient. For many municipalities, it is difficult to take these factors into account when planning for the future. Recent studies show opportunities for improving the unbalanced urban water cycle through the use of buffering and infiltration of rainwater (Ahiablame, 2012; Scholz, 2013; Stahre, 2008). Public space plays an important role in achieving a more climate-minded planning. The existing public spaces can be used for temporary water storage to cope with the rainfall levels and subsequently discharge the precipitation over a longer period of time. However, space in an urban area is limited and therefore valuable. A big challenge is to design the public space in such a way that it is integrated into the entire water cycle, applying a more natural approach to water management by temporary storage, delay flow, or better utilisation of rainwater.

Many municipalities are willing to adapt their cities to climate change. Over the last years, sustainable alternatives for below ground solutions have been developed to improve water resiliency and to create an attractive living environment. However, local governments struggle to put into practice above ground solutions such as of green roofs, removing impervious surfaces, and the use of rainwater. Wavin, as the market leader in water-related products, can guide in developing climate adaptation measures, such as above ground solutions. In general, cities need more input from the market or the private sector throughout the development of new solutions into adaptation plans. This research contributes to the domain of climate adaptation by aligning strategies to Wavin to develop above ground solutions that minimize the effects of climate change.

1.2 Wavin company

Wavin is a leading supplier of plastic pipe systems and solutions in Europe. Wavin provides systems and solutions for tap water, heating and cooling, soil and waste water, foul water, storm water and cable ducting for home, civic and commercial buildings. Wavin has developed solid wall and multi-layer PVC pipes to near-silent transport foil water from buildings. As the force of gravity is the most common way of transport sewage, nobody wants to hear the flush in homes or buildings. Wavin's multi-layer sewer pipes use recycled material in the core, offering the most sustainable solutions. To ensure a long life time and high performance, the sewage transport systems need to be inspected and maintained. Wavin offers a wide range of manholes and inspection chambers for safe and easy access. While PVC pipes and fittings are produced according to a standard manufacturing process – pipes are produced by extrusion, pipe fittings by injection molding – the Tegra manholes and inspection chambers are manufactured according to customer requirements. The Tegra range is an essential part of the foul water systems. Figure 1, on the next page, shows the manufacturing processes and the Tegra range.

Figure 1: The extrusion process of PVC pipes (left), the injection molding factory (middle) and the Tegra range (right), derived from Wavin Brand Portal.

Furthermore, Wavin is part of the Mexichem Group, the leader in plastic pipe systems and in the chemical and petrochemical industry in Latin America. This master assignment was conducted in Storm Water Management (SWM) at the department of Marketing & Technology in Zwolle. SWM develops products to deal with the storing and discharging of rainwater, like the collection, transportation, infiltration, attenuation, and filtration. Besides, SWM is closely related to Wavin Technology & Innovation B.V. in the process of linking market needs with technical knowledge and developing integrated solutions for its customers. An overview of the brand segments and a short description can be found in Appendix A.1.

1.3 Research methodology

This research served as a plan to support Wavin in developing and implementing above ground SWM solutions. The methodology to achieve this is briefly elaborated in the research questions below. Afterwards, a summary of the research methodology is presented.

1.3.1 Research objectives

The objective of the research is to show how Wavin can make the public space more resilient by (a) creating an overview of the existing SWM solutions and trends concerning above ground systems; (b) translating these findings into a new above ground product or product system, and c) aligning the findings to Wavin's capabilities. The market research focuses on identifying the most interesting and relevant SWM solutions and compare them to literature, experts' experience, and practice. Then, problems and interests from the stakeholder that are relevant for Wavin will be used to align the findings to Wavin's capabilities.

1.3.2 Research questions

The main research question in this thesis is:

"What are feasible solutions that Wavin can develop and implement to improve storm water management, in order to minimize the effects of climate change in the present and in the future?"

The subquestions are:

1. Which trends have been researched in the context of temporary water storage, delay, and other (re)use, in the urban environment?
    a. According to literature, which problems in the implementation of sustainable urban SWM methods can be identified?
    b. According to literature, which trends in sustainable urban SWM methods can be identified?

2. Which existing solutions have been researched in the context of temporary water storage, delay, and other (re)use, in the urban environment?
    a. According to literature, which solutions in sustainable urban SWM methods can be identified?
    b. According to Wavin's portfolio, which products are currently developed and which product ranges can be extended?

3. What are the lessons learned from the existing solutions and trends in sustainable urban SWM?
    a. Which aspects of sustainable urban SWM measures could be helpful to improve the urban climate resilience?
    b. Which of the SWM solutions do align with the problems and interest that Wavin's stakeholders currently have and

bring to light new opportunities?
   c. What are possible SWM solutions for temporary water storage, delay and other (re-)use near surface or above ground that could be effective and applicable by Wavin, and why?

4. Which of the identified solutions are feasible for Wavin to develop and implement in order to improve sustainable storm water management?
   a. Which product ideas can be developed or produced according to Wavin's capabilities?
   b. Which product idea is recommended as a feasible and innovative solution from a SWM perspective?

1.3.3 Research design

In order to achieve the research objectives and to answer the research questions, a strategy was devised. A brief overview of the research design is visualized in Figure 2 on the next page.

Step 1: Identify existing solutions and trends

Through reviewing the literature, the effects of climate change and growing urbanisation were identified to distinguish the urban SWM methods to climate adaptation. Besides, Wavin's portfolio was analysed to gain insight into the SWM product range. For the existing solutions, a market research was carried out to create an overview of the existing SWM solutions, which then was validated with the key players. The key players in the development and implementation of SWM products were schematized in the stakeholder analysis.

Step 2: Analyse current solutions and trends

With the help of experts and key players (e.g. municipalities), the most important aspects of storm water management solutions were selected. The existing solutions and trends from the theoretical point of view served as a framework to address the stakeholders' problem and interests, and Wavin's interest with regard to solutions. These solutions were analysed on effectiveness and application in practice through conducting interviews.

Step 3: Aligning possible solutions and Wavin's capabilities

After that, the research zoomed in on Wavin to discuss the feasible solutions that Wavin can develop or implement. Findings from both literature and practical experience were used to create product requirements. The product ideas were ranked according to their feasibility and selected related to Wavin's capabilities. In this way, the final concept was defined.

Step 4: Proving the new product system

The main research question aimed to assess what feasible solutions align with present and future plans at municipalities in the field of climate adaption. Tests were performed in order to gain deeper knowledge of how the mechanism works. Findings from both literature and the tests were used to present a detailed concept, followed by recommendations to further research the climate change mitigation potential.

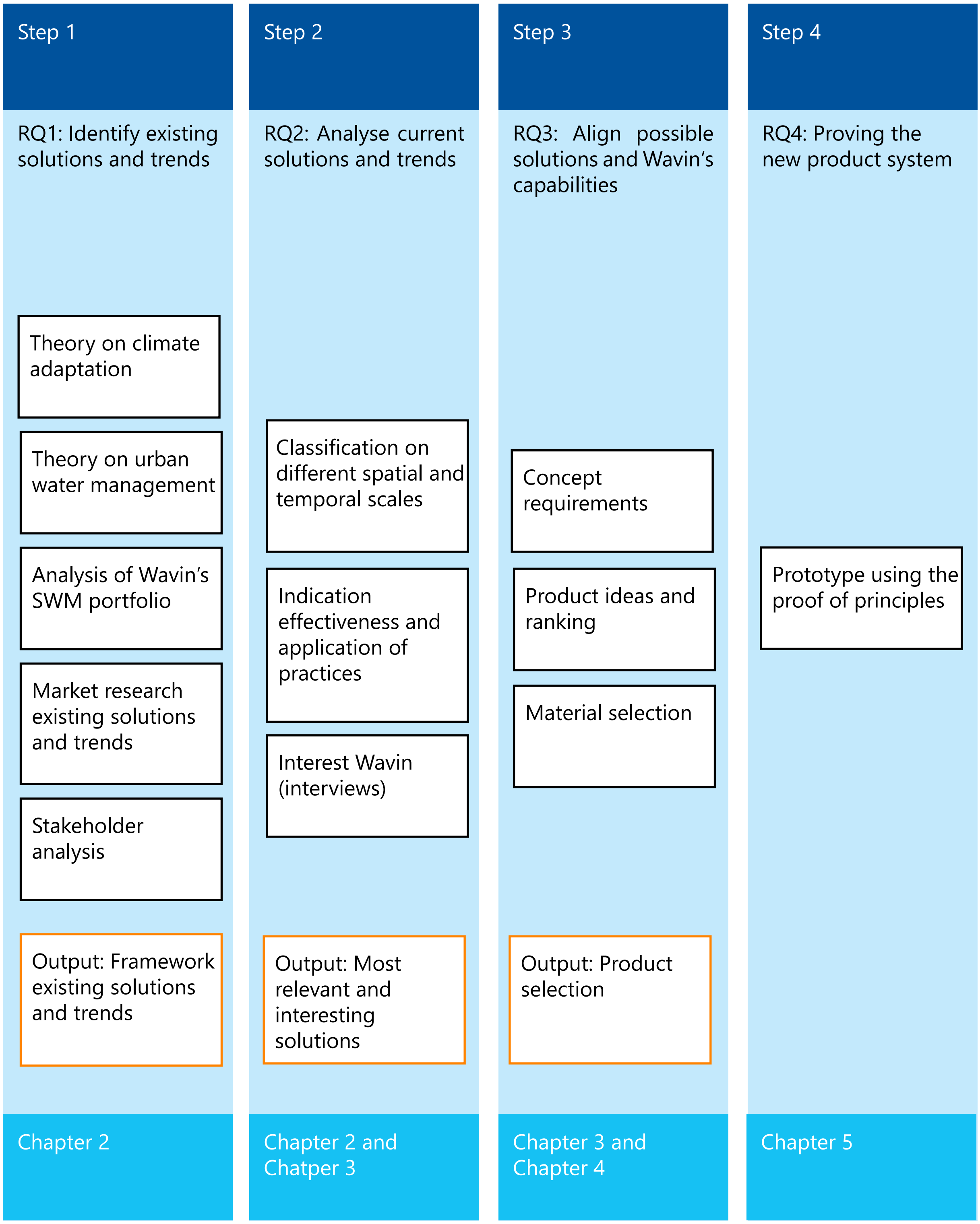


Figure 2: Main research questions in relation to the research design

2. ANALYSIS

This chapter outlines the focus point for this thesis and describes the challenges of the assignment. It starts by introducing insights into climate adaptation and urban water management approaches. Linked to Wavin's portfolio, this is followed by a market research of existing solutions that municipalities should consider while developing climate-resilience cities. After this, the main problems and interests of experts, clients, and Wavin are discussed. Combining these different facets, a structured and detailed customer profile is presented.

2.1 Problem definition

The focus of this chapter is on understanding the catalysts for climate change and the role of cities within it. Firstly, the effect of urbanization will be discussed. Section 2.1.2-2.1.3 focus on a selection of climate challenges which are relevant for urban areas: 1) flooding; 2) heat; and 3) water scarcity and drought. Furthermore, the integration of climate change adaption into urban planning, such as green areas, will be discussed.

2.1.1 Urbanization

Urbanization is an accelerating trend as shown in Figure 3. Globally, more people live in urban areas than in rural areas (ESA, 2014). Urban areas are not only growing, but they are also becoming denser. Currently, the most highly urbanized countries include Belgium (98%), Japan (93%), Argentina (92%) and the Netherlands (90%). Over the coming decades, the level of urbanization is expected to increase in all regions.

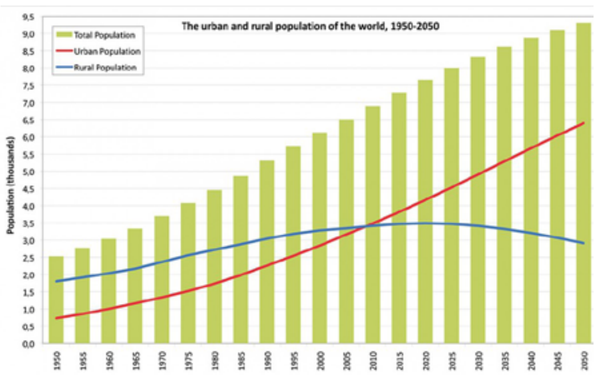


Figure 3: The urban (red line) and rural population (blue line) of the world between 1950 and 2050 (ESA, 2014).

Water enters the city in various ways: as surface water, groundwater, precipitation, or as drinking water via the water supply system. The drinking water used in urban areas is extracted from groundwater or surface water. Afterwards, it is mainly expelled through the sewer system to a wastewater treatment plant where it is treated and discharged into the surface water. Notably, in many cities existing vegetation is removed and it is replaced by impermeable areas (sidewalks, paved streets, roofs, parking lots, etc.). Due to this impermeabilization, there is a reduction in rainwater infiltration, leading to a strong increase in rainwater runoff (Poleto & Tassi, 2012). This phenomenon involves the transfer from the natural water cycle into the urban water cycle, shown in Figure 4.

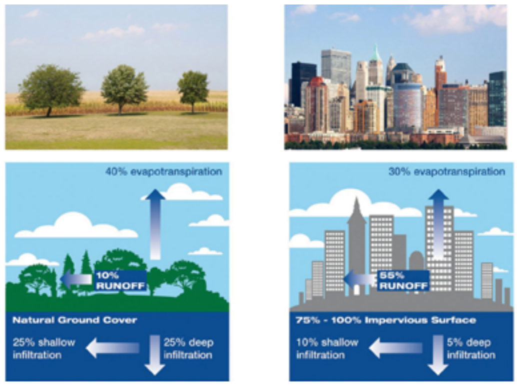


Figure 4: Important changes between natural and urban water cycle, derived from Wavin Brand Portal.

Urban energy and water balance are connected through evapotranspiration. Evapotranspiration can directly modify the urban water balance, so it is a fundamental controller of urban climates (Coutts et al., 2013). The urban water balance is defined as:

$$P + I = E + D + \Delta S \ (mmh^{-1}) \quad (1.1)$$

where P is the precipitation, I the piped water supply, E the evapotranspiration, D the drainage (comprising storm water and wastewater) and S is the net change in water storage of the urban system. Precipitation and related peak discharge cannot be influenced but adaptation measures involving increased rates of evapotranspiration and storage capacity will relieve existing pressures on urban water systems.

This vulnerable and artificial balance of the urban water cycle is becoming increasingly more unbalanced due to the effects of urbanization and climate change. Therefore, cities need adaptation measures ensuring that urban water systems can cope with heavier precipitation, higher temperatures, low water availability or flooding.

2.1.2 Flooding

According to the European Environment Agency (EEA), "Heavy precipitation events have become more intense and more frequent in Europe." Past trends show increases up to 5mm per decade over northern and north-western Europe in winters and up to 4 mm in summers (Figure 5 left). In south-western Europe, the observation shows decreases of more than 5mm per decade in winter and between 2 and 3mm in summer (Figure 5 right). Several studies (Besselaar et al., 2013; Zolina, 2012; Rajczak et al., 2013) agree that heavy precipitation has become more intense in northern and north-eastern Europe since the 1950s, and will continue to increase.

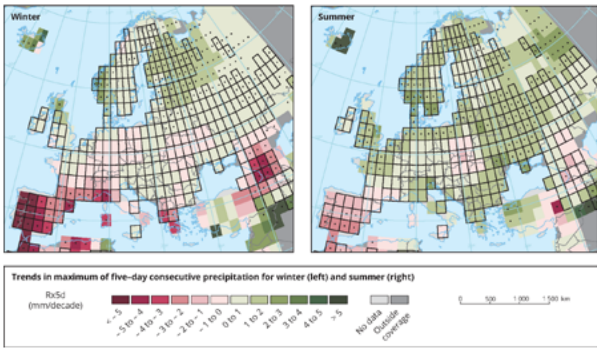


Figure 5: Observed trends in maximum annual five-day consecutive precipitation winter and summer (EEA, Data and Maps, 2016).

Projections show an increase in heavy daily precipitation in most parts of Europe in winter, by up to 35% during the 21st century and with a 30% increase in north-eastern Europe (Figure 6 left). In summer, an increase is also projected in most parts of Europe, but decreases are projected for some regions in southern and south-western Europe (Figure 6 right). In general, daily precipitation is expected to increase in most of Europe but decreases for southern and south-western Europe during summer months.

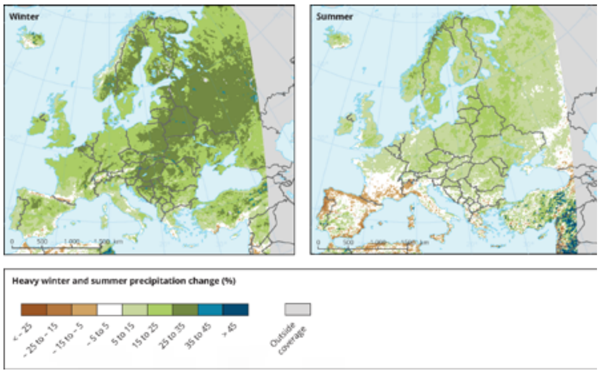


Figure 6: Projected changes in heavy percipitation in winter and summer (EEA, Data and Maps, 2014).

Heavy rainfall can lead to increased flooding incidents and decreased water quality. In Europe, different types of floods appear. These are visualized in Figure 7. In short, pluvial (from intense rainfall) flooding is different from riverine (from river) and coastal (from sea) flooding. Cities are often experiencing a combination of riverine and pluvial floods (Sörensen, et al., 2016). In addition, intense rainfall can deplete the urban drainage systems causing flooding in lower lying urban areas, known as urban drainage flooding (EEA, 2012). Pluvial or urban flooding is generally local and is the focus of this thesis.

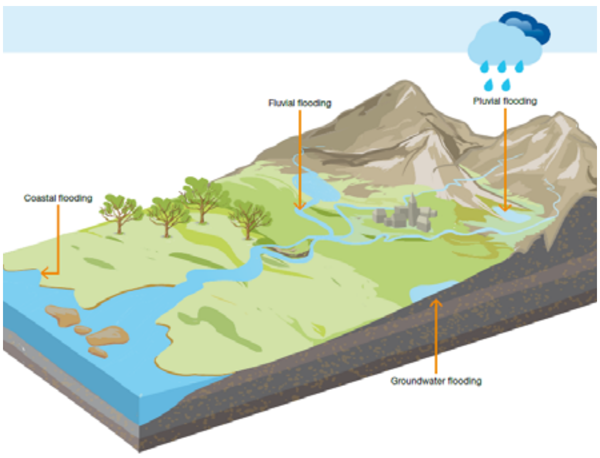


Figure 7: Projected changes in heavy percipitation in winter and summer (Wavin, Whitepaper, 2017)

2.1.3 Heat

In Europe, heatwaves have caused the most human fatalities (EEA, 2012). Extreme summer heat waves, such as the ones experienced in different parts of Europe in 2003 and 2010, will become more common in the future. Heatwaves have strong direct impacts on human health and well-being. Exposure to hot weather can also have other negative impacts on society (e.g. labour productivity), ecosystems (e.g. forest fires) and agriculture (EEA, 2012). In particular, the elderly, young children and those using certain medication are sensitive to heat as well as pregnant women. In August 2003, the heatwave caused up to 14,800 excess deaths in France (IPCC, 2007).

According to EEA, since 1960, "the number of warm days have almost doubled across Europe" (Figure 8). As a result, 500-year-old temperature records were broken over 65% of Europe in the period 2003–2010 alone (Barriopedro et al., 2011). The EEA projections show that extremely high temperature will become more frequent and to last longer in southern and south-eastern Europe.

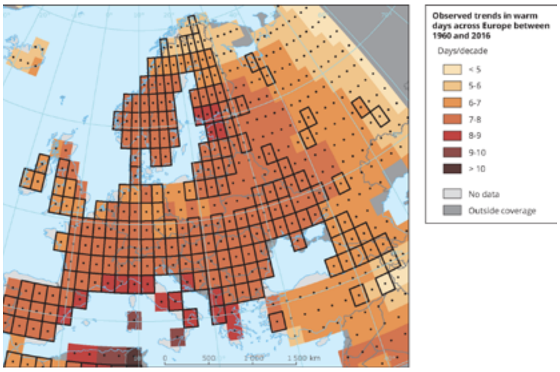


Figure 8: Observed trends in warm days across Europe between 1960 and 2016 (EEA, Data and Maps, 2017).

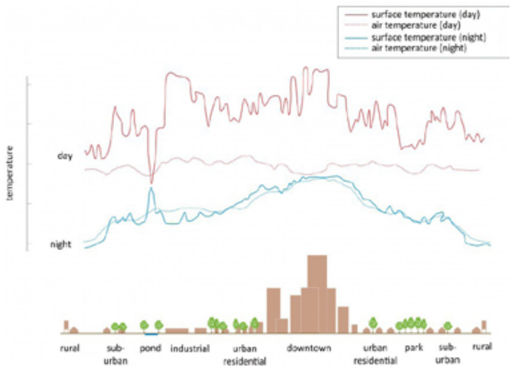


Figure 9: Air and surfaces temperature during the day and night regarding UHI profile (EPA, UHI Basics, 2008).

Other parts in Europe will also experience a rise in annual temperature.

Cities are especially vulnerable to these higher temperatures. A recent study shows that The Hague experiences the greatest difference in surface temperatures between rural areas and highly urbanized areas as much as 15,4°C on hot days (Stadswerk, 2016). This phenomenon, in which cities are generally warmer than its rural landscape, is described as the urban heat island effect (Theeuwes, 2015). The temperature difference between the urban and rural weather and climate is the urban heat island effect (UHI), as follows:

$$UHI = T_{urban} - T_{rural} \quad (1.2)$$

where T_{urban} is the urban temperature and T_{rural} is the rural temperature. The differences between the urban and rural temperature that result in the UHI in cities are illustrated in Figure 9. The UHI is much higher during the night due to the slow release of heat stored in buildings during the day.

2.1.4 Water scarcity and drought

During long periods of drought, the city feels unpleasantly warm. A distinction should be made between water scarcity and droughts. Water scarcity refers to long-term water imbalances between water demand and available natural resources whereas drought is defined as a temporary decrease in water availability. High air temperatures and evapotranspiration rates can increase the duration of droughts.

According to the EEA, "Between 1950-2012, the frequency of droughts in Europe has increased in parts of southern Europe and central Europe, but drought have become less frequent in northern Europe and parts of eastern Europe (Figure 10 left). Trends in drought severity (Figure 10 right), in terms of economic and environmental damages, also show significant increases in southern Europe, and decreases in northern and parts of eastern Europe (EEA, 2017).

Water scarcity is expected to increase in Europe as a result of the increasing imbalance between water demand and water availability. To overcome water scarcity, cities will be more dependent on other regions. This will increase competition between water users and cause the price of water to rise (EEA,2012).

Cities in Europe will be affected by the impacts of climate change. Current observations of change are well in line with trends of the average climate change, which suggest:

- a change of precipitation patterns with wetter winter conditions in north-eastern Europe and drier summer conditions for regions in the southern and south-western Europe
- a rise in the annual temperature across Europe will become more frequent and last longer
- an increase in water scarcity and drought have become an issue in many regions across Europe

While cities will generally experience the same exposures to climate as their surrounding region, the local city characteristics (its form and human

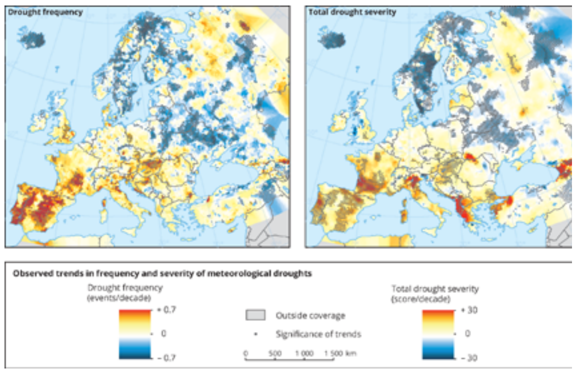


Figure 10: Observed trends in frequency and severity of meteorological droughts (EEA, Data and Maps, 2016).

activity) makes cities more vulnerable to climate and other stresses. Built-up areas create unique microclimates due to the replacement of green urban areas with paved surfaces. Urban design can offer a range of options to be better prepared for future flooding, heavy rain events, and heat conditions, including SWM solutions.

2.1.5 Planning urban adaptation

The traditional urban design aims to immediately discharge storm water. Storm water is discharged through sewer systems which uses the same pipes for sewage water. However, heavy rainfall can exceed the capacity of the city's sewer system. The objective of water management in urban areas is to ensure that no damage is caused during peak periods of peak discharge. In municipal planning of renewal or restructuring of the sewer system, the combined system is replaced by an improved separated system which uses separate pipes for sewage and storm water flow. However, due to the lack of space or required investment, the combined system cannot always be replaced by a separated system. So, municipalities need good alternatives.

In recent years, the number of alternative concepts for resilience and sustainability have evolved considerably; Low Impact Development (LID), in the USA and Canada; Sustainable urban Drainage Systems (SuDS), in the United Kingdom; and Water Sensitive Urban Design (WSUD), in Australia (Fletcher, et al., 2014). These concepts have in common that they manage not only the peak flows, but also the volume, the frequency, the duration, and the quality of runoff and drainage (Poleto & Tassi, 2012). All urban drainage approaches to sustainable systems ought to be feasible not only economically but also socially and environmentally (Sörensen, et al., 2016).

The trend towards a more natural approach highlights the use of micro-scale distributed techniques like natural buffering, infiltration, or delayed discharge and reuse of rainwater, to treat storm water close to the source and to balance its effect on the water cycle (Poleto & Tassi, 2012). It can be concluded that public areas play an important role to integrate the techniques. Studies demonstrate that, generally, evapotranspiration increases as vegetation increases. Thus, vegetation is an important conduit for evaporative water loss to the air (Coutts et al., 2013). Although scientists try to highlight the importance of green areas, the preference for cost-effective and low maintenance measures is a barrier to its implementation.

In new urban development and restructuring projects, cities can implement adaptation measures. Climate adaption is focuses on sustainable storm water management solutions as a means to solve the water challenges and mitigate the effects of heat and water scarcity. Therefore, the use of micro-scale distributed techniques was taken as a starting point in the idea generation for this research.

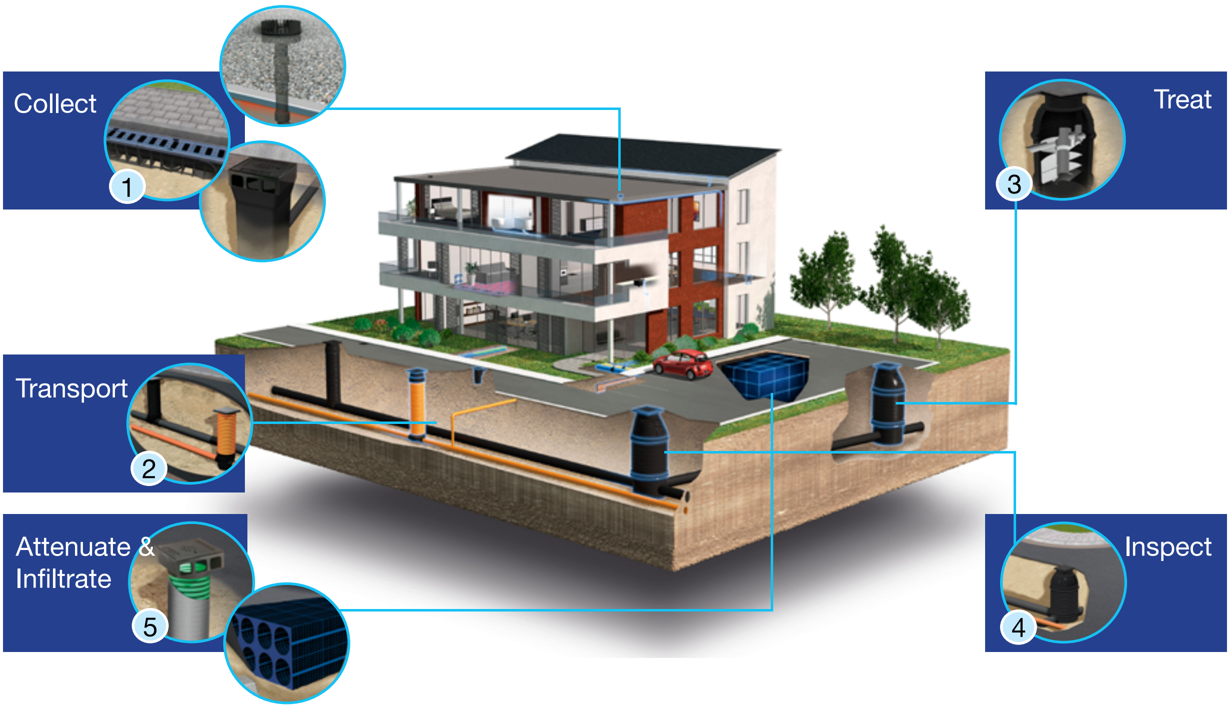


Figure 11: Graphical overview of Wavin Storm Water Management functions

2.2 Wavin's portfolio

As the master thesis is conducted in Storm Water Management (SWM), the analysis of Wavin's current portfolio only focused on the brand segmentation of this particular business unit. The storm water products offer a range of special functions: 1) collection; 2) transportation; 3) attenuation and infiltration; 4) filtration; and 5) re-use of storm water. The products aim to better use water as a resource as well as reduce risk of flooding, building damage, and water pollution. The current portfolio is analysed according to its functions of managing storm water. The description of these functions is given in Table 1. Figure 11 shows where the main SWM solutions are located. The functions are related to a specific stage starting from rainwater falling onto road and rooftops until its route back into the soil or surface water. The products Wavin offers as rainwater solutions are schematically visualized in Figure 12. The scheme follows the steps according to the roadmap of storm water. The next paragraphs provide a description of the function and performance of the related products following these steps. An extensive overview of the SWM products can be found in Appendix B.1.

Collection
The first step is the collection of rainwater for buildings and roads. In contrast to traditional gravity drainage, Wavin QuickStream is a siphonic roof system that prevents air from entering the system. This offers a highly efficient and extremely cost-effective way to discharge rainwater from large or complex roof areas.

Capturing rainwater from impermeable surfaces like pavements, car parks, and even airport runways requires the use of Wavin Channel Drainage or Wavin Road Gullies. The new launched road gully drains surface water, separates surface water from dirt and sand to prevent the sewer from blocking. The circular bottom results in less maintenance compared to alternatives.

Table 1: The description of the different functions

Function	Short description
Collect	Collecting rainwater from roofs, roads and paved surfaces
Transport	Transporting of rainwater to water drainage systems
Treat	Separating oil sand and dirt from rainwater
Inspect	Reuse of rainwater
Infiltrate/Attenuate	(Temporary) storing water and infiltrating into the soil in a controlled manner

Figure 12: Wavin rainwater solutions presented by following the roadmap of rainwater

Transportation
The second step is the transport of storm water through plastic piping into the below ground system. The pipes are produced in different plastic materials, namely PP, PE, and PVC drainage systems. The Wavin X-Stream PP pipes have a structured external wall with a smooth internal wall which results in a lightweight design.

Treatment
Before water is discharged, the third step is to remove pollutant from collected rainwater to comply with all legal requirements. This is provided into a variety of mechanisms and filters. For example, the Certaro HDS Pro contains a filter which removes sediment and floating soil. The Certaro NS oil separator is a tool to filter oil from the water. The system is applied at Schiphol Airport to prevent oil from entering groundwater in the environment which makes it unsuitable for use as drinking water.

Inspection
Besides treatment of the water, the rainwater is inspected through Wavin Tegra inspection chambers. The inspection chambers are used as access points for inspection, cleaning, and maintenance of pipe systems. The Wavin Tegra 600 is a unique inspection chamber with flexible connections at its base.

Attenuation and infiltration
From there, the rainwater is allowed to infiltrate into the ground, either directly or by using a perforated horizontal pipe wrapped with geotextile. The Infiltration and Transport (IT) pipes combine transport, storage and infiltrate rainwater. This increases the infiltration surface. In case of high groundwater level, Drainage and Transport (DT) pipes can be used. The IT pipes can also be constructed vertically (VIT). This lead to an infiltration capacity with a high discharge.

Wavin infiltration units help to bring rainwater under control and retain it in temporary storage before releasing it into the soil, surface water or drainage systems. Wavin offers AquaCell and Q-Bic infiltration units whereas the Q-Bic units are inspectable and cleanable. The AquaCell ranges are approved as SuDS solutions. The difference between attenuation and infiltration is visualized in Figure 13. Basically, attenuation means capturing and releasing rainwater slowly into surface water or drainage system, whereas infiltration allows rainwater into the soil. Whether to apply an infiltration or attenuation system depends on soil properties. The units are wrapped in geotextile to allow infiltration into the surrounding ground, or the units are sealed in a geomembrane to hold the rainwater temporarily. The units are assembled together in single or multiple layers to create below ground structures. The configuration depends on the type of soil, traffic load, and groundwater level.

Competitors of Wavin, for example ACO, Fränkische, and REHAU, offer comparable infiltration boxes. The ACO StormBrixx, Fränkische RigoFill, and REHAU Rausikko box are produced with a pillar structure resulting in a cost-efficient transport component. However, the working principle of their crates are similar to Wavin's boxes. A broader competitor analysis can be found in Appendix B.2.

Interesting to note is that Wavin's portfolio features products that are part of the water cycle or the roadmap from roof to river. The strong position of Wavin relies on proving a complete and fully integrated system. Within the portfolio, there are opportunities to vary in facilities. Currently, the AquaCell (high groundwater, non-inspectable) is mainly used for housing. The Q-Bic Plus (inspectable) is used in bigger projects for municipalities. In some situations, the boxes are used in combination. This also depends on the different market needs of European countries. Wavin is mainly interested in widely circulating products on a major scale or city-broad scale. This is schematically visualized in Figure 14. In order to expand the portfolio, the focus is on expanding the full system. In line with the today's trend, there are opportunities to take a market position in the public space as most of Wavin's products are part of below ground systems. Therefore, the market analysis of this research aims to gain deeper insight into sustainable above ground solutions.

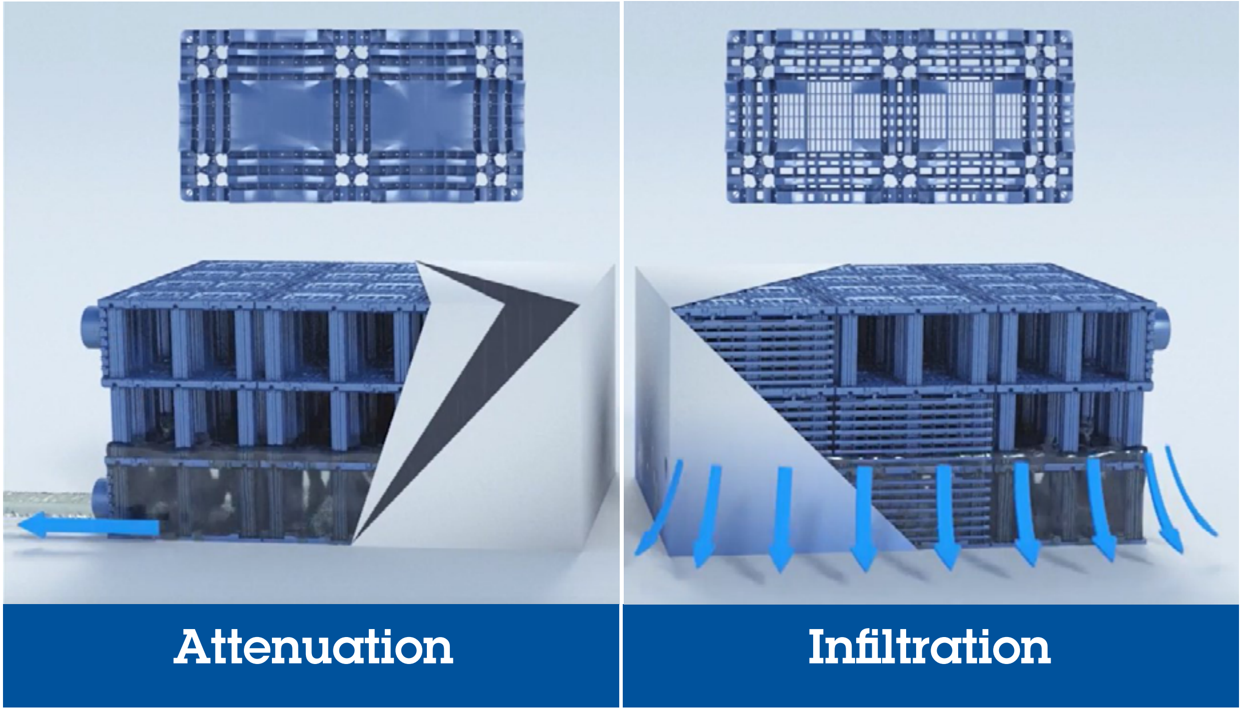


Figure 13: The AquaCell shows the difference between attenuation (left) and infiltration (right).

Interest Wavin

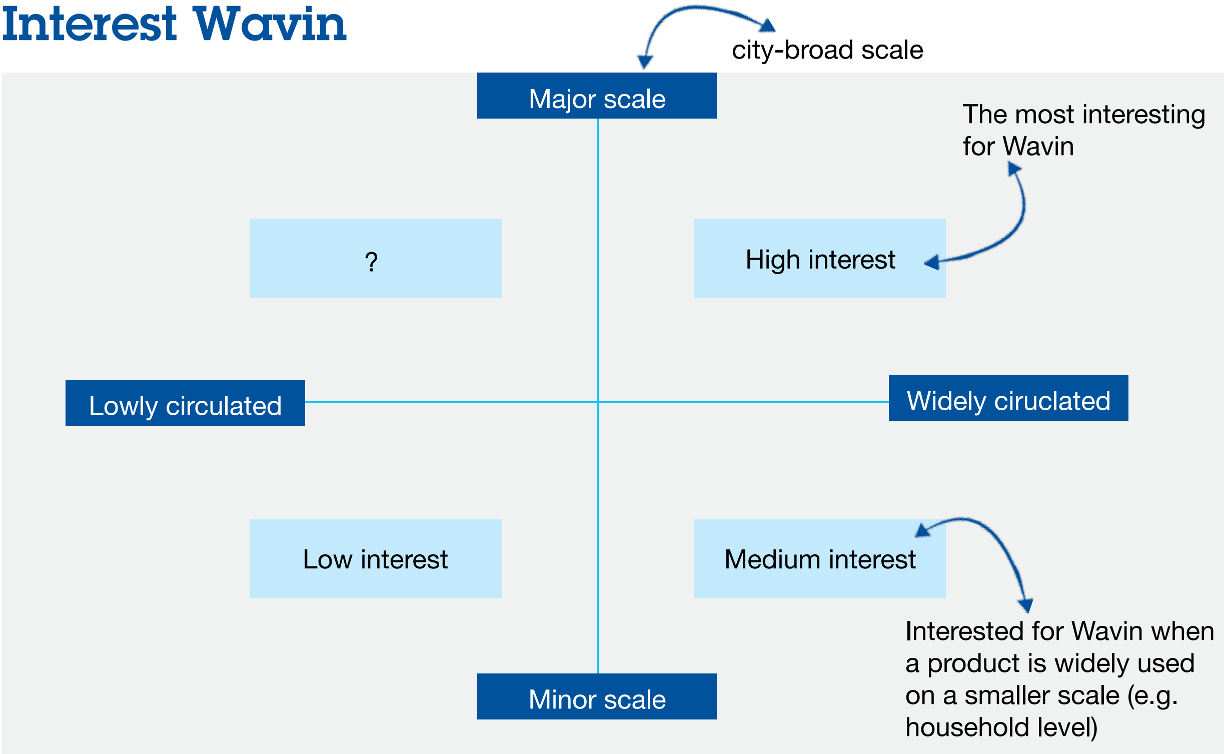


Figure 14: The interest of Wavin on spatial and temporal scales

2.3 Market research

This section shows the currently existing solutions in the urban environment to answer the second research question: Which existing solutions have been researched in the context of temporary water storage, delay, and other (re)use, in the urban environment? Firstly, a comprehensive mood board is presented that visualizes a range of solutions. Secondly, the focus area for solution directions is defined based on the applicability of solutions in practice and Wavin's interest. These findings provide an indication of the effectiveness of the most relevant and interesting solutions.

2.3.1 Mood board

The data is collected from the website Urban blue-green grids, showing 129 solutions, and Amsterdam Rainproof, which already includes 57 solutions to make the city rainproof. In addition, reports of Saxion and University of Twente

Bioswales
systems for infiltration, buffering and drainage and enhance biodiversity

Ditches
a narrow channel at the side of a road or field to infiltrate and transport water

Urban water channels
an open water channel for rainwater drainage

Reintroducing sidewalks
to keep water in the streets

Raised floor level
offers protection from flooding up to several centimetres

Open gutters
visibly drain water but can be an obstacle for road users

Covered gutters
drain water and can be used in urban situations to cross safely

Permeable pavements
contain or create open parts through which water can infiltrate

Porous paving material
consist of porous material through which water can pass

Urban infiltration strips
buffer and slowly release water into the ground

Water squares
rainwater collection system in densely built-up urban areas

Rainwater ponds
temporarily capture rainwater and allow it to drain off slowly

Disconnect rainwater drainage
reducing runoff to the sewer system

Rainwater storage below parking garages/buildings
additional underground storage capacity

Rainwater tanks
capture rainwater from roof surface and used for irrigating plants

Rainwater fencing
the fence around the house is used for storing and reusing water

Systems for using precipitation in home/ buildings
e.g. for flushing toilets

Sprinkling water
on surfaces to increase evaporation and lower temperatures

Fountains
evaporation from fountains has a cooling effect on the surrounding area

Water elements
playful elements in urban spaces related to water

Figure 15a: The mood board

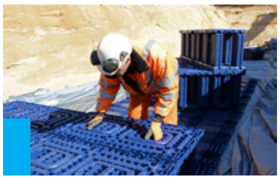
students who mapped existing solutions for private owners (Pioneering, 2018) provide useful input. The water board, Waterschap Vechstromen, has set up a commission to investigate the problem of households' resilience to climate change impacts. The findings of the study help to prioritize intervention measures for residential areas. These sources of information were combined with observations in Rotterdam and experiences from Stadscafé Leiden, the conference Normaal Amsterdams Peil (NAP) and conference Hittestress.

Synthesis of the independent studies resulted in an overview of solution directions, visualized in Figure 15a-b. Instead of only focusing on water solutions, the themes Water, Greenery, Landscaping and Construction material were represented to keep a broad scope in this early stage.

Water **Landscaping**
Greenery **Construction material**

Infiltration wells
vertical installation on the surface for rainwater to infiltrate into the ground

IT drainage
horizontal installation which combines transport and infiltration



Infiltration boxes
buffer and slowly release into groundwater which requires no above ground space

Green roofs
a collective term which includes sedum roofs and is walkable or used for retention

Green facades
building attract and lose less heat helping to mitigate urban heat

Green verges
vegetation along roads and between traffic lines can be used for rainwater infiltration

Patios out, green in
reducing pavements and improving the ground

Planting facade gardens
allows the rainwater to infiltrate into the ground

Green squares/ playgrounds
reducing paved surfaces to lower temperatures

Urban forests/parks
proving recreational space and shading

Height differentiation
raised landscape or artificial hills that rise above the highest water level

Raised evacuation routes/ paths
to ensure an area remains accessible during a flood

Urban wetlands/retention areas
overflow areas for rivers and natural rainwater buffers

Floating areas
floating buildings and public spaces can be designed to float

Temporary flood protection
movable dams and bulkheads for protecting existing areas

Buildings as flood protection
can act as barriers to excess water during floods

Cool paving material
light colours keeping the surface temperature down

Cool facades
light-coloured materials with a high albedo will warm up less

Cool roofs
light foils or tiles with special coatings to replace gravel as ballast

Constructed blinds
architectural measures to create sun shading

Figure 15b: The mood board

2.3.2 Solution directions

Six solution directions were identified that capture the way to deal with rainwater:

- Water transport – the transportation of rainwater to designated areas to reduce damage to infrastructure and environmental and health impacts in urban areas
- Water collection and storage – the collection of rainwater is a way to temporary buffer and delay discharge of rainwater
- Water infiltration – the infiltration of rainwater directly into the soil if the soil type and groundwater level allows it
- Water reuse – the collected and stored rainwater is used as an alternative water supply to water plants or to flush toilets
- Water resilience building – the ability to adapt infrastructure to water challenges related to heavy rainfall, not including high water levels from river or sea, if rainwater collection or storage is not possible
- Other – alternative solutions of using water to reduce the risk of flooding, heat, and drought

Despite the categorization, the solution directions present potential measures from the mood board for each category. The selection of the measures is based on their applicability in practice and fit to Wavin's interest (widely circulating products on a major scale). As the themes Landscaping and Construction material are not part of Wavin's capabilities, these solutions were not further analysed. The measures related to a category are presented in Figure 16.

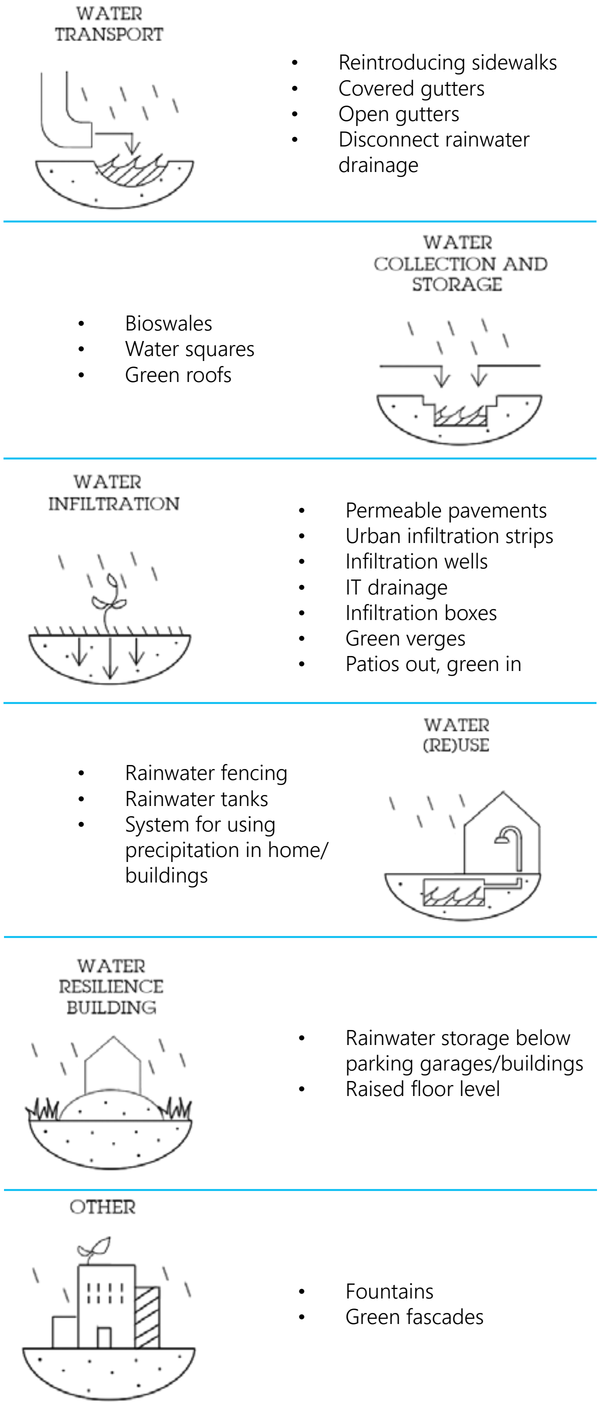


Figure 16: The value chain

Some measures are covered by several solution directions. So, overlap exists between the categorization. For example, 'Water collection and storage' including bioswales provides additional functions, namely: temporary storage, increasing infiltration of rainwater and transportation. The measures are categorized according to their main function. To verify the application in practice and to indicate the measures' effectiveness, the selection forms the input for the expert sessions. This which will be further discussed in section 2.5.

The category 'Other' provides freedom to come up with other specific measures to reduce the water problem, heat stress or drought. In this way, other themes such as health and circularity can be covered. For example, adding green facades in the category 'Other' is not only good to attract and lose less heat but simultaneously increases biodiversity and reduces air pollution. Based on today's trends, multifunctional solutions are desired as they do not only focus on the water related challenges but also provide an added value.

As Landscaping and Construction material solutions are not included, an additional part of the market research focused more on product related solutions. From this product related part, it can be concluded that the need for smart solutions is becoming more important. Currently, most of the water systems (e.g. rainwater tanks and rainwater fencing) are reactive, not automated or self-adaptive. Therefore, it is interesting to look for pro-active and adaptive solutions; solutions that take control or adjust to a situation instead of waiting for something to happen. An extensive overview of the products can be found in Appendix B.3.

2.4 Stakeholder analysis

A stakeholder analysis was conducted to decide which stakeholders to involve in the design process. Here, the stakeholders in the field of SWM are identified to analyse the variables which influence the stakeholder participation in the design of SWM solutions. As the focus of the solutions relates to the regional or city-broad scale, the analysis only focused on involved regional level authorities and the water bodies. In the sections, the stakeholder analysis is presented from an European perspective as Wavin's products have been used for SWM throughout Europe. This analysis provided useful knowledge to prepare the interviews for the expert sessions (section 2.5).

2.4.1 Value chain

To identify stakeholders, a decision tree for participation in SWM was developed from Wavin's perspective. This tree is internally known as the 'value chain'. The value chain is schematically visualized in Figure 17. This value chain includes all stakeholders' activities to deliver a valuable product for the market. The value chain indicates that two variables influence the stakeholders' participation, namely value generation and decision making. On the left, the creation of economic value and to the right the influence of stakeholders in making product decisions. Five stakeholder groups can be identified from the value chain: 1) Supplier; 2) Distributor; 3) Contractor; 4) Municipality; and 5) Consultancy. From the scenario-based perspective, two stakeholder groups are involved: water board and residents. The two groups work in a vertical direction, influencing and/or informing the municipality. The value chain generally applies to product development in Europe. Small differences exist, for example, in the UK the municipality and the water board work more closely together. In addition, not all European countries acknowledge the water board in the same responsibility. A broader view on the comparison between differences in European countries is discussed in the next section.

2.4.2 Stakeholder identification

To involve stakeholders in SWM development they must be identified and their interests and needs must be understood. Firstly, the interests and opportunities were described for each stakeholder group. Secondly, the level of influence (power) they hold according to Wavin is shown in Figure 18, on the next page. The diagram is applicable to the Netherlands and it shows that the municipality plays a central role in the process. The diagram was validated during an interview with a product manager Storm Water at Wavin, the Netherlands. A matrix was used as a framework to guide the interview. The framework can be found in Appendix B.4.1. From an European perspective, the diagram was discussed with Germany and the UK in mind, two of the leading countries in SWM for Wavin. For these two countries, the diagram is structured differently and can be found in Appendix B.4.2.

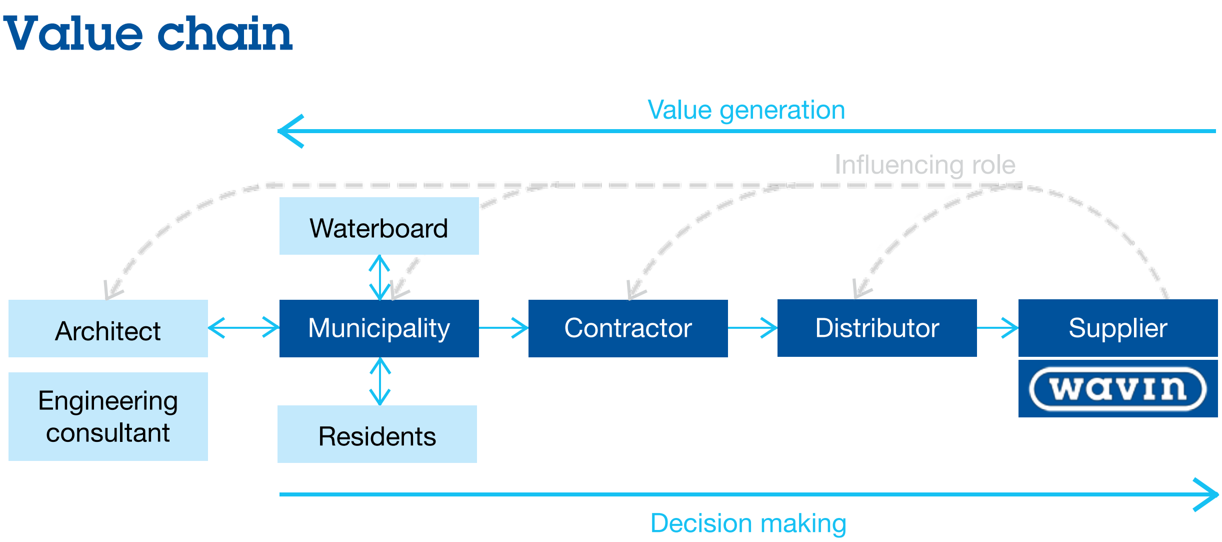


Figure 17: The value chain

Key player I Example

Municipality I Municipality of Zwolle, Municipality of Enschede
The municipality wants a liveable city by creating an attractive place for houses, work, nature, and recreation. The approach to water is properly embedded in urban design and planning processes. Local flood risk management and urban runoff control are incorporated into local and green agendas. Since rainwater management prevents flooding, the city takes advantage of the development of SWM products. The municipality is the key player regarding high interest and high influence. They decide whether or not to buy the product. They assign which contractor will perform the new building project.

Other stakeholders I Example

Water boards I Waterschap Vechtstromen
Water boards are regional governments managing water barriers, waterways, water levels, water quality and sewage treatment in their respective regions. Current events show that the water board supports residents, neighbourhood associations, businesses, social organizations, and education institutions to contribute to making their own living environments climate-proof. As municipalities are responsible for water supply in urban areas, water boards are concerned about the water entering the waste water treatment system. In this way, the water board has an interest in urban water. Nowadays, the water board is commonly involved in renewable projects in order to support them with their knowledge, especially in smaller municipalities. This field of interest is schematically visualized in Appendix B.5.

Project developers I Bouwfonds
Project developers see new opportunities to build houses and apartments. A stakeholder group that is not involved in the value chain but interfere with the municipality and the consultancy. They buy land from the municipality and sell it back after a finished project. Due to the high groundwater level, they have to deal with construction challenges to guarantee safety.

Contractor I Van Gelder
The contractor provides supplies or performs work at a certain price or rate. The contractor establishes a budget for the building project and follows that budget as closely as possible. This is the price that is agreed on with the municipality or project developers and formed by the distributor. The contractor is responsible for the construction and ensures that all necessary measures are obtained to result in the completed finished product.

Distributor I Saint Gobain
The distributor or wholesaler sells goods to the public, as opposed to a supplier, who normally sell their goods to another businesses. Distributors sell products to customers through multiple channels of distribution to earn a profit. To optimize value generation, a distributor will price the product

Relations of Wavin

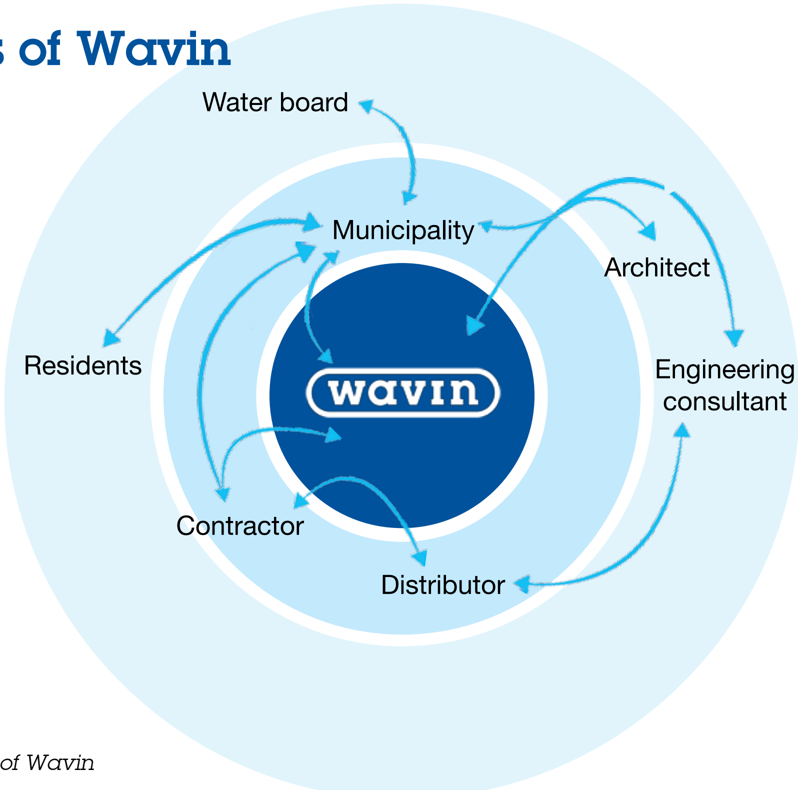


Figure 18: Relations of Wavin

most sharply relative to the competition. In the Netherlands, the distributor is generally skipped. This results in a direct relation between supplier and contractor.

Supplier I Wavin
The supplier delivers the high quality products. As they play a major role in the business, the companies enhance supplier relationship. Customer satisfaction leads to stronger branding. So the supplier has to deal with other suppliers, customers, and other parties to sell the products and to keep a leading position in the market.

Consultancy I Architects and engineers I Arcadis
The architectural engineer plans, designs, and oversees how the elements of landscaping, road routing, and building use combine into creating the urban environment. Nowadays landscape architects are in high demand because cities increasingly become interested in green planning, renewal of urban spaces, and increased efficiency of its existing public spaces. As SWM solutions will become more visible, the advisory role of the architects to the municipalities increasingly becomes a decision making role.

The engineer provides expert advice in a particular area such as water, ecosystems, and energy to improve living circumstances. Currently, municipalities and project developers value the use of this advisory role. Commonly, bigger municipalities have architects and engineers in service. In contrast, smaller municipalities assign environmental planning to an external consultancy bureau.

Residents I Amsterdam RainProof
The residents live in houses, either alone or with other people, in a particular municipality. However, the house is not necessarily owned by this person. Therefore, the term homeowner is used instead of the house owner. On the homeowner's property, the municipality has no rights. So, in general, homeowners have relatively low interest and high power. For example, in the neighbourhood, they want to have a functional place for the car, but also a nice atmosphere, a green one particularly.

2.4.3 European stakeholders
In the Netherlands, multiple stakeholders are involved in SWM development. As Wavin intends to develop and implement the research results throughout Europe, the aim is to understand the differences in European stakeholders and their approach towards climate adaptation measures. The leading countries in SWM are: 1) France; 2) UK; and 3) Germany. Besides this, Poland, the Netherlands, Denmark, and Norway are also involved but on a smaller scale. Scandinavian countries are interesting players as these were early adopters of the sustainable urban drainage concept (SuDS). The European position of Wavin in SWM is visualized in Figure 19. As the research is conducted in the Netherlands this is taken as focus point within the visualization.

European position of Wavin

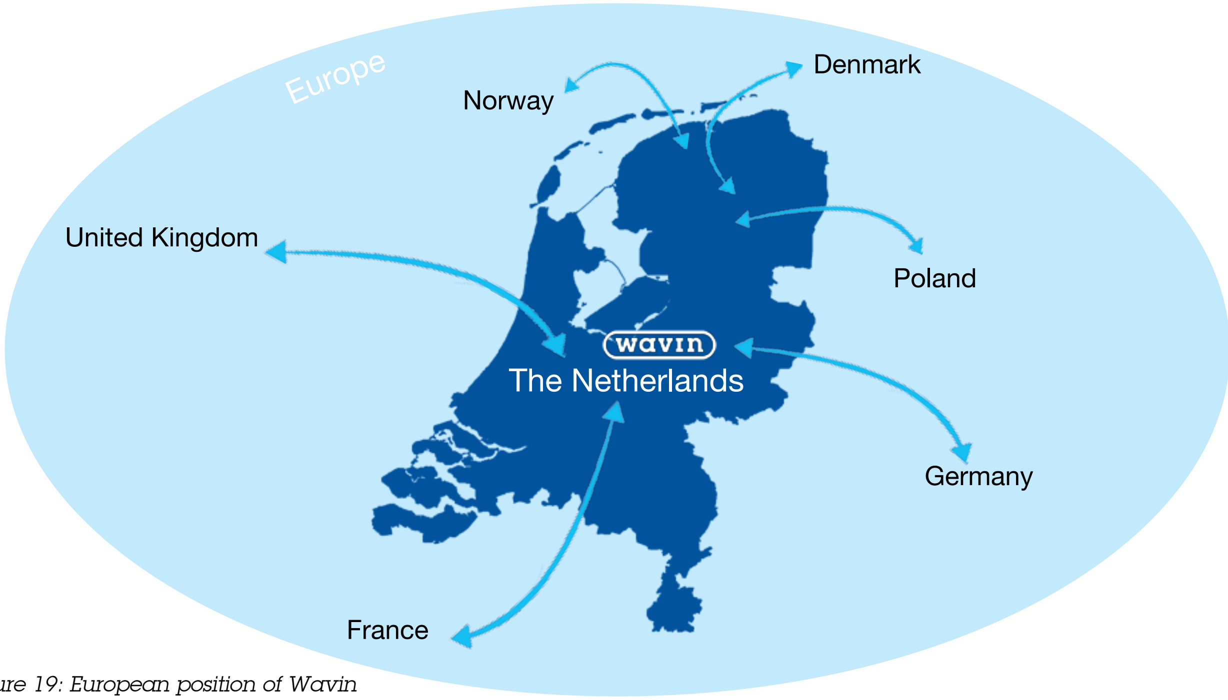


Figure 19: European position of Wavin

There has been an increase in the number of countries that have adopted a national adaptation strategy (NAS) and this is expected to continue (EEA, 2012). The strategy guides countries to make progress in adapting to the impact of climate change. However, analyzing the climate change adaptation plans show all countries take a different approach on how to implement the NAS. The NAS gives insight into governance action. The main reasons for different approaches in climate change adaptation plans are:

- In France, water and river basin management are not comparable with other countries
- Germany addresses adaption planning on international, regional and local level
- UK is a frontrunner in many aspects of national initiatives on adaptation
- In Germany and the UK, private companies play an important role
- In the Netherlands, the regional water board has strong influence on water and spatial planning
- Scandinavian countries has not adopted a formal NAS but operates on the individual level

The EU developed a shift toward sustainable development, greater emphasis on water quality, and coordination at the scale of the river basin (Woltjer & Al, 2007). The change to a larger, regional scale created a great impact especially in Germany where large rivers exists and are shared with many regions (Woltjer & Al, 2007). Water plays a key role in regional areas, as it can provide environmental, economic, and social benefits and costs. As the water infrastructure can be owned by private companies, rather than the water authority, it can provide a new business opportunity for private investors or project developers and municipalities. Thus, the developments in EU policy converted water into a stronger strategic element.

2.4.4 Stakeholder approach

This section provides deeper insight into the stakeholder management of Wavin, as part of its efforts to improve stakeholder engagement of Wavin. The contemporary challenges of a climate-resilient city call for improved collaborative urban storm water management: a multi-disciplinary approach of key players and stakeholders who share the same goals. A multi-tier approach, visualized in Figure 20, aims to bring the people around the table to provide interaction to discuss different functions. What is the storage demand in a specific area, how and where to implement the solution? There are numerous solutions for dealing with the problem, but what do the local residents prefer, and how can that be integrated?

Figure 20: Concept for an multi-tier stakeholder approach to improve urban flood resilience derived from Sorensen et al. (2016).

Municipalities must take a leading role in starting the debate (van de Ven, 2017) by bringing parties together, not only the different divisions within their own organization but also the local experts and residents. As mentioned in section 2.4.2, municipalities and water authorities work closely together in storm water management (SWM). The broader integration of disciplines is an opportunity to view the problem from a new perspective. For example, collaborating architects and water engineers can decide to employ existing elevation in the landscape as an extra defence to the water, or use elevations or hollows to direct the water to lower populated areas where it can do less harm or where it might be of use. The water repository can be used for multiple purposes to create a water-resilient landscape.

Private involvement is needed to create climate-resilience cities (van de Ven, 2017). Private involvement means that the private sector, such as companies, investors, and residents, are involved in the design process. However, private involvement is a big challenge to arrange. It could be partly arranged in legislation to create enforcement. Regarding to Wavin, the residents are not included in the stakeholder engagement, due to their small-scale presence for Wavin.

Wavin frequently visits municipalities to discuss the SWM portfolio. The goal is to sell the products as part of new construction projects. However, the contractor can still deviate from the construction contract. The construction contract is an agreement between the owner, in this case the municipality, and the builder or contractor. Therefore, the municipality is an important key player to ensure the products are recorded in the contract and the contractor does not switch to a competitor or another company more familiar with product. This implies that it is important for Wavin to build and hold a strong relationship with the municipality. Like its their competitors, Wavin is an important knowledge provider concerning water related solutions. To continue delivering better solutions and fulfilling the customer demand, Wavin should be more active in the debate and work more closer together with the customer. This will improve the understanding and behaviour of customers in an early stage of the product development process.

2.5 Exploratory expert sessions

The expert sessions consist of separated exploratory interviews with a water expert. Each interview consists of an exploratory interview and the use of a gamified tool. The exploratory interview aims to verify and obtain information about the application of climate change adaption in practice. The game technique is used to indicate the effectiveness of the existing solutions. The exploratory expert sessions are focused on the client's problems and their interest. At a later stage, the deepening expert sessions provide a deepening interview to validate the defined product scenarios. All expert sessions were conducted in the Netherlands, which chosen as a focus point in this research from here on.

The exploratory expert sessions contribute to answering the third research question: What are the lessons learned from currently existing solutions and trends in sustainable urban SWM? The interview consisted of a semi-structured part and an unstructured, interactive part. The first part aims to verify knowledge about the current state of water problems and challenges in climate change adaptation. This is related to the trends which are researched. The goal is to validate the findings and verify future use of SWM solutions. After the customer's problems had been discussed, the second part discussed the selection of the existing solutions. This interactive part involves a game technique, called card sorting, so the interviewee is actively involved. While playing the game, the interviewee has to come up with important criteria while sorting solutions on effectiveness. The next section describes the set-up of the gamified tool and discusses the participants involved, the data analysis, and the results. A matrix was prepared beforehand to make notes during the interview and can be found in Appendix B.6.1.

2.5.1 Card sorting

Active user involvement methods help stakeholders express and analyse their current product use and let them reflect on future use situations (Thalen & Garde, 2013). Cart sorting is chosen as a practical and action-oriented technique and adapted to fit the research goals. The goal is to integrate stakeholders needs and ideas into the design phase. In general, card sorting works with card sets that describe product features or tasks. These card sets consist of: 1) picture cards; 2) solution (direction) cards; and 3) problem cards. In Figure 21, the picture cards and the solution (direction) cards show the possible solutions and the related solution directions from section 2.3.2. The problem cards include the effects of climate change: flooding, heat stress, and drought.

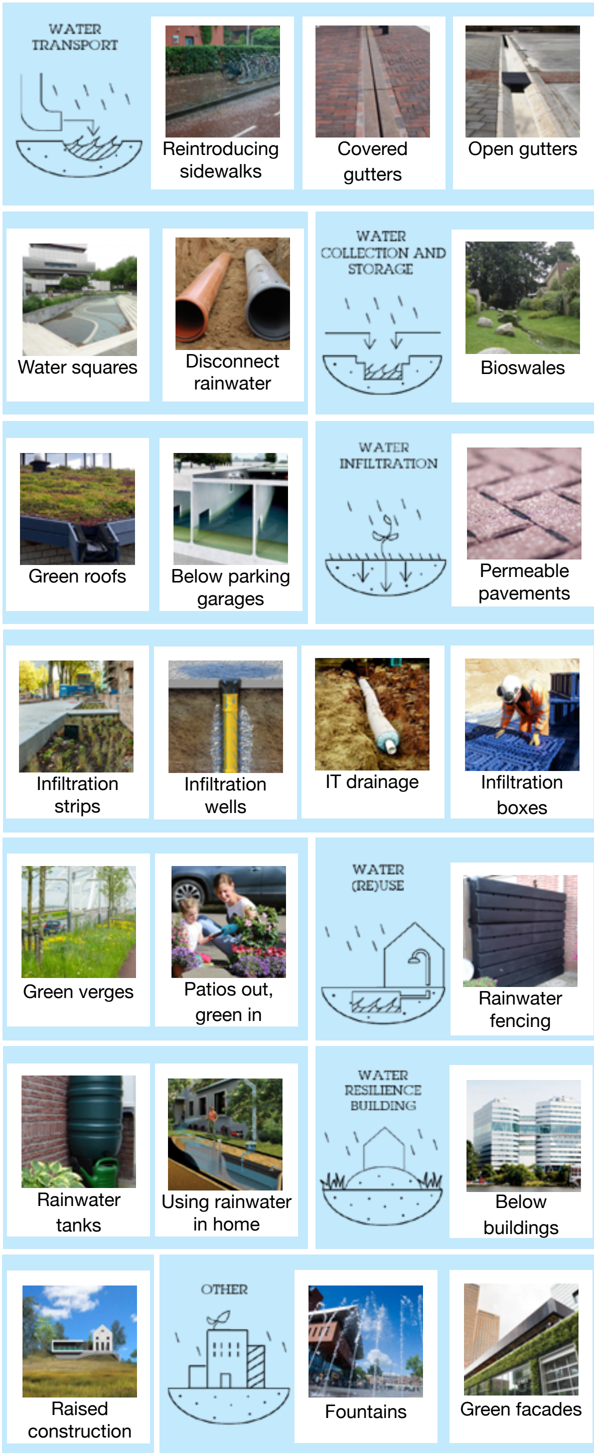


Figure 21: The picture cards and solutions cards

The water expert was asked to organise or sort these cards in partly pre-defined categories; the solution directions in horizontal direction, and the problem cards in vertical direction. This forms a matrix, shown in Figure 22, which was designed as the motivation behind the game. The picture cards and the matrix open the dialogue on effectiveness in solving the problems of water, heat, and drought respectively. By doing this, experts provide insights into the way they organise features of the use and context of the solution (Nielsen & Sano, 1995).

The matrix, in Figure 22, was filled in beforehand and guided the comparison of the results from the expert sessions. The hypothesis was as follows: "•" the drainage system cannot be permanently increased and "•" rainwater for reuse may not be available during dry periods. No desired solutions directions are represented by "-" as for example water transport during high temperatures. In that case, collection and storage is more preferable. The area in which the solutions were expected to take place are represented by "+". So, the criteria used to organise the cards can be translated in a way that product features match the users' preferences or experience.

The participants who were involved in the expert sessions are schematized in Figure 23. During one session the municipality of Zwolle was involved as municipalities are the main customer. The other sessions involved (water) experts from the stakeholder group Consultancy.

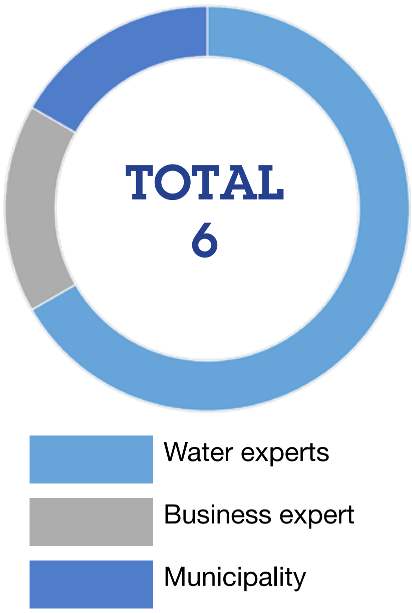


Figure 23: Selection of interviewee participants

The first part of the expert sessions analysis systematically compared the experts' answers. The

	WATER TRANSPORT	WATER COLLECTION AND STORAGE	WATER INFILTRATION	WATER (RE)USE	WATER RESILIENCE BUILDING	OTHER
WATER	●	+	+	+	+	+
HEAT	-	+	+	+	+	+
DROUGHT	-	+	+	●	+	+

Figure 22: The matrix used as framework for the design game

second part was partly transcriptional; labelling argumentations from experts, and concluding with differences and similarities between perspectives of the water experts. It is interesting to look at the link between the two parts; is the solution defined as most efficient in line with the problem statement? The reports of the interviews contain a summary of what was said in the interviews. When part of an interview is cited in the main text, this has been translated freely. The summary was written in Dutch as it concerns Dutch organizations. These can be found in Appendix B.6.2.

The game technique proved useful to start the dialogue and understand the users' experience. After executing the sessions, Wavin expressed interest in incorporating the technique in its frequent meetings with municipalities. In that case, the marketer is usually talking and aiming to sell the products, while this technique pays attention to what the client really wants. It ensures keeping the dialogue open and provides opportunities for bonding. The game proved a successful tool during the expert sessions and received an overall positive and enthusiastic reaction.

As has been illustrated by this section, the game tool offers several benefits for Wavin:

- Facilitation of communication – the game actively transfers knowledge between different domains in the early stage of the design process.
- Better understanding – the cards and the matrix environment enable experts to express their routines and explain workflows directly in their own words, thus sharing knowledge that would otherwise not be available.
- Related to experiences and practical knowledge – the cards visualized an example of a solution through the use of images. This enabled experts to explain issues and opportunities for product concepts if they knew the solution from their own practical expertise.
- Gaining user commitment – including stakeholders in product development, if executed in a way that both parties benefit from the cooperation, can validate the previous findings.
- Triggers open dialogue – the expert is the main player in the dialogue. The expert is the speaker, and the designer is not pre-defining solutions or answers. The picture cards allow them to work more quickly and think-aloud.

For further development, some reflections and limitations are presented below:

- Time – The tool presented in this research covers only a small part of the range of solutions from the market research. Discussing the whole inventory of solutions can be time-consuming.
- Experts' knowledge and attitude – It is necessary to know what they know about a project or product in order to create a situation of meaningful involvement. The first semi-structured part helped of becoming aware of their state of mind.
- Visual knowledge – The image for the picture card should be carefully chosen. In some cases, the card did not show the "right" example from the experts' perspective.
- Language – A word or phrase to describe the product on the card should be clear and simple. For example, the term water (re)use can be widely interpreted as reusing rainwater or using rainwater in the context of swimming to cool down.
- Degrees of freedom – An appropriate degree of freedom should be maintained during stakeholder involvement. For example, one expert switched the order of the matrix. Besides, they were not afraid to put a card aside as being not effective.
- Confidentiality – Including external participants in product development bears the danger of leaking confidential information about the company's developments and innovations.

To conclude the discussion for further development of the gamified tool, it is important to acknowledge the design of the picture cards. It was found that it is important how the cards are visually designed in order to support the dialogue and collaborative design work. Therefore, a consideration should be made between the use of abstract or concrete visuals for the picture cards. Currently, picture cards with concrete visuals (real images) are used. This raised remarks that the chosen image was not the "right" example. However it helped the interviewee to come up with their own practical expertise regarding the presented solution which supported the dialogue. In the end, an abstract image could help to lift design thinking to a higher level. This research goal focused on assessing the effectiveness of the existing solutions to create an understanding of the customer. For future use, in frequent meetings with municipalities, abstract images might be more useful to support the collaborative design work.

2.6 Combining analysis results

The outcomes of the trends, market research, and stakeholder analysis were used to create a combined analysis result, the customer profile, including the customer's issues and needs. The different facets of the analysis were combined in a structured and detailed customer profile presented in Figure 24. The profile consists of three main blocks:

- Block A – what the customer is looking for
- Block B – what the customer is trying to solve
- Block C – what the customer is encountering regarding trends and developments in the sector

These blocks are the outcome of the exploratory expert sessions. Especially, the experts came up with project examples which were valuable input for the block A, B, and C. The following paragraphs first explain the blocks. Afterwards, the result of the gamified tool is discussed. This result defined the focus area to look for potential new solutions. Thereupon, the lessons learned from the existing solutions are discussed. The section concludes with the link between the first part (exploratory interviews) and the second part (interactive game) referring to incorporating the next steps in the idea generation.

2.6.1 Customer profile

Block A I The customer is looking for
The experts' project description gives a good insight into the current developments in the context of climate change adaption. Most municipalities are focused on developing an adaption strategy to guide their city in urban planning. Therefore, municipalities perform stress tests (including risk of flooding, heat stress, and water scarcity) to guide projects and initiatives on urban climate resilience. Local projects include trying to find alternative solutions for the water problem. Besides preventing damage, another purpose is creating an added value (e.g. higher visibility, relation to green, biodiversity, playful).

According to the customer, above ground solutions can offer solutions if the street profile does not provide sufficient space for below ground solutions. New solutions in the form of retention areas which slow the water from running off too quickly, making it suitable for infiltration into the soil, as well as better utilization of rainwater, and the use of public green areas to store water for plants and trees, can simultaneously improve the design, experience and natural value of a neighbourhood.

The urbanization, ongoing density, and paving of ground surfaces affect not only the water challenges but are causing higher temperatures and heat stress in cities. Higher temperatures affect the health, wellbeing, and productivity of people, but also cause a greater energy consumption for cooling and greater water consumption for cooling and for irrigating green areas. The experts acknowledge the impact, but cite challenges related to quantifying the effect and raising awareness among residents. A simple measure tool, as exists for water damage, is missing. In a research of the Hogeschool van Amsterdam, Gregor van Lit and Lisette Klok provided an extensive mind map with the causes of heat stress (Kluck et al., 2017). The mind map can be found in Appendix B.7.

Block B I The customer is trying to solve
A shift in the perspective of the waste water system takes place in the context of climate change adaption. The sewer system as a transport pipe is currently more focused on precipitation, groundwater and water quality. These findings are in line with the literature found in obtaining resilience and sustainable storm water management solutions. The increasing peak period of precipitation either within or outside of the city influences the groundwater level together with prolonged periods of drought. Continuously fluctuation between high and low groundwater level causes problems in the city. The effects of drought are lower on the agenda due to the lack of awareness, but could be of greater damage. It could cause: low groundwater level, ground level decline, and urban green areas becoming dried out. Especially the cities on high permeable soil type are vulnerable. The existing urban environment consists of a sand bed that can store a small amount of water. For example, the higher parts of the Netherlands, east and south, mainly consist of sandy soils.

Currently, a trending topic is water in the street. A hollow road increases the storage capacity of the street combined with pavement and a raised threshold. It can store the water in an efficient use of space and prevent flooding in houses. Residents should accept that water in the street can happen more often. Public consensus should be reached about the definition of water damage; are water problems acceptable as long as they do not cause damage to private properties. Besides, water in the street creates awareness. In this way, urban water management could contribute to making the system more robust against climate change and visible.

Block C I The customer is encountering trends and developments in the sector

Klantbeeld

Context

Water
Heat
Drought

Transport
Storage
Infiltration

Op zoek naar...

Alternatieve oplossingen voor de wateropgave

Focus niet alleen op wateroverlast oplossen, maar water opslaan en hergebruiken voor hitte bestrijding

Stedelijk gebied verkoelen, want in de stad al snel 7 graden warmer

Toegevoegde waarde creëren

Water niet laten afstromen, maar langzaam laten wegzakken

Andere opbouw onder straat om de water capaciteit van de bodemlaag te vergroten

Regenwater afkoppelen van het gemengde stelsel

Groene berging in de openbare ruimte om water vast te houden voor planten en bomen

A

Om of door...

Te voorkomen dat de bui anders op het maaiveld blijft liggen en overlast veroorzaakt

Wateroverlast op doorgaande rijwegen voorkomen

Stedelijke verharding beperken

Maaiveld anders inrichten om extra berging te creëren

Water op straat; liever in de berm

Rioolstelsel robuuster maken

Het gemengde stelsel ontlasten

Groen van watertoevoer voorzien tijdens neerslag tekort

Watertekort kan leiden tot verdroging, verzilting of verzakkingen

Grondwaterstand aanvullen

Zichtbaarheid, relatie met groen en esthetische betekenis

B

Trends...

Uiteindelijk gaat het om de gebruiker

Naast de metrologische trend een enorme verstedelijking

Sinds een aantal jaren is er een verschuiving gaande van afvalwater keten; dus de riolering als buis, naar meer klimaatverandering: neerslag, grondwater en waterkwaliteit

Noodzaak om publieke en private ruimte te betrekken om hevige buien te bergen

Decennia lang een verandering waarbij de private sector en gemeenten veel meer worden uitgedaagd tot 'zelfredzaamheid'

Sociaal dilemma waarbij bewoners en ondernemers zelf moeten investeren in een publiek belang

Langzamerhand keert trottoir band weer terug

Fluctuatie van grondwaterstanden leidt tot aantasting fundering

Wateroverlast, hittestress en droogte gekoppeld aan bodemdaling een internationaal concern

Waterkwaliteit verwikkeld in de drie problematieken

Systemen op weersvoorspelling gaan reguleren

Op gebied van droogte in Nederland nog niet verder dan de regenton; onze buurlanden België en Duitsland meer zelfvoorzienend

C

Wavin biedt 3 scenario's...

De oplossingen dragen bij aan hitte bestrijding. Wavin richt zich op riool ofwel gevolg bestrijding. Deze nieuwe richting neemt juist de oorzaak weg en vermindert het versterkende effect van stedelijk gebied op de waterbalans

A — 1 De opbouw van het groen en de onderliggende bodem / 2 Water opvangen en hergebruiken in droge tijden / 3 Wateroppervlakken zo vormgeven dat ze water kunnen bergen en zichtbaar afvoeren

B — Het systeem robuuster maken qua hoeveelheid water + Extra berging rondom het maaiveld creëren

C — Focus op neerslag (tekort) naast de zorg voor het rioolstelsel + Grootschalige oplossingen in de openbare ruimte

Figure 24: The customer profile

There is a greater housing demand in addition to the wish to create more public green and blue areas. Solutions for heat, water, and drought should be combined to improve the cohesion between functions. For example, the approach for heat can at the same time save energy and water consumption. Similarly, locations, where water problems occur, are often also the heat spots.

The opportunities for climate adaptation lie among neighbourhood level as these are the most effective. Residents should be involved to solve the water problem but it takes a lot of effort and time and the results are few. There is a demand for large-scale solutions that fits into the existing urban environment and this fits the interest of Wavin.

The Netherlands plays an important role in the water sector on a global level, but based on adaption to heat and reuse of water, the neighbor countries and other countries abroad, e.g. Japan, are further developed. Thus, it does not only concern the supply of water but also a more efficient use of water, reduce vulnerability for water scarcity and creating and using alternative, internal sources within the city.

2.6.2 Focus area

Figure 25 shows the overall matrix as a result from the gamified tool in the six interviews. The matrix compared to the matrix filled in beforehand in section 2.5 shows some new insights. The matrixes are compared and the differences are highlighted with grey squares in Figure 26. Remarkably, solutions regarding water collection and storage during a period of drought do not exist. Regarding water (re)use, solutions are not linked to water or heat stress but might only be of use during dry periods. Finally, the water resilience building only has an effect on the water problem and does not answer to the heat stress and drought problems. This can be due to the fact that construction material is not included in the set of solutions.

In addition to the data collected in the first part of the interview, this results in a specific focus area. The focus area is schematically visualized in Figure 25 through a blue triangle. In short, solutions should not only focus on preventing water damage but store water for periods of higher temperatures. So, there is a need to include the categories of water transport, water collection and storage, and water infiltration. Water resilience building and water reuse will not be analysed further. Firstly, water resilience building is a construction method and mainly concerns building materials which is not part of Wavin's capabilities. Secondly, water reuse is desired but is currently not feasible for private use. Drinking water is relatively cheap and drinking water is sufficiently available in the Netherlands. The urgency is not present and will not be considered for the parties on the market, neither for Wavin. On the other hand, customers expressed high interest in systems for using precipitation in public spaces.

Figure 25: The overall matrix derived from the results from the second part of the interview

	WATER TRANSPORT	WATER COLLECTION AND STORAGE	WATER INFILTRATION	WATER (RE)USE	WATER RESILIENCE BUILDING	OTHER
WATER	+	+	+	-	+	-
HEAT	-	+	+	-	-	+
DROUGHT	-	-	+	+	-	-

Figure 26: The results compared to the hypothesis. The gray squares implies the different outcomes than expected.

2.6.3 Most interesting and relevant solutions

The indication of effectiveness based on the set of solutions is visualized in Table 2. This shows especially water related solutions are included. The distribution of water related solutions mitigating the effect of heat and drought is shown in Figure 27. This implies less attention to heat and drought. The criteria to indicate the effectiveness of the set of solutions is summarized in Figure 28. Solutions with multiple purposes and an additional social and economic value are highly desirable. The solutions like Bioswales, Green roof, Urban infiltration strips, and Green verges are therefore ranked as high effective solutions. Together with the most relevant and interesting solutions, shown in Figure 28, this guides the set of design principles in the concept development.

Table 2: The indication of the effectiveness based on the set of solutions.

Current existing solutions	Water	Heat	Drought
Reintroducing sidewalks	●		
Covered gutters	●		
Open gutters	●	●	
Disconnect rainwater	● ●		
Bioswales	● ● ●	● ●	●
Water squares	● ● ●		
Green roofs	●	● ●	
Below parking garages	● ●		
Permeable pavements	● ●		
Infiltration strips	● ● ●	●	● ●
Infiltration wells	● ● ●		●
IT drainage	● ● ●		● ●
Infiltration boxes	● ● ●		
Green verges	●	● ●	●
Patios out, green in	●	● ●	●
Rainwater fencing	●		●
Rainwater tanks	●		●
Using rainwater in home	●		● ●
Below buildings	● ●		
Raised construction	● ● ●		
Fountains		● ● ●	
Green facades		● ● ●	
Rainwater ponds	● ● ●	● ●	●

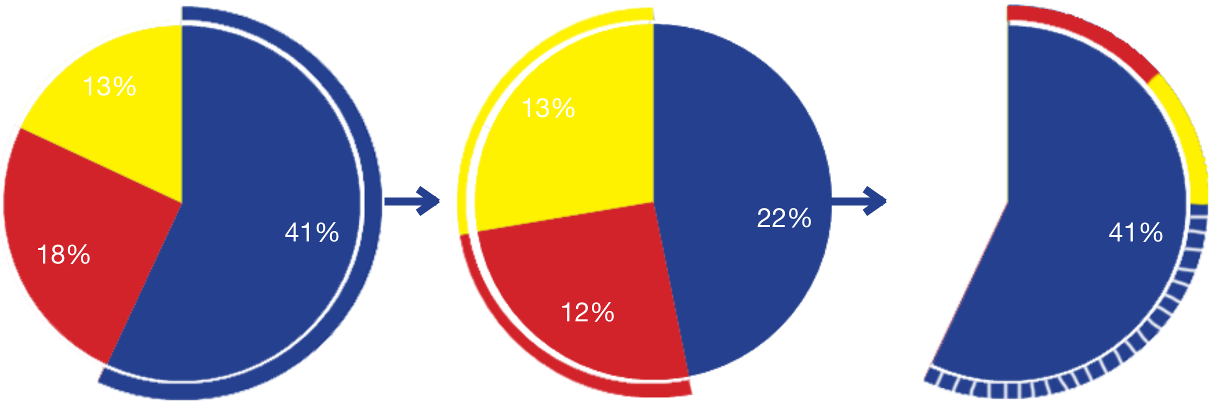


Figure 27: The ratio of distribution water-related solutions

Figure 28: The most interesting and relevant solutions based on the different criteria

It is important to consider the criteria that decide why a solution is not included. The criteria used to indicate low-effective solutions are provided in Figure 29. Interestingly, water squares only do something with water, so they are assessed as low-effective, similar to the Permeable pavements. The low efficiency is covered in the criteria named functionality. As many sidewalks have disappeared in cities to increase wheelchair accessibility in recent years the Reintroduction of the sidewalk is taking place. Besides, experts are convinced that Disconnection of rainwater has to be adopted into standard building regulations to make the system more resilient. Other solutions are rejected because of health risk due to low water quality. In addition, Rainwater storage below parking garages

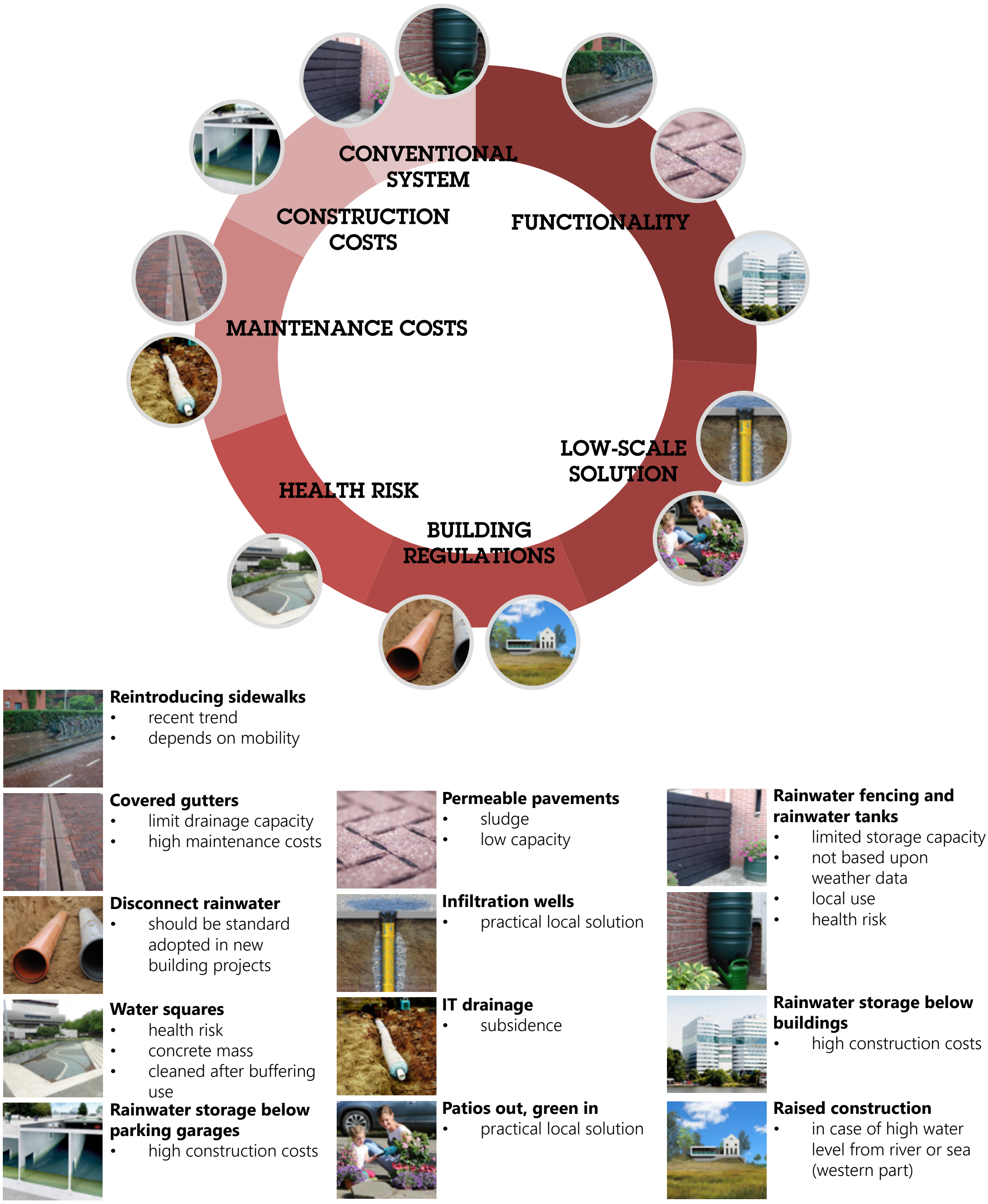


Figure 29: The solutions not included based on different criteria

or buildings and Raised construction are not considered due to high construction costs. While playing the game, suggestions were discussed to create combinations or improve the system to make the solution more efficient. For example, the Rainwater fencing and Rainwater tanks are actually conventional systems and applied on a small-scale. In most circumstances, the tank is full or not-used during heavy rainfall so the water storage function cannot be performed. It would be interesting to use an pro-active weather-based control system to achieve higher efficiency. This was also found in the product related market research. In this way, the smart solution can be applied on a greater scale in the neigborhood.

In short, important lessons learned from the existing solutions are:

- Green roofs should only be adopted if it contains water retention.
- Infiltration boxes only do something with water, but a pro-active or adaptive system could provide opportunities to address heat and drought.
- Green verges should only be applied if they are located lower (deeper than the road or pavement).
- Fountains and green facades are effective for heat but could be multifunctional by addressing water and drought functions.

Moreover, fountains are an interesting solution because they provide a desired cooling effect but they also involve health risk and water quality. In the Dutch media, this led into a trending topic about 'small cheaters'. Therefore, in most cases drinking water is used in the system. Based on the trends, this does not nothing to alleviate cities' water scarcity and drought issues.

Conclusions
Concluding and linking part 1 and part 2 shows that a difference exists between the results. The demand of the client does not directly fit the currently existing solutions on the market. As can be concluded from part 1, cities provide good water resilience and safety of flood resilience but insufficient adaptation to high temperatures in the current urban environment. This is similar to the outcome of the matrixes which show a wide area of water related solutions, and similar to the trend, that the Netherlands retain a strong position in water development. Besides the water challenges, public areas require more green areas, shadow and waterways to align with the reinforcing effect of urban environments on the water balance. In contrast, the market has to come up with multifunctional solutions focused on heat and drought to reduce the impact of the extremes on the urban water balance. This provides new opportunities and will drive the market in the coming years.

Problem perception
The link between part 1 and part 2 leads to a specific problem-solving direction. The urban water cycle is becoming increasingly more unbalanced due to growing urbanization and climate change. There is not one solution but a combination of measures are required on different scales. Therefore, future solutions should be multifunctional; solving both heat and drought problems as well as the water challenges. The design vision is to achieve a more natural balance through improving the coherence between functions:

- Water transport – the transportation of rainwater to designated areas to reduce damage to infrastructure and environmental and health impacts in urban areas
- Water collection and storage – the collection of rainwater is a way to temporary buffer and delay discharge of rainwater
- Water infiltration – the infiltration of rainwater directly into the soil if the soil type and groundwater level allows it
- Cooling – the evaporation of water to lower the temperatures in urban areas
- Water availability – the availability of water in periods of drought to mitigate shortage in prolonged dry periods

These directions are set as main problems through the use of a TRIZ tool called Problem perception mapping (PPM) described in Appendix B.8.

In conclusion, the future solutions have to focus on multifunctional solutions to: 1) achieve the water challenges; 2) mitigate the effect of higher temperatures; and 3) provide added value. It can be concluded that the current solutions only cover a respectively small part of the problems existing in the public places. Therefore, this research seeks to bridge the gap between the indication of vulnerable locations and the customer's search for multifunctional water systems. The greatest challenge for Wavin's customers and stakeholders, especially municipalities, water boards, and consultancies is to come up with solutions for solving the real problem, heat and drought, the next decades. From here on, potential solutions are generated in the next chapter.

3. IDEA GENERATION

This chapter describes how the results from the analysis were used to develop product features. To this end, ideas were generated using multiple methods. Firstly, the TRIZ innovation technique was applied to generate innovative new solutions. Secondly, the new and existing solutions from the market research in chapter 2 were clustered into three scenarios. The results of the analysis and the customer profile were validated through deepening expert sessions to, in the end, choose a specific scenario direction. In this research, the scenario include a description of a practical problem and an explanation of possible solutions in order to create a product strategy solving the problem.

3.1 TRIZ

The existing solutions, analysed in the previous chapter, provide valuable insight into customer problems. However, to go beyond existing solutions, the Theory of Inventive Problem Solving (TRIZ) (TRIZ, 2017) was used to analyse problems and generate new solutions. As the solutions all relate to problems, the TRIZ innovation technique is an appropriate method to develop abstract solutions for problems. To this end, the overall problem to solve is: Urban adaptive capacity is insufficient. As applied to an urban water system, the problems are indentified as follows: 1) Urban temperature is too high; 2) Water availability is too low; 3) Minimal presence of public green areas, and 4) Valuable properties are frequently flooded. The problems were further extracted and formulated in contradictions. As an example from the analysis, a problem related to the second problem, Water availability is too low, is the not automated or self-adaptive water systems (e.g. water tanks and rainwater fencing). To store a heavy rainfall, the water tank have to be empty and to meet greater water demand during a period of drought, the water tank have to be full. Due to the not automated features, the product is insufficient adaptive to heavy rainfall and dry periods.

The contradictions are defined as a problem contributing to a positive as well as a negative effect. A full tank is mainly caused due to the fact that the water is not used after a period of time or after the previous heavy rain event. Therefore, the contradiction related to water is not used is defined as, "the water tank should be full to meet greater demand and empty to provide storage during heavy rainfall." The contraction definition is visualized in Figure 25. The TRIZ problem-solving tools allow breaking out of the traditional patterns of thinking to deliver innovative new solutions. The 40 Inventive Principles tool is applied to solve the contradictions. The positive effect of the problem water is not used, greater peak demand, it translated into the improving feature Volume of moving object. The negative effect of the problem, water storage is full, is embedded into the worsening feature Material quantity. From the 40 Inventive Principles, this results in the selected principles: 30, 31, 7,4 ,29. Inventive principle 7 is nesting which refers to components or parts being 'nested' within a system to conserve space, use unused volume, or contain one thing inside another in a controlled way.

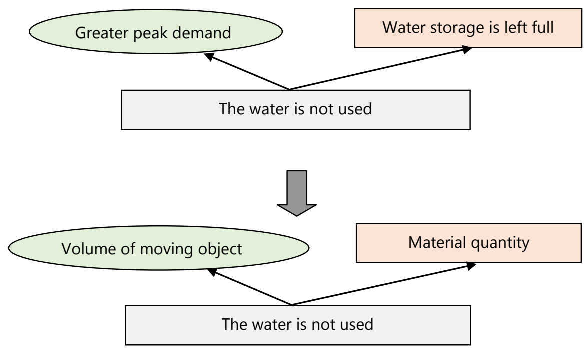


Figure 30: The contradiction definition of "water is not used"

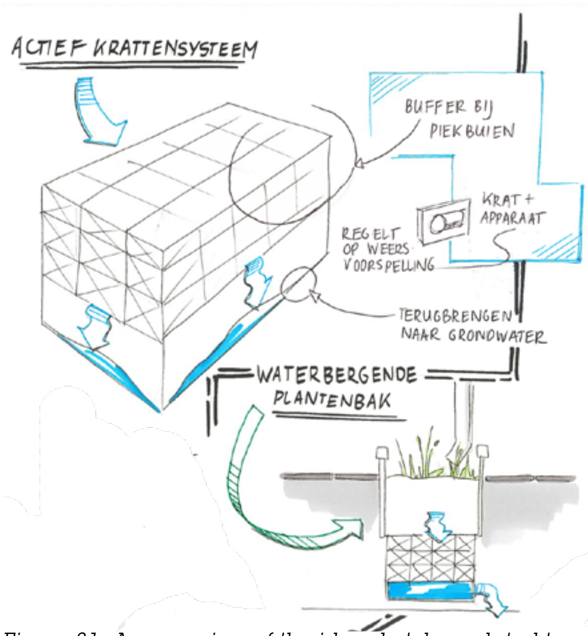


Figure 31: An overview of the idea sketches related to this situation

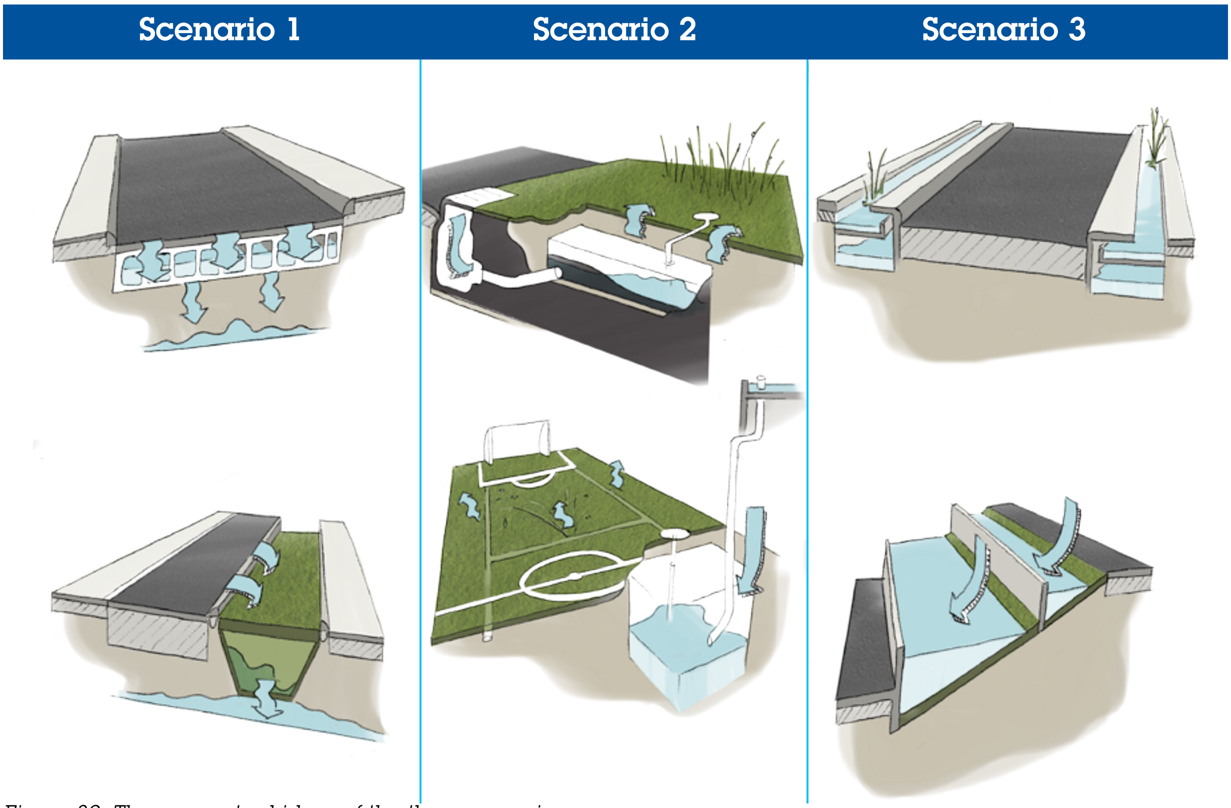


Figure 32: The conceptual ideas of the three scenarios

So, the principles guide to change the product's function in conditions most suitable for its operation. For this contradiction, the principle leads to an idea to make an adaptive, automated infiltration box and to incorporate a planter with an infiltration box. In this way, each part of a product fulfils a different and useful function; the planter infiltrates and evaporates water with a below ground storage tank. The sketches related to this situation are visualized in Figure 26. The analytical tool to model the problems in an abstract way is called Root Conflict Analysis (RCA). The RCA model, the problem-solving process, and the sketches are further described in Appendix C.1.

3.2 Scenarios

As a result of the customer profile, three scenarios were created to fit the client's problems and needs. The idea sketches related to the scenarios are visualized in Figure 32. The description of the scenarios is provided in the next paragraphs. The goal was to choose one product strategy to narrow down the idea generation. In addition, a decision was made to develop a new product or to combine existing product(s) into a total product system. Therefore, a clustering of the sketches relating to a new or existing product was made. This includes a short description for who and which problem will be solved. So, the customer is central to the clustering technique. The clustering of idea sketches is provided in Appendix C.2.

Scenario 1 – Water availability for cooling effect

A big problem in the current construction of paved surfaces is the compact subsurface soil. To withstand traffic loads, the soil strength change from "loose" to "compact". In general, loosely packed soil has larger particles which enables water movement whether compact soil consisting of smaller particles restrict these movements. So, the capacity of the subsurface for retaining water is extremely limited. Ongoing density and paving of surfaces reinforce this effect. This product scenario focuses on water availability in the subsurface for use at the surface. The product scenario provides a cooling effect to the city. The ambition for more green areas in urban areas is not always feasible. So, not more green but efficient, cooling green.

Existing solutions from the product related market research I Permavoid, Bufferblock

Scenario 2 – Water collection and re-use in dry periods

Increasing urbanization shows a greater peak on water demand. Systems for using rainwater in homes or buildings are not widely adopted as sufficient sources are available in the Netherlands for producing drinking water. Therefore, this scenario focuses on rainwater use in the public area for purposes that do not require drinking water, such as irrigating plants and water elements. In the Netherlands, the government does not (yet) offer any incentives for using rainwater. However, this might change as a result of longer dry periods in the Dutch climate. The product scenario supports a more efficient use of rainwater.

Existing solutions from the product related market research I Blue bloqs, Stormharvester, EWB sportwater

Scenario 3 – Water storage and making water visible

The urban area is mostly paved with roads, parking lots, and squares. The rainwater that falls on the urban surface can be infiltrated into the subsurface to a limited extent. Designing above ground drainage keeps the water visible in the city. Furthermore it contributes to the natural environment in the city and has a reducing effect on paving surfaces. Possibilities for above ground drainage includes open gutters, sunken roads, and open water elements. Such elements can provide water storage as well. The product scenario increases residents' awareness of urban water systems and promote higher liveable cities.

Existing solutions from the product related market research I Rainroad, Rain(a)way

3.3 Deepening expert sessions

The deepening expert sessions consisted of separated, deepening interview about the identified problems and interests from the exploratory expert sessions. The deepening expert sessions were conducted as a method to verify the results of the analysis and to validate the customer profile. Furthermore, the interviews contribute to the third research question and provide the answer to the following two sub-questions: 1) Which of the SWM solutions do align with the problems and interest that the clients currently have as well as bring to light new opportunities?; and 2) What are possible SWM solutions for temporary water storage, delay and other (re-)use near surface or above-ground that could be effective and applicable by Wavin, and why?

Comparable to the exploratory expert session, the interview consisted of a semi-structured part and an interactive part. The first part consisted of general questions to gain more knowledge about problems and interests by discussing the same themes as the exploratory expert sessions. It is mainly focused on validating the following design vision as a result of the first part:

"Enhancing large-scale solutions which fit the greater housing demand in addition to the wish to create more public green and blue areas. The future solutions should be multifunctional, responding to heat and drought besides the managing of storm water. So, it should improve the coherence between functions (water transport, collection and storage, and infiltration) as well as provide water availability for cooling, and improve the efficiency in the use of rainwater."

After discussing the customer's problems, the second part discussed the selection of the existing solutions. This interactive part involved a game technique similarly to the one described in section 2.5.1. Here, too the interviewee had to come up with criteria to sort the cards on effectiveness. However, the card set-ups included not the same picture, solution direction, and problem cards. The goal was to validate the selected set of solutions and scenarios. Therefore, the picture cards consisted of the most interesting and relevant solutions (Figure 24) and the idea sketches related to the scenarios (Figure 26) in a more abstract way. In addition, the card sorting was not based on the solution direction-problem matrix, but a new game technique, called the User game (Brandt et al., 2006). In the next section, the set-up of the User game is described after which the participants involved, the data analysis, and the results are discussed.

3.3.1 User game

The game technique in section 2.5.1 proved useful to start the dialogue and understand the users' experience. In addition, the User game contributes to the research goal of identifying the SWM solutions which do align with the problems and interest that the clients currently have. The goal is to incorporate stakeholders' criteria into the concept development phase. In general, the User game works with moment cards and sign cards. The sign cards are used to label the stories created with the moment cards (Brandt et al., 2016). In this case, the card sets consist of: 1) picture cards; 2) criteria cards. The picture cards or moment cards show the most interesting and relevant solutions and the abstract scenario sketches. The criteria cards or sign cards include the words: Functionality, Multifunctional space usage, Social-economic value, Economic aspects, Maintenance costs, Construction costs, Health, Biodiversity, and Energy.

The water expert was asked to choose at least five moment cards and creates a story about the above ground solutions the user mainly obtain in practice. Secondly, the expert created a new story that elaborates on the story created by placing a sign card that intersects with the line of the moment cards on the table. In this way, a web of stories is created that gives an overview of the user's experience with sustainable SWM solutions. Besides, a game board or landscape was designed to assess the effectiveness of relevant and interesting solutions. The game board consists of a circular diagram divided into three equal regions: water, heat, and drought, related to the three main effects of climate change. As final task, the water expert was asked to rank the picture or moment cards within the landscape. The moment cards have numbers. These numbers are written within the problem field. An extensive description of the User game and game board can be found in Appendix C.3.1.

Different experts from the first session were involved, shown in Figure 33. The municipality was involved for the second time, but this time the municipality of Enschede. Besides, a new stakeholder group was involved namely the water board. This could help validate the results from the first session in which they were not included. Like the first expert session, the interviews were performed in Dutch. The matrix used as a framework for the interview can be found in Appendix C.3.2 and the reports in C.3.3.

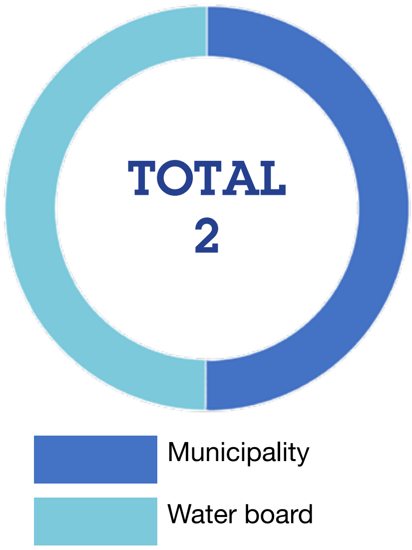


Figure 33: Selection of interviewee participants

The first part was analysed by comparing the answers through the structured process. It is interesting to notice the shifting trends in water storage. More often, storing rainwater is set as a requirement and increasingly imposed on new building projects. Besides, the stakeholders agreed on the fact that heat stress is much lower on the agenda. According to the municipality, it should be mapped first to indicate the vulnerable spots. Increasingly, cities perform stress tests (including risk of flooding, heat stress, water scarcity) to guide projects and initiatives with regard to urban climate resilience. Commonly, the 'heat spots' interfere with the risk areas of flooding. Although, water problems occur also individually.

The second part was analysed by summarizing the results of the card sorting and labelling argumentations of experts. The main considerations of the municipality are focusing on the maintenance aspect followed by functionality (in use) and social and economic value. The ranking of these criteria can be derived from Figure 34. The integration of technical, innovative products in SWM is mainly restrained due to the preference for low maintenance costs. Further preferences of the municipality are visibility of the design and a minimum lifetime of 40 years.

Conclusions

The deepening interviews show interest in the three different scenarios. Especially the design game shows strong interest in Tree ground solutions, Blue bloqs and Permavoid solutions, which are part of the first two scenarios. During the interviews, it was noticeable that the solutions are mainly focused on water collection, storage and transport. Accordingly, discussing the theme of water quality offers new insights. Namely, an improved water quality can actually be obtained within the three problems but is not explicitly described in the Delta program. This creates a big challenge, along with making the city climate-proof. As Wavin does not have the knowledge capacity on water quality, it is not included within the design vision of this research. In addition, an important remark is based on the practical experience with Bioswales. Before disconnection from the combined sewer system, the roots of the substrate have to be evolved first. However, roots do not reach that deep. Most of the time, drainage systems are too deep to feed the above ground vegetation. But the interesting thing about bioswales is to transport rainwater there were it falls, and contribute to the collection and retention of storm water in an ecologically sustainable way.

The deepening interviews validated the results of the analysis and the customer profile. Through executing the sessions, the water experts expressed interest in the three scenarios. The insights of the water experts do align with the search for large-scale, multifunctional solutions focusing on heat and drought problems besides the water challenges. Besides the validation, the deepening expert sessions provided new insights, especially, with regard to the customer's demand for new innovative techniques requiring less maintenance.

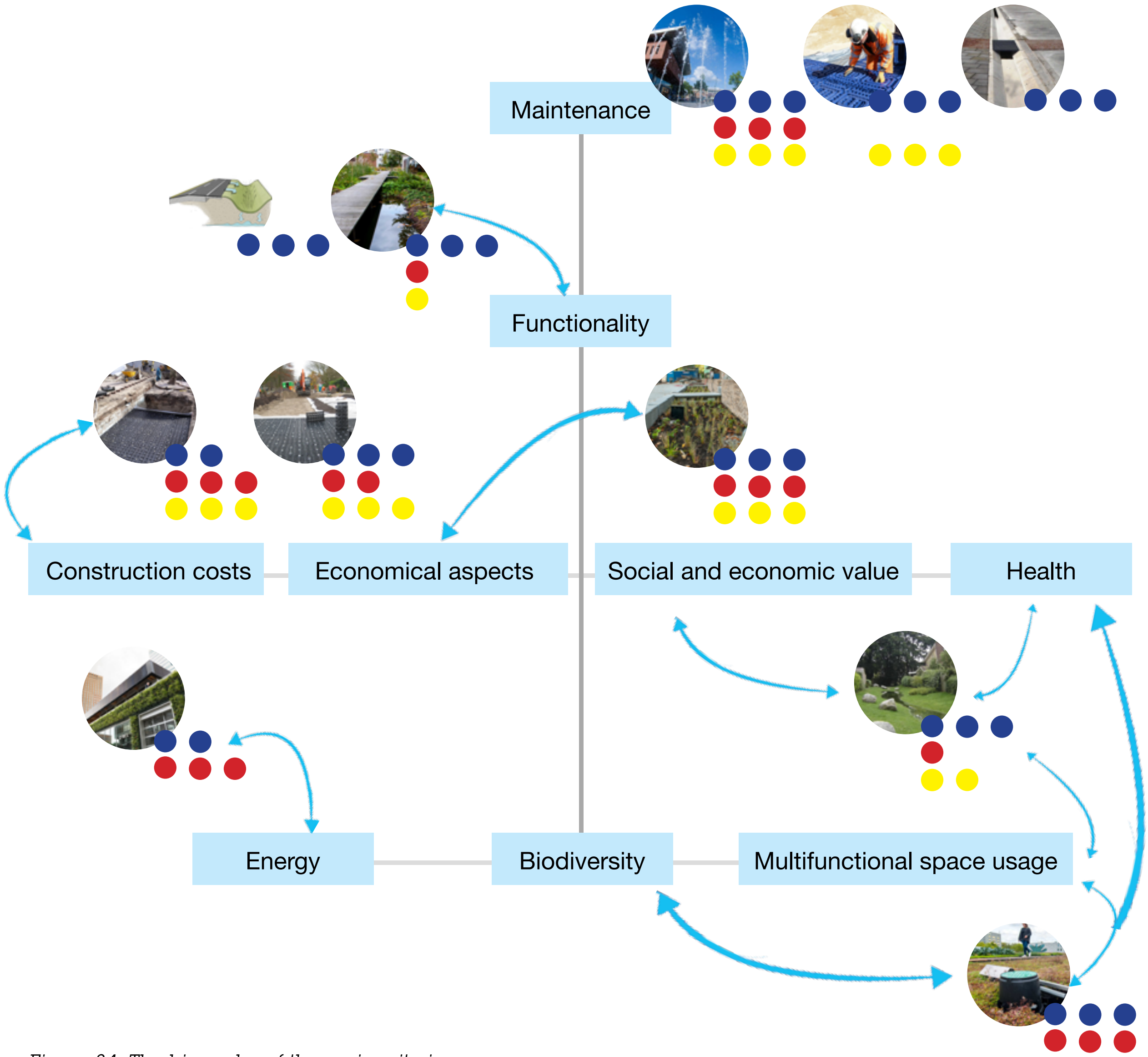


Figure 34: The hierarchy of the main criteria

In short, a challenge in designing a product system will be to:

- Provide multifunctional water systems – as a solution to the water challenges, higher temperatures, and providing an added value
- Prevent designing mechanical systems – as the customer prefers low maintenance products without the assistance of pumps
- Enhancing large-scale systems – as the functionality of climate change adaptation lies in public spaces on neighbourhood level

Based on the validated customer profile and the new insights, the scenarios will be aligned with Wavin's interest in the next section.

3.4 Scenario direction

This section summarizes the potential solutions from the idea generation and the results of the deepening expert sessions to conclude with a specific scenario direction for Wavin. In addition, the validated analysis results and customer profile demonstrate a need to introduce products that relieve heat stress more than water related challenges.

To create a resilient, climate-adaptive city, products have to level out and balance the city's surface temperatures. Therefore, water has to "sweat" according to a metaphorical expression used during the intern milestone meeting. A guiding principle is the cooling effect of green roofs. For cooling, green roofs have to retain water, as mentioned in section 2.6.3 as water retention roofs, because evaporation through vegetation provides cooling (Hendriks et al., 2016). Vegetation in combination with water retention results in a higher cooling rate in contrast to the functions separated. So, the decision is made to further develop Scenario 1 – Water availability for cooling effect. This scenario described that the current construction of paved surfaces consists of a compact subsurface soil. So, the capacity of the subsurface for retaining water is extremely limited. Further development of Scenario 1 will focus on retaining and transporting water from the subsurface to the surface to enable evaporative cooling.

Scenario 2 – Water collection and re-use in dry periods and Scenario 3 – Water storage and making water visible are not developed further. In Scenario 2, the challenge would be to investigate the opportunities to reuse stored rainwater. As Wavin's portfolio includes the collection of rainwater, deeper insight is needed in developing a pro-active, adaptive system for use in irrigating green spaces or other water elements. Wavin already made progress in developing a weather regulated infiltration box in cooperation with StormHarvester. Furthermore, the second scenario focuses more on managing storm water runoff and providing water in dry periods instead of mitigating heat stress. In addition, Scenario 3 is more related to a secondary, social problem namely the lack of awareness among residents and keeping water visible in the city. Although public awareness for the Urban Heat Island (UHI) has increased during the past decades, the effects are not as visible as water in the street and water damage. Besides this direction moves towards a more architectural approach which does not fit with Wavin's capabilities. On the other hand, municipalities and water boards experience that rainwater from such surfaces usually contains too many pollutants and brings several negative impacts (e.g. water quality and smell).

Thus, Scenario 1 was chosen to develop further. The aim is to design a product system that contributes to reducing the city's surface temperature. The product elements enable constant transport of water from the subsurface to the vegetation root zone, which provides day-to-day evaporation to locally decrease air temperature. In this way, a subsurface will transport water and the surface (e.g. green area) will evaporate water to provide a cooling effect. Therefore, the space between the surface and the below ground products (e.g. pipes and cables) can be efficiently used

3.4.1 Wavin's product scenario

In addition to the current trend of rising temperatures, "about 20% of highly urbanized cities could experience a total warming higher than 4 degrees (Estrada et al., 2017)." Obviously, it is important that increasing heat waves will affect human health and well-being (Rovers et al., 2014). Therefore, the customer's need for cooling the city's surfaces will become greater. This section links the customer's need to the findings from the analysis. The urgency of heat stress is described based on five facts on current developments and trends. Certain effects are noticeable after a longer period of higher temperatures (e.g. human health and well-being, or drought). Other factors have a direct impact, for example on the expansion of bridge construction. Figure 35 summarizes the important factors to consider for developing and implementing a water system that enables cooling in the urban environment. It is important to make a distinction beforehand between indoor and outdoor climate. The indoor climate depends on outdoor air temperatures. Besides the physical outdoor air temperatures, the effect is strongly related to subjective heat perception. In this context, special attention is paid to outdoor temperatures on microclimate (near the surface).

Facts showing the Urgency:

1. The temperature in cities compared to rural areas can rise to 8 degrees. The Hague measured a maximum difference of 15,4 degrees in 2006 (Stadswerk, 2016).
2. Heat-related sleep problems due to high temperatures during the night lead to loss of work productivity (Kluck, et al. 2017).
3. Air conditioning for the cooling of indoor space has a negative impact on the environmental heat and energy consumption.
4. Green can help to reduce UHI effects. 10% more green brings the temperature down by 0,6 degrees. In addition, urban green areas contribute to environmental benefits (e.g. storm water control, air quality improvement, and biodiversity).
5. The urban area consists of 30 to 40% public area, the rest is a private area (individuals and companies). Despite the growing trend in vegetable gardens and community gardens, a recent study shows that only 17% of the Dutch population has the front garden full of plants.

The next chapter, the concept development, will focus on further development of designing a multifunctional water system to provide a cooling effect on the city’s surfaces.

8 factors that play a role in cooling urban areas

Adaptation scenario

Due to climate change heat waves will become more common in the future. This adaptation scenario provides the option to reduce the city's outdoor temperature close to the surface. Therefore, the storm water solutions provide:

- Evaporative cooling
- Water collection and transport from the subsurface to the surface
- Water retention in a dry period

The scenario brings the storm water solution closer to people and prevents severe change during heat waves.

Existing options

1. Trees
2. Green roofs and facades
3. Sufficient airflow
4. Sun shading
5. Reflective roofs and walls

Customer preferences

For many customers, it is important to improve the retention capacity of the subsurface. In general, a water retaining subsurfaces are limited due to compact, paved areas.

Microclimate

At several places, the UHI will be lower. Effectiveness on macro-level depends on

- Wind
- Buildings
- Shading

Traffic load

The water system in the subsurface must be able to bear the weight of a fully loaded truck.

Groundwater level

The water system must be located above groundwater levels.

Trade-offs between storage/transport and evaporation

Designing a water system to cope with fluctuations in rainfall. Peak events need to be buffered, and warm days needs to be cooled, with the buffer size depending on many factors:

- Available rainfall that needs to be buffered
- Minimum rainfall that needs to be evaporated
- Minimum rainfall to retain in a dry period

Space available

The space available between the surface and the below ground products can be efficiently used to transport water. Determines the possible storage and transport solutions, for example:

- Pipes
- Boxes
- Or new installations

Soil type

The soil porosity characteristics influences the possibilities:

- Poor permeability: clay, peat
- Presence of a loam layer makes a special solution necessary
- Coarse sand is very permeable

wavin

Figure 35: The important factors for cooling urban areas

4. CONCEPT DEVELOPMENT

The concept development focuses on improving the potential idea of providing a cooling effect on the city's surfaces. The concept and its iterative development is described in this section. Firstly, the concept requirements are provided based on the analysis steps. Secondly, the concept systems and elements are presented as a result of the brainstorm session with technical experts at Wavin Technology & Innovation (T&I) in Dedemsvaart. Simple calculations based on theoretical background are provided to understand the amount of water required for the multifunctional water system. The integration of potential concept systems and elements resulted in four improved concepts. The concept with the most potential was chosen to develop further.

4.1 Concept requirements

The concept must be based on seven principles, that derived from the product scenario in 3.4.2 and Figure 35. The principles are as follows:

1. Evaporating water to reduce the temperature near the surface – The current surface holds warmth, which causes late heat losses during the night. The new concept must be able to evaporate water to reduce the temperature near the surface.
2. Transporting water – The new concept must be able to transport water to the surface layer. The mechanism makes use of forces that transport water against gravity, like the roots of a plant to its leaves.
3. Holding rainwater – to supply water during the dry period. In the current product portfolio, this is done by infiltration boxes, which controls the outflow to surface water or the sewer system. The new concept must be able to hold rainwater within a storage capacity.
4. Applying the product in public spaces – to deal with surface water runoff as close as possible to where the rain falls. SWM products are generally functioning to the end of the catchment. Currently, the customer needs slow water, managed at a catchment level.
5. Connecting to separated sewer – The new concept must be able to connect to a separated sewer system; a drainage system taking surface water from roads and roofs to a pipe network disconnected from foul sewage.
6. Low maintenance – The conventional methods for water efficient systems involve a pump, but several techniques have been implemented without the assistance of pumps. This requirement is based on customer preferences.
7. Creating visible, simple and robust concepts – to allow contractors to understand how the system works, and care for the drainage and regular maintenance.

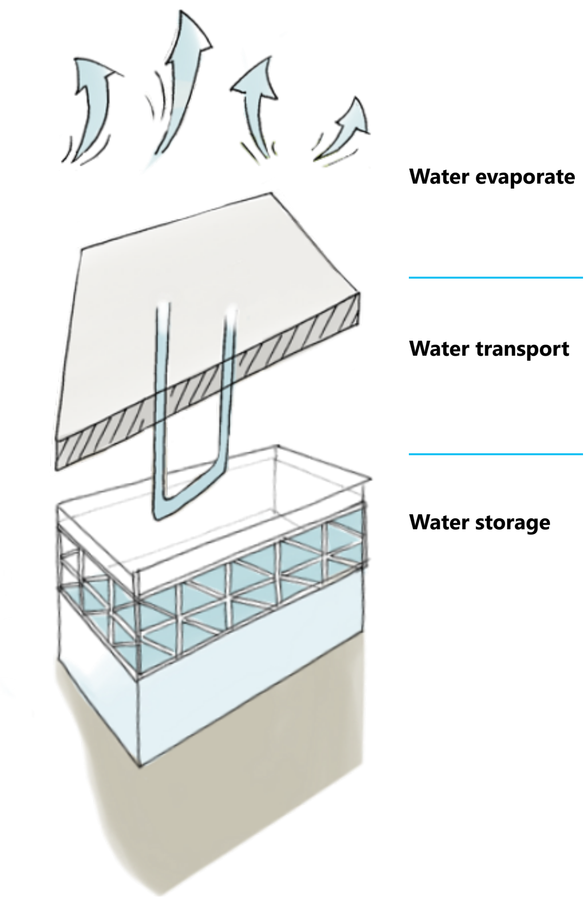


Figure 36: A simple visualization of the product system

4.2 Concept generation

In order to incorporate the concept requirements into the product system, the functions of the system are derived to provide assistance in the design phase. When dealing with complex technical systems, i.e. systems delivering more than one function, or composed of many different subsystems, the need for an overview arise. The multifunctional water system is simplified and visualized in Figure 36. The product system provides the following functions: 1) store water; 2) transport water, and 3) evaporate water. To generate concepts related to the product system, a brainstorm session is conducted to explore all possible solutions and provide new insights. The aim was to assess the feasibility of the ideas and facilitate Wavin's employees to think along.

4.2.1 Brainstorm session

The brainstorm session was organised at Wavin T&I in Dedemsvaart to involve technical employees. The brainstorm participants were two product developers, one laboratory technician, one technical advisor, one process engineer and two project leaders within Storm Water Management (SWM). The designer facilitated the brainstorm session, guiding the process, but did not take part in the brainstorm session. Most ideas were already studied in the idea generation, and interesting new solutions were discussed further. Including non-designers in the session resulted in a completely different view. The detailed plan and set-up are given in Appendix D.1.1.

The brainstorm was focused on how to design a cooling effect on the city's surfaces. The goal was to develop ways to achieve that. To warm-up, a mind map "heat stress" was written with the whole group. This tool was selected to introduce the heat stress and research objectives to unknowing participants. Beforehand, the participants were informed by email but may still leave some people not fully understanding the topic. The mind map proved useful to stimulate the participants to think about the problem. The most interesting word was "damage" in terms of infrastructure, greenery, and health. Besides, bioswales, fountains and water ponds were defined as solutions to heat stress.

After introducing the guiding principle "Water has to Sweat", or what is called evaporative cooling, the first exercise was introduced. How would you arrange the elements of the ground layer to create a cooling effect? The goal was to come up with individual elements at first in regard to provide water evaporation. The model and sketching interaction started and afterwards the ideas were presented and directly reflected on. The challenge as designer, guiding the process, was to not reject out-of-the-box ideas. Therefore, I created an overview of the ideas discussed and highlighted the most interesting ideas. However, ideas about using air ventilation and other systems for housing were rejected due to the scope of this research. Overall, the brainstorm provided valuable input due to the preparation and well-structured session. The mind map and the overview of ideas can be found in Appendix D.1.2.

While a wide set of ideas were discussed, the ideas inevitably had to be narrowed down. Therefore, five ideas that kept coming up where discussed further. These were:

- Capillary action – a capillary system to supply water against gravity through peat layer of vegetation in green verges
- Pipe network – a network of pipes underneath the road for heating and cooling of the surface
- Porous material – a lightweight absorptive material in a honeycomb celled panels for roofs and walls
- Open gutter – a surface drain system that uses rainwater for irrigation of the surfaces of public squares and streets
- Air as heat transformation – an air conditioning system in buildings without mechanical ventilation

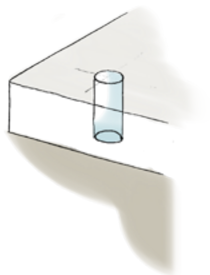
These five potential ideas were finally discussed based on their feasibility for Wavin to develop or implement the SWM solutions. In conclusion, the capillary action and pipe network can be implemented in two of Wavin's products, namely the infiltration box and the plastic road. In both cases, the Wavin product provides the function of storing water. Therefore, the function of transporting water and evaporating water is developed further in the next section.

4.2.2 Concept systems and elements

The five ideas that resulted from the brainstorm session are embedded in concept systems and elements. The concept systems focus on the mechanism to transport water upwards and the concept elements focus on the evaporation of the stored water. The concepts were separated into systems and elements to manage the overview of the product system. The capillary action is provided by concept systems A and B, pipe network in concept systems C and D, porous material in concept element 1, open gutter in concept element 2, and air and heat transformation in concept elements 3 and 4. The concept systems and elements are described and visualized in Figure 37.

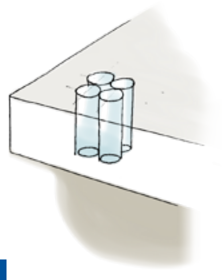
The function to store water is provided by a Wavin product. Figure 38 shows the two Wavin products for storing water and their specified opportunities. The decision was made to focus on the infiltration box instead of the plastic road during an intern-advisor meeting. The first pilot of the plastic

Concept systems



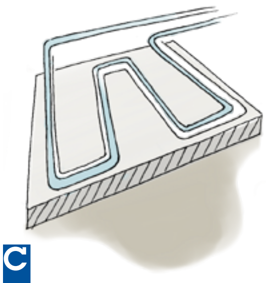
A

Rods of textile
Concept A provides the capillary function through a cotton cord or other rods of textile. The characteristics of the textile fit the technique to constantly transport water to the above ground level.



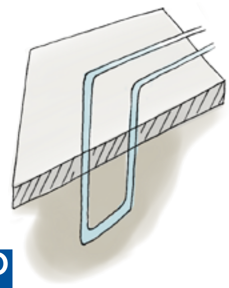
B

Small plastic pipes
Concept B provides the capillary function through small plastic pipes. A relation exists between the diameter of the pipes and the velocity of the water rising through the pipes. Finer pipes result in high rising water.



C

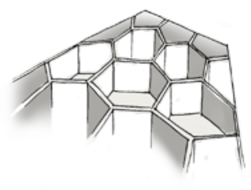
Underfloor heating and cooling
Concept C provides the heat transfer through a horizontally-oriented underfloor heating and cooling system. The surface is cooled to a temperature cooler than the surrounding air.



D

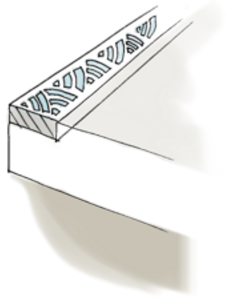
Network of pipes
Concept D makes use of the temperature difference between the top layer of the surface and the below ground layer. The system will pass water from a ground source (10-12 degrees) through a network of pipes to the surface (35-40 degrees). This could also be provided by air.

Concept elements



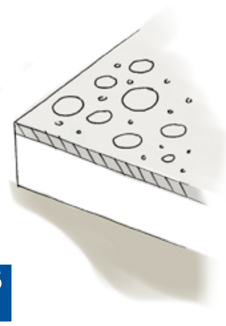
1

Honeycomb stabilization
Concept 1 consists of a foundation of connected honeycomb cells filled with a light-weight, absorptive material. Especially applicable for green roofs and green verges.



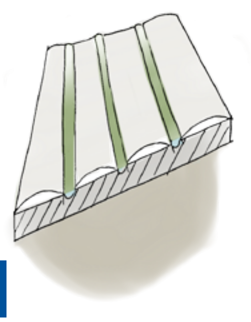
2

Grate design
Concept 2 is an open design to provide evaporation and to cover a water surface to cross safely. It could also be designed as an open gutter to obtain low maintenance.



3

Surface grains
Concept 3 exists of permeable surface grains. The grains are designed to allow percolation of chilled water through the surface.



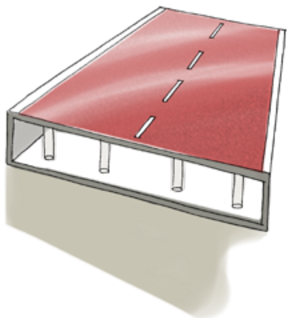
4

Vegetation
Concept 4 allows water to take up slowly to the surface and distributed over low or high vegetation. The system is based on surface irrigation.

Figure 37: The concept systems and concept elements

road was launched on September 11, 2018, in Zwolle. This pilot concerns a 30m long biking path. It is therefore a current project and still in the development stage of the configuration. The implementation of the new mechanism will be more complex in contrast to the infiltration box where clear application, performance, and quality has already been developed. In addition, the top surface of the plastic road must be changed to provide a cooling effect. Based on this information, further development of the concept was focused on the infiltration box. The infiltration box is the products subsystem that provides water storage. The "add-on", as visualized in Figure 39, will provide the function to transport water and to evaporate water.

Plastic road



The product is applied to roads. Water is supplied at the edge of the road or by the road gully. The water is drained to a tank allowing it to infiltrate slowly or drained to surface water. The plastic road can function as a buffer for rainwater by capturing it as long as possible or allowing is to infiltrate immediately.

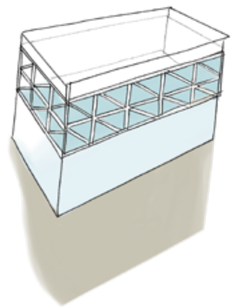
Strength
- Modular variation in the application area
- Element on surface level so direct interaction with the user

Weakness
- High heat capacity
- Limited variation in size due to prefab element
- Below ground product is not visible for users

Opportunities
- Paving material on the top surface of the element
- The hollow space provides room to implement the new system

Threats
- A closed product, not in relation with the subsurface

Infiltration box



The product is applied below parking lots, airplane lanes, roads and partly along green verges. The infiltration box provides temporary storage or can be used as a soakaway. The boxes are installed between a range of 70 cm to 1,20 m depth with a maximum depth of 2 m. The depth of infiltration or buffering that is selected depends on the permeability of the ground, the groundwater level, the slope of hydraulic decline, and traffic load.

Strength
- Modular variation in the application areas
- Easily implementation due to light-weight, separated parts

Weakness
- Below ground product is not visible for users
- Deep installation requires a pump

Opportunities
- Create a box near the surface

Threats
- Decreasing strength closer to surface level

Figure 38: The plastic road and the infiltration box

Add on + Infiltration box

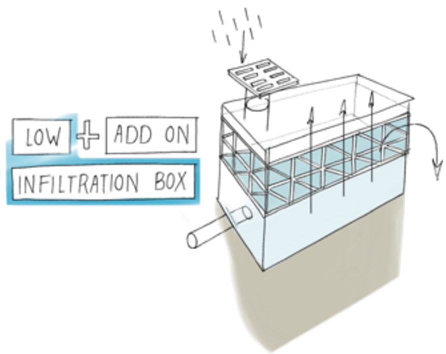


Figure 39: The "add-on" infiltration box

4.3 Further concept development

The design of an "add-on" or subsystem that provides the transportation and evaporation of water is further developed in this section. The rainwater available for cooling city's surfaces is needed to design the storage capacity and to define the water transportation technique and the medium to evaporate water. Firstly, simple calculations are conducted to create a feeling for the amount of water required to store and to understand the effect of different variables in reducing the surface temperature. With these deeper insights, an overview of advantage and disadvantage is shown to select the most effective solutions. The concept selection is based on the eight concept systems and elements from the concept generation. The further development provides a systematic approach to separating the potential concepts and improving concepts to be converted to the next stage, a detailed design.

4.3.1 Simple calculations

To understand the mechanism behind the different variables of the system and the required water, simple calculations regarding the energy balance were performed. The intent of this analysis was to assess the potential effect of reducing the surface temperature and air temperature.

The total energy (E_{tot} (kJ/kg)) in the product system, shown in Figure 32, is the energy necessary for transporting the water (E_1), the energy for diffusion of the water towards the surface (E_2), and the energy necessary to evaporate the water (E_3). To simplify this equation, the analysis focuses on the heat transfer to evaporate the water (E_3). Therefore, the calculations describe the energy available to cool the surface and the air. A recent study from Solcerova (2018) shows a comparable concept, water sprinkling known as "uchimizu" (Japanese tradition) to locally decrease air temperature around houses and gardens. The measurements show a decrease in air temperature of up to 1.5°C at a height of 2m, and up to 6°C for near-ground temperature. This research is used as the foundation of the energy balance analysis and enables detection of the required water.

Figure 40 shows the measurement boundaries of the simplified energy balance including a 1m x 1m surface. To evaporate water, water needs to be heated. Q_1 (J/kg) is the amount of energy transferred as heat for increasing the water temperature and Q_2 is the energy necessary for changing liquid to gas.

$$Q_1 = c_{p,water} * m_{water} * \Delta T \quad (2.1)$$

$$Q_2 = m_{water} * H \quad (2.2)$$

where m_{water} (kg) is the mass of the applied water, $c_{p,water}$ (4.2 kJ $kg^{-1}K^{-1}$) is the specific heat of water, ΔT is the temperature difference between the ground temperature and the water used, and H (2257 kJ/kg) is the latent heat of evaporation.

Based on the weather measurements of the Royal Netherlands Meteorological Institute (KNMI), a monthly rain event is 65 mm. This means 65L per m^2, therefore, 1mm is 1L per m^2. So, the mass of applied water (m_{water}) is 1kg. From the calculations in Box 1, 1290J is needed to cool down the air by 1°C. For 2 m^3, 2580J is necessary.

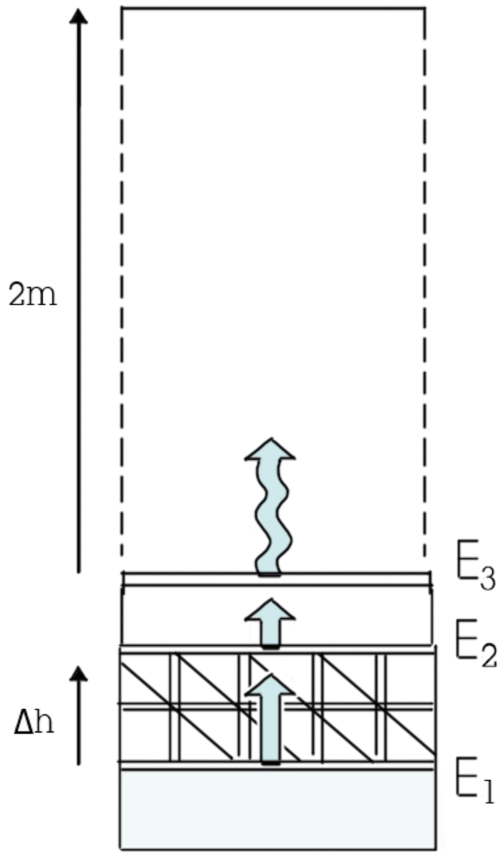


Figure 40: The energy balamce analysis

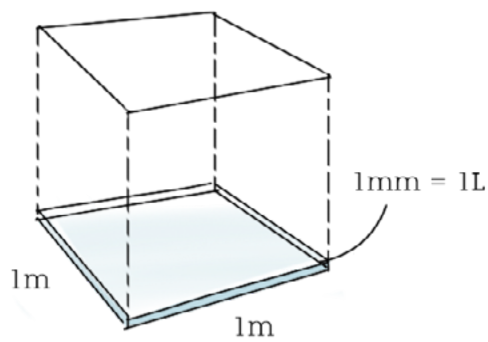


Figure 41: The contextual analysis

Box 1

The energy needed to cool down the air by 1°C

4.2kJ is needed to cool down or heat up 1L water by 1°C (Figure A). 2257kJ is needed to change 1L water liquid to gas (Figure B). So for 1L water, 2257kJ is subtracted from the environment (sun, ground, air) to cool down 1m³ with 1°C.

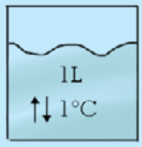


Figure A
$c_{p,water}$

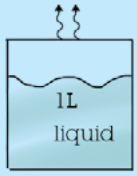


Figure B
H

Based on the boundaries (Figure C), in this case, the heat is subtracted from the air. Where $c_{air,dry}$ is 1290J and p_{air} is 1,29 kg/m³. So for 1 m³, 1290J is needed to cool down the air by 1°C. For 2 m³ (Figure D), 2580J is necessary.

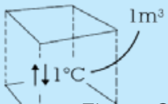


Figure C
1 m³

Box 2

The air temperature decrease with 1L water on 1 m²

Therefore, the water temperature increases by 1°C which leads to an air temperature decrease of 3,25°C calculated using:

$$\Delta T = c_{water}/c_{air} \quad (2.3)$$
$$= 4200/1290 = 3,25$$

For 2 m², the air temperature will show a decrease of 1,6 degree using 4200/2580.

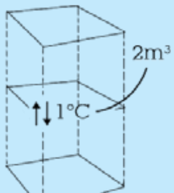


Figure D
2 m³

Box 3

The amount of water required to cool Enschede

Therefore, a layer of 1 mm water is needed. This means 1L water per m². The center of Enschede has a surface area of 0,54 km². Assuming that about 90% of this areas has a paved surface, the amount of water is:

$$m_{water} = A\ (m^2) \times q_{paved} \quad (2.4)$$
$$= 540\ 000 \times 0.9 = 486\ 000L$$

Figure E
comparable to a swimming pool

When the amount of water, a layer of 1mm, is applied, the air temperature decreases with 3,25°C. The calculation is provided in Box 2. These amounts are in line with the experiments from Solcerova (2018). From the calculations and other experiments (Solcerova et al., 2018; Slingerland, 2012), it can be concluded that water is an effective medium for the cooling effect. Due to the greater heat capacity or high c_{water} compared to air. Besides, the evaporation enthalpy is an important related factor which extracts energy from the environment. The latent heat of evaporation (H) (2257kJ/kg) compared to the specific heat of water $c_{p,water}$ (4,2 kJ/kg) shows the evaporation of water requires a lot more energy. Basically, more than 500 times. Based on other experiments, the effect of the applied water did not show a clear relationship with the cooling effect. Applying large amounts of water (>5mm per 1m²) correspond with more cooling close to the surface but disappears when height is over 1m. Since water in an urban area is scarce during summer a good consideration should be made, whether to use more water for cooling or not. Of course, it is not needed to use tap water, stored rainwater will be used in the product system.

Rainwater availability

To investigate the water availability for evaporative cooling, the following calculations are used to understand the water needed and the required size of the reservoir to store rainwater. The amount of water needed is calculated first and investigated to find out how much water is needed in order to cool a city like Enschede by 1°C up to 1 meter height. From the calculations in Box 3, 486m³ is needed to cool this area by 1°C. This is comparable to the size of the swimming pool (25m x 12,5m) at the University of Twente.

The total water availability from rainfall is calculated in Box 4 as 52L/m². This is almost the size of a 60L container.

As the water availability is defined, the calculations can zoom in on the product system and define the size of the reservoir. To cool down the surface on a warm day it is not desired to use all rainwater but to store water for dry periods as well. To provide such a calculation, a warm day in July is taken as an example. The KNMI measurements of 12 July 2018 can be found in Appendix D.2. The water is applied between 12:00 and 17:00, when the temperature is above 25°C with a maximum of 26,5°C at 13:00. The average wind speed was 3 m/s according to the KNMI. In the city, the wind speed was sometimes lower. To simplify the calculation, it is expected the cooling effect lasts about one hour when 1 mm water is applied (Solcerova et al., 2018). So, for 6 hours of cooling (1 L per m²), therefore, 6L of water per day is needed which can be compared to 4 water bottles of 1,5L. As calculated in Box 5, it can be concluded that water availability from rainfall provides 8 days of cooling effect. According to the KNMI, the longest period of dry days in 2018 was 15 days (25 June-9 July). So to create a robust retentive product, the system should at least include a 100L/m² storage, to feed around 16 hot days. This size is comparable to a rainwater storage roof which is able to store 80-100L/m².

The product system is especially designed to capture rainwater and make it available to cool down the surface. However, the calculations are simplified to a basic level, it showed together with other research (Solcerova et al., 2018; Slingerland 2012), promising potential for mitigating the UHI at a local scale by decreasing both the air and ground temperatures. The potential evaporation depends on temperature, relative humidity, wind speed, and solar radiation. Slingerland shows that it took about 30 minutes to evaporate 1 mm of water, which means that it was possible to evaporate 2 mm per hour. This could be related to the fact that the surface was already very warm when water was added. The type of ground surface is not included in the calculation.

The concept element might, to a certain extent, limit the effect of cooling. The simplifications introduced in the energy balance analysis results in an overestimation. The type of pavement seems to play an important role in the cooling effect. Solcerova (2018) shows the importance of the density and heat capacity of the paving material (clay bricks). Surfaces with higher density and lower heat capacity, such as asphalt, might require less energy for cooling than clay bricks (Solcerova et al., 2018). According to Shashua-Bar (2009), compared to paved areas, planting grass gave 0.3°C cooling of the air above. Shading the grass, either by

Box 4

The water availability from rainfall

Figure B
q

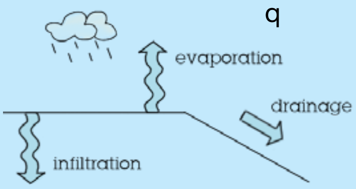
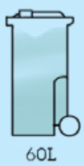


Figure F
comparable to a container



The total water available from rainfall is calculated as:

$$A \times q_{drainage} \times I \quad (2.5)$$
$$= 1 \times 0.8 \times 65 = 52L/m^2$$

where A (m²) is the surface area (A=1m²), q is the drainage coefficient, I is the average monthly rainfall intensity (mm). A drainage coefficient of 0,8 means 80% is available for drainage and the other part of the water evaporates (green areas) or infiltrates (Figure 39). This supplies assuming an average monthly rain event of 65 mm about 52L/m² rainwater is available for storage.

Box 5

The water availability to cool

As defined earlier, it can be concluded that 6L is needed from the 52L rainwater availability so using:

$$52L/6L = 8,67$$

results in about 8 days of cooling effect.

Figure G
comparable to a 4 bottles of 1,5L water

trees, had the effect of increasing the cooling effect to 0.5°C and reducing water consumption. Trees provide by far the most efficient means of reducing outdoor air temperature by 1.1°C, relative to their water consumption (Shashua-Bar et al., 2009). In general, green causes a reduction in the UHI effect of approximately 0.6°C per 10% more green (Theeuwens, 2015). Apparently, there is also a negative part about trees in urban areas, which is caused by the fact that trees decrease the wind speed. Moreover, the wind speed reduction of buildings. Theeuwens (2015) highlights the effect of smaller streets offer more cooling effect in summer (shadowing) and warmth during winter (the retention of thermal radiation from buildings), despite the heat produced by human activities.

Currently, a discussion about the mitigating effect of water on the UHI exists. Cities water surfaces are cooling during the day, however, experiments in the Netherlands (Klok et al., 2018) show that water during the night is absorping heat. Theeuwens notes that this new insight is not yet implemented in urban planning. Spatial distribution of small water surfaces in the city affects a larger part of the city than a single large water surface. However, the cooling effect is the greatest for a single large water surface. In conclusion, Klok (2018) states that "the cooling effect of small blue urban spaces is negligible".

4.3.2 Potential concepts

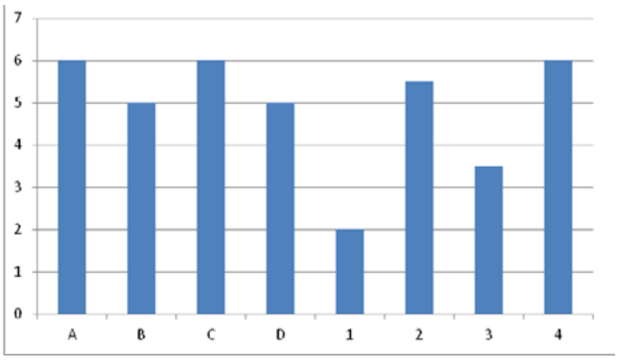
This section defines the potential concept systems and elements, from section 4.2.2, related to the calculations. The energy necessary for transporting the water (E_1) depends on the concept system and influences the rate of evaporation. So, the most potential concept system and the element must be integrated into one product system. Firstly, the selection obtains a ranking of the concepts. Secondly, the advantages and disadvantages are provided to integrate the most potential elements into a concept.

The ranking is based on the scale of application, near surface installation, their suitability to different soil types, and traffic loads. However, within the selection the input from Wavin is used. The ranking gives a structured insight into the potential concepts. The higher the score, the better. The results of the ranking system are shown in Table 3. A detailed explanation of the ranking is provided in Appendix D.3.

Based on the results, Concept element 1 – Honeycomb stabilization and Concept element 3 – Surface grains scored the lowest. Especially, there are low suitable for multiple soil type and traffic loading. In addition, Concept element 3 is comparable to Permeable pavement, one of the existing solutions which is assessed as low efficienct

Table 3: The results of the ranking system.

Concept systems and elements	Score
A: Rods of textile	6
B: Small plastic pipes	5
C: Underfloor heating and cooling	6
D: Network of pipes	5
1: Honeycomb stabilization	2
2: Grate design	5,5
3: Surface grains	3,5
4: Vegetation	6



Based on

- Scale of application
- Suitability for multiple soil types
- Suitability for traffic loading
- Suitability for near-surface installation

and not included within the most interesting and relevant solutions. According to Concept element 1, some cities in Japan, are testing the effectiveness of water-retentive pavements (EPA, 2008). The effect is comparable to water sprinkling. So, based on literature the element showed promising results in keeping surface temperatures low.

However, none of the concept systems can be clearly distinguished from the rest, the use of the customer profile and input from Wavin was decisively. They expressed strong interest in concept system A – Rods of textile and B – Small plastic pipes as these concepts include techniques without the assistance of pumps. In contrast, concept system C – Underfloor heating and cooling and D – Network of pipes require a pump which does not satisfy the concept requirement related to low maintenance. The advantages and disadvantages are shown in Table 4.

Based on the outcomes of the calculation for water availability, Concept element 4 – Vegetation is a potential an reliable solution. Compared to paved areas, planting grass gave 0.3ºC cooling of the air above (Shashua-Bar, 2009). In addition, the cooling effect of Concept element 2 – grate design will significantly lower than direct evaporation from a water layer sprinkled on the surface. Concept element 1 and 3 require further development to prove the cooling effect in practical application.

From the synthesis of the concepts to practical application, the decision is made to further improve concept system A and B, as a non-pump installation is desired. The concept improvement focus on integrating concept A and B with Concept element 4 into an efficient water system.

Further improvement of the concepts focus on integrating:

- Concept system A: Rods of textile
- Concept system B: Small plastic pipes
- Concept element 4: Vegetation

The next section presents the integrated design and the selected concept.

Table 4: Advantages and disadvantages of the concept systems and elements.

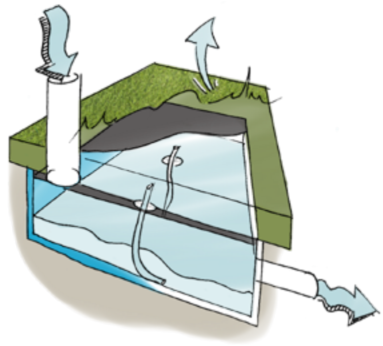
Concept systems and elements	Advantages	Disadvantages
A: Rods of textile	• Constant water supply to surface element • Low water usage	• A geotextile is required to separate the water in tank from the soil • Requires non-plastic material
B: Small plastic pipes	• Constant water supply to surface element • Low water usage • Plastic material	• A geotextile is required to separate the water in tank from the soil
C: Underfloor heating and cooling	• At-source solution	• Requires a pump
D: Network of pipes	• If horizontal space is insufficient	• Requires a pump • Deep installation requires other installer equipment
1: Honeycomb stabilization		• Higher production costs due to merging of different materials
2: Grate design	• Chain drainage fits to grate design • Visible design	• Lower effectiveness compared to open water
3: Surface grains		• Low effectiveness due to sludge • Not specific Wavin business
4: Vegetation	• High efficient evaporation	• Vegetation roots can damage pipelines

4.5 Concept selection

The two most potential concept systems based on capillary action are improved by integrating the potential concept element. This resulted into four integrated concepts. For imaging the feasibility for Wavin, the advantages and disadvantages are shown in Table 5. This selection was done to decide which concept is the most promising and will be further developed. A detailed description of the four concepts can be found in Appendix D.4.

Concept 1 – Oil lamp, visualized in Figure 42, is chosen to develop further. The capillary action is based on the mechanism of an oil lamp. The technique enables constant transport of water through absorbent material (e.g. cotton cord) from the infiltration box to the vegetation root zone which provides evaporation. The simple calculations in section 4.3.1 highlighted the importance of effective green areas. Therefore, the capillary rise (e.g. cotton cord) must reach the root zone of the vegetation. The interface between the root zone and capillary rise is schematized in Figure 43.

The concept development resulted in a simple, multifunctional water system to cool urban areas. The concept can function as an adequate soakaway to manage storm water as well as efficiently reuse stored rainwater for evaporative cooling. An interesting link to a practical application is Pre-fabricated Vertical Drainage (PVD). This application in road construction, known as wick drains, are installed to provide drainage paths for the water on the road. Instead of a drain, the selected concept transport water from the subsurface to the surface. The characteristic of PVDs can improve and inspire the development of the final concept.



1

Oil lamp
Concept 1 provides water transport from the infiltration box through porous material (e.g. cotton cord) to the surface. The concept is inspired by the mechanism of a oil lamp. The vegetation on the surface provides the evaporation of water.

Figure 42: The selected concept

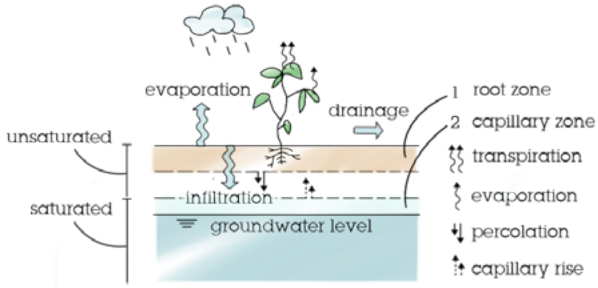


Figure 43: The root zone, the capillary zone and the related variables

Furthermore, the mechanism of capillary action in cords or foam pipes (based concept 2) will be examined in the next chapter.

Table 5: Advantages and disadvantages of the four concepts.

Concepts	Advantages	Disadvantages
Concept 1 Oil lamp	• Easy implementation due to the vertical connection • Raise idea to connect with PVDs (Pre-Fabricated Vertical Drains)	• Cotton cord cut into the seal component of the geotextile
Concept 2 Foam pipe	• Easy implementation due to the horizontal connection • Modular expansion of the mechanism in parallel direction	• The L-shaped component is a critical point in the distribution of water
Concept 3 Water squeeze tile	• Additional playful object in public areas	• Non wide-scaled solution
Concept 4 Evaporation cistern		• Functioning questions • Low effectiveness due to 1/3 of m^2 enables evaporation

5. FINAL CONCEPT

In this chapter, the final concept as described in chapter 4 is detailed and further developed. This refinement covers the proof of concept (PoC), a phase in development stage where experimental studies are constructed and tested to explore the feasibility of the concept. To structure the concept into a detailed concept, the Technology Readiness Levels (TRL) (NASA, 2012) is used to determine the level of PoC. The use of TRLs manages the process of research and development. In the 1990s NASA adopted the current nine-level scale shown in Appendix E.1. Firstly, this chapter present the existing innovative technique and the integration into the final concept. Afterwards, the experiments are conducted to assess the effectiveness of the technique and provides suggestions for future experiments. Finally, the PoC is reflected and linked to the feasibility of the final concept.

5.1 Detailed concept

The final concept describes an efficient water system using capillary action to provide evaporative cooling near the surface. At this stage, the technology status of the final concept is approaching TRL 2 as the following paragraphs describe the basic principles (level 1) and the concept is detailed in terms of application, optimization, and situation (level 2). The steps described in this chapter aimed to reach TRL 3 or 4, experimental proof-of-concept (level 3) and validation in laboratory (level 4) respectively. Therefore, the following paragraphs describe the capillary action, refinement of the technique within the concept and the concept itself.

5.1.1 Capillary action

Capillary action is the main mechanism around which the idea of the detailed concept is structured. Capillary action is defined as the upward vertical movement of water through narrow tubes and spaces without the assistance of external forces (Sharabaty et al., 2008). Capillary rise is the adhesion of water to the sides of the tube and cohesion, the attraction of water molecules (Sharabaty et al., 2008). When the forces of adhesion are greater than the forces of cohesion then capillary action occurs. In very small-diameter, the cohesive forces can naturally flow the water upwards noticeable distances as schematically visualized in Figure 44. The water continues to rise in the tube until an equilibrium is reached with the downward force of gravity on the water. The primary driving forces responsible for the movement of water along the tube are the forces of capillary action. Capillary wicks are an alternative irrigation system which supplies water directly from a reservoir into the substrate via an absorptive cord. The textile yarns can be treated either as porous media or as capillary tubes.

The capillary wicks have open pores in which fluid flow is effectively taking place. Wicking in fabrics can only occur when a liquid wets fibres assembled with capillary spaces between them. The capillary spaces can be considered as the spaces between yarns within a fabric and between fibres within a yarn constituting the fabric (Chatterjee & Singh, 2013), shown in Figure 45. The resulting capillary forces drive the liquid into the capillary spaces. Thus, capillary forces are influenced by the properties of the liquid, liquid-medium surface interactions, and geometric configurations of the pore structure in the medium (Chatterjee & Singh, 2013). In order to prove the concept, different wick materials are selected and tested in section 5.2.

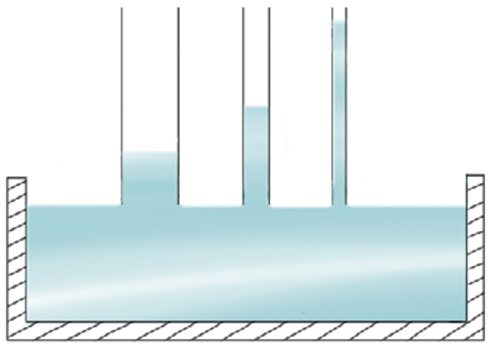


Figure 44: Water rises to different heights depending on the diameter of the capillary tube.

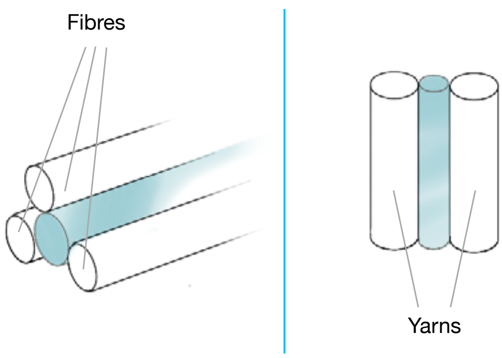


Figure 45: Capillary rise betwee fibres in a yarn and between yarns derived from Chatterjee & Singh (2013).

5.1.2 Unique selling proposition

The capillary wick system proposes the storage of precipitation and transportation of water to increase evaporation, and thus potentially mitigating the Urban Heat Island (UHI) effects. However, space on the surface level is scarce in cities. Given the large areas of unused space around the surface layer (see section 3.4.1), the water system might be a promising solution for green areas in a city. In line with market research, products already exist within the range of green roof systems. Compared to the Permavoid storage and capillary irrigation system, stored water was available for passive irrigation via capillary cones, consisting of hydrophilic rock wool fibre. These cones were placed inside tubes within the Permavoid units, and they supplied the root zone with water by capillary forces. The maximum storage level in a Permavoid unit was 80 mm. However, only 30 mm could be allowed on the specific roof based on the maximum allowable static load (Cirkel et al., 2018). The Wavin AquaCell storage tank enables a large storage capacity. In addition, the AquaCell requires a deeper installation in contrast to the installation depth from 10 to 100 mm of the Permavoid units. The Unique Selling Proposition (USP) that differentiates the Wavin capillary wick system from its competitors and other sustainable Storm Water Management (SWM) solutions are:

- (re)using storm water
- reduction of load on drainage networks
- water storage limits water stress
- better green spaces
- increasing evaporative cooling
- reducing urban surface temperature and the air above

To demonstrate the USPs, the effectiveness of capillary action is tested in section 5.2. The tests provided quantitative insights to assess the success of a deeper installation in evaporating and storing rainwater and potentially cooling the air. In this research, a visual end prototype is created but not tested. Beforehand, the refinement of the concept is presented in the next section.

5.1.3 Product design

Through combining the use of capillary wicks, Wavin AquaCell and a soil depth between 30 and 60cm, water levels are determined by the capillary rise relative to the content of the soil. Capillary irrigation activates only when the plants are evaporating water and sucking the water, requiring no external forces or pumps. Figure 46, on the next page, provides a description of the function and performance of the related design features.

Root zone

The goal is to constantly supply water to the root zone of plants. Therefore, the capillary wicks depend on the depth of the root zone. The variation in depth of roots is wide. The thickness of a permanent grassland is generally 20-25 cm (Van Soesbergen et al., 1986). For most of the trees, the optimum depth is around 1 m (Olsthoorn et al., 2003). According to the application area, the capillary irrigation system focus on the shallow rooting layer. Therefore, the wicks should reach a minimum depth of 0.2 m. This requirement also influences the water storage level.

Evaporation

Well-watered vegetation provides day-to-day evaporation. Moreover, due to the higher water efficiency of the capillary wicks, it takes longer before the water runs out in the systems an evaporative cooling declines. To assess the potential effects on UHI, a vegetation cover should be modeled. Furthermore, the wick maintains a constant moisture level in the medium and the rate of water movement is related to the evapotranspiration loss.

Water availability

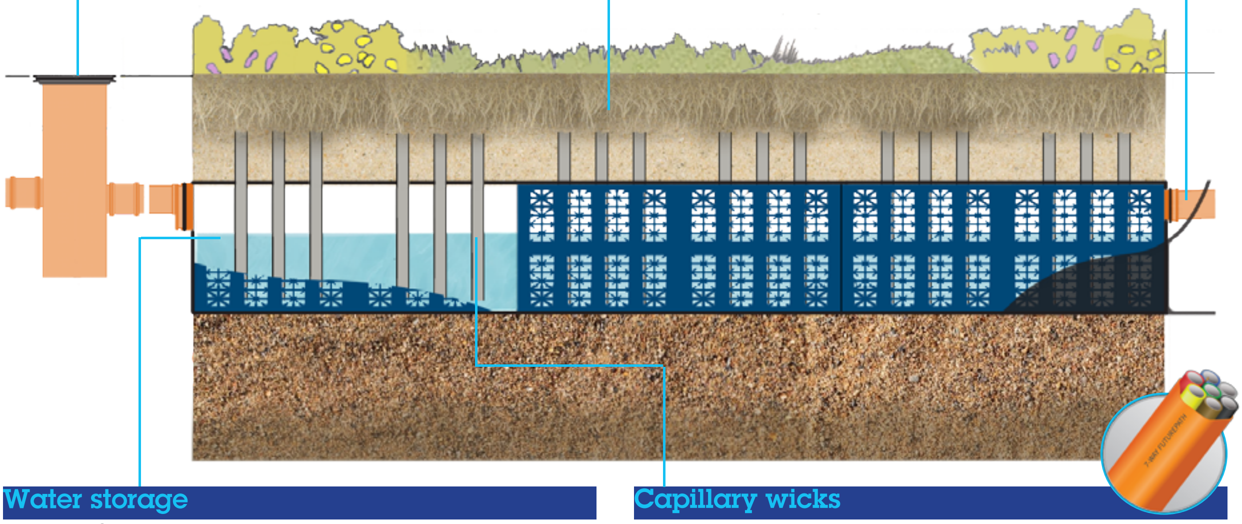
- Storm water from roofs
- Surface water run-off
- Treated grey water
- At last tap water (if required)

A weather-based system can control the water volume especially in expecting dry periods.

Water discharge

- To surface water
- Separated sewer system
- Sewer system (as a last request)

Careful planning of the position outlet can achieve no discharge.



Water storage

The AquaCell is a modular, lightweight polypropylene storage system or soakaway, and is suitable for applications including landscape areas, parks, domestic gardens, residential developments, car parks & roads, industrial/commercial areas. The application area depends on traffic load, soil type, groundwater, surface finish, and depth over cover. For example, in clay, the maximum installation depth is closer to the surface compared to sand and gravel. In contrast to the Wavin Q-Bic range of geocellular systems, the AquaCell is designed for shallow applications with average depth 0.70 m and is manufactured for 0.3 m minimum depth in contrast to an average depth of 1.20 m of the Q-Bic. To realize the capillary action, the installation depth must not be too deep. Thus, preferable cascade to green (landscaping) area on lower levels.

Capillary wicks

Transport of water takes places through the phenomenon of capillarity. The capillary wick system uses minimal amount of water. Wicks bound together in a PVC pipe restrict intrusion of soil particle. Dura-Line, part of Mexichem in the same business group Fluent as Wavin, consists of multiple cable ducting in specific sizes are bound together. The figure on top shows the FuturePath which can accommodate up to 432 fibers in each MicroDuct. The wick material can be extruded through this pipe so fluid flow is effectively taking place. Therefore, capillarity action and durability of the wick material are attributes for the success of capillary irrigation system.

Water storage level

- Fully controlled through the positioning of the outlet
- Minimum depth to saturated wick material
- Air layer must be maintained to encourage aerobic conditions.

The dimensions of all AquaCell units have identical dimensions (1m x 0.5m x 0.4m). So 400 mm height to store. The unit volume per storage cell is 0.19 m^3 (19L). For optimum performance, the units can be mixed and matched in layers to optimize a tank or soakaway design. Two layers result in 0.38 m^3 and three layers in 0.57 m^3. However, the capillary action has to able to transport the water to the surface.
The units are wrapped in geomembrane seal. As an attenuation tank in impervious ground (e.g. clay) where infiltration is not possible, here the units are encapsulated in a geomembrane (which is in turn wrapped in a protective geotextile layer) so that the structure can hold the stormwater temporarily until local drainage flows can accept it for normal disposal at a permissible outflow rate. In the product design, infiltration is not desired to keep it available for re-use. Depends on the storage, whether to use as a soakaway whereby the units will be installed in suitable pervious soils so the units can be wrapped in a geotextile to allow infiltration of the stormwater into the surrounding ground.

Figure 46: The product design

5.2 Test

To test the effectiveness capillary irrigation, a series of laboratory tests were executed using water with colouring to evaluate capillary rise in wick materials. To identify the best wick material for use in the concept different parameters are measured including water holding capacity (WHC), water absorption pattern (WAP), maximum capillary height (MCH). To determine WHC as follows:

$$WHC\ (\%) = (M_s - M_d)/M_s \quad (3.1)$$

where M_s is the mass of the saturated wick material and M_d is the dry mass of wick material (oven dried at 70 degrees). The picture of the experimental set-up for measuring the WAP and MCH is shown in Figure 47. For capillary rise, the samples clamped on a stand and were placed into a 250 ml beaker with coloured water. The water was coloured to facilitate visual tracking of the movement of water. Water rise is measured in centimetres on an exponential timescale over 2-hour. For some material, there was further water rise. So, the experiment was repeated with the best wick material over 15-hours.

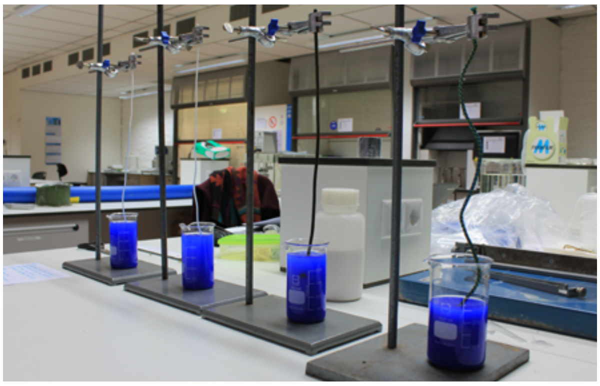


Figure 47: Experimental setup for measuring water absorption pattern and maximum capillary height

The goal is to find out up to what height water can rise through the porous material due to capillary forces. Therefore, valuable porous material is selected. Afterwards, the results are presented and compared to literature. Finally, recommendations for further tests are provided to indicate the USPs and feasibility of the product design.

5.2.1 Step-by-step process

The first step included the selection of wick material. To select materials, broad inventory techniques were used that include 1) using familiar materials (e.g. paper towel); 2) contacting expert (laboratory technician at T&I), and 3) searching journals and the web. To quickly identify the valuable wicks, locally available materials were used.

Step A I Material selection

Wettable material such as cotton, nylon, and polyester are widely used as wick material (Semananda et al., 2018). Most materials tested achieved a capillary rise of at least 25 cm and some passed 50 cm (Brainbridge, 2012). Brainbridge (2012) showed the 11 mm nylon has the best capillary rise, reaching 25 cm in 100 minutes and 55 cm in 20 hours. Other wicks including polyester yarn and 11 mm double braid polyester rope performed almost as well. Thereafter, capillary rise comparison showed the highest capillary rise for polyester ropes (Brainbridge, 2012). From the research, it can be concluded that there is a significant difference in capillary rise depending on material and width.

In addition, commonly used wick materials in Asia, bonded non-woven fabric, braided cloth, and synthetic fibre were tested (Lee et al., 2010). Bonded non-woven fabric made from 100% polyester had the highest absorbability. As time elapsed, the pots attached with bonded non-woven fabric as a wick took up water more and faster than pots attached with other materials. Thus, an important factor is the physical characteristics of the weave, namely woven or non-woven, also known as braided or twisted. Furthermore, the polyester material has good water absorption characteristics and was later found not susceptible to rotting (Wesonga et al., 2014). The cotton material would probably not survive and thus be not sustainable in the long term. To better understand the differences in capillary rise depending on material, width, and weave, several materials are selected varying in weave and width. The two desirable properties on a wick are a high rate of absorption and resistance to rotting.

Current advances in the manufacture of fibrous materials with high absorption capacity open up new opportunities (Rivela et al., 2013). Classically porous materials are involving polymeric foams. Foams have been widely used in a variety of applications for insulation, sound-absorbing, and other construction materials. Polymeric foams can also be defined as closed-cell or open-cell foams (Figure 48). In closed-cell foams, the foam cells are isolated from each other and capillary spaces are surrounded by complete cell walls. Generally, closed cell foams have lower permeability. In open-cell foams, cells are connected with each other. For example, a sponge comes into contact with water, it absorbs the liquid while swelling simultaneously. So, open-cell foams provide better absorptive capability (Monaenkova, 2012).

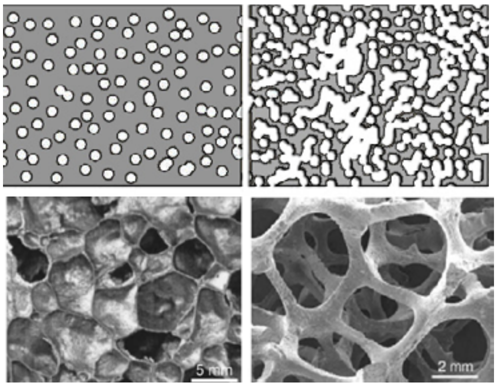


Figure 48: Schematically visualization (top) and micrographs (down) of (left) closed-cell foam and (right) open-cell foam

As the application in the concept relates to water transport, only open pores were of interest. The open pores can be viewed as capillary tubes and the porous material as a bundle of capillaries (Karagiannis et al., 2016). According to these requirements, polyurethane (PUR) foams are among the most promising materials. This includes spray polyurethane foam and cold foam used in mattress and pillows. Besides other isolation material like glass or rock wool comply with the listed requirements.

Based on the literature and experiments found, the following fabric and foam materials were selected:

1. Nylon cords (braided)
2. Polyester cords (braided)
3. PUR foam (open structure)

Figure 49: An example of a braided cord (material S-2)

Wool and cotton were considered but not included due to decay on a short term. Besides, an explicit choice was made to use braided ropes (Figure 49) as the core consists of straight, parallel fibres. In recognition of a wide scale of polymeric foams, this study selected only local available PUR foam.

B I Medium pick-up

As described in the Product design, the capillary wicks will be integrated into a pipe to restrict intrusion of soil particles. The movement of water in a wick system will be slow and of less quantity. Therefore, a growing medium to be highly efficient at absorbing and retaining water is desired. So, the capillary movement in soil depends on the soil type and the chances that it will migrate up. In sand, water moves quickly and it will not migrate up very far due to very large pores. Clay soil has such small pores that the water absorbed will act as closed-cell. However, silt has well-arranged, large and small pores and show the highest capillary rise of any type of soil (Purdue extension, 2017).

In addition, trends show choices include coconut coir, perlite, and vermiculite (Xiong et al., 2017). Increased organic content results in a higher capillary rise. The experiment to efficient growing medium will not be included within this study but suggestions will be given.

C I Bringing it all together

For the final experiment, an integrated system is developed to bring all system elements together. An ideal solution is capillary wicks in the pipes as prefabricated material like described in the Product design. Compared to PVDs, the wicks consist of a core (wicking material) wrapped in a geotextile material. The core serves as a flow path (capillary action) and the “filter jacket” restricts intrusion of soil particles. Preventing installation at location will be cost-effective.

5.2.3 Experimental results

The first experiment consists of two parts. Firstly, several samples of cords were tested. Secondly, foam material was tested in a comparable set-up, described in the introduction of this section (5.2), but already integrated into a transparent pipe. The list of material that were evaluated can be found in Appendix E.2.

A I Selection of wick material

Cord

Eighteen wick material samples showed significant differences in water absorption over the 2-hour time course. The polyester material (P-2) had the highest water absorption pattern with 37.5 cm at 180 minutes while one wick material did not show any effect (T-1B). The lowest capillary action was recorded in the wooden diffuser sticks (S-4) with 6.5 cm and natural sisal cord (P-4) with 9.5 cm at 180 minutes. The results of all material can be found in Appendix E.3.1.

For the four best wick materials, the capillary action

Table 6: The results of the four best wick material.

Top 4 Wick material	Short description	Type of material	Diameter (mm)	WHC (%)	MHC (cm)
P-2	Mamutec	PA	3,5	19,9	37,5
N-1	Jaloeziekoord	PA	2,6	18,1	31,0
N-4	Mamutec	-	4	20,3	32,0
S-2	Lichtgrijs koord	-	8	50,1	34,5

followed the order P-2>S-2>N-4>N-1 with 37.5 cm, 34.5 cm, 32.0 cm, 31.0 respectively. Significant differences also exist in WHC (Table 6). P-2, N-4, and N-1 were not significantly different in WHC with 19.9%, 20.3%, and 18.1% respectively. However, the synthetic material (S-2) had a significantly higher water holding capacity of 50.1%. P-2 and N-1 consist of polyamide (PA), also known as nylon. The type of material N-4 and S-2 will be further determined by the laboratory technician at Wavin T&I. The WAP and the best wick material are schematized in Appendix E.3.2.

For these four wick material, the experiment was repeated over a time course of 15-hours to find out the maximum capillary height. The MCH followed the order P-2>S-2>N-1>N-4. The polyester (P-2) and the synthetic (S-2) have the highest water absorption pattern with 40.0 cm and 37.5 cm respectively. P-2 and S-2 were significantly different in WHC with 9.5% and 30.0%.

The polyester (P-2) had a slightly higher maximum capillary height compared to the synthetic wick material S-2. However, S-2 had the highest water holding capacity of 30.0%. The diameter of S-2 is 8 mm. The structure is closely observed and shows a cohesion of multiple smaller cords. So, a bundle of capillary tubes. Therefore, the P-2 with diameter 3,5 mm should be bundled at least 3 times to reach the WHC of S-2. This results in a bundle of 10,5 mm. In conclusion, multiplying the core of the P-2 wick material cannot comply with the water absorbing characteristic of S-2. Thus, the synthetic S-2 material performs better than all other materials in WAP and WCH.

Foam

The polymeric foams were significantly different in terms of water absorption patterns compared to textile material. The spray foam and isolation material behave like closed ones and do not play a significant role in the water movement into the material. When zooming in on the material, Figure 50, the spray foam contain closed pores and non-connected open pores containing air. Capillary rise only occurred in cold foam with 19.0 cm at 512 minutes. Significant difference was also observed in the available water. The water absorption rate was high with 75.0 ml at 4 minutes, 105.0 ml at 32 minutes and 130.0 ml at 64 minutes. In between the water was filled up to 200ml again. Cold foam needs significantly more water compared to the textile material P-2 and S-2. The extended results are provided in Appendix E.3.3.

Figure 50: The spray foam

Of importance in capillary action are two characteristic points: the diameter of the tube and distribution. To understand the differences between the diameter of the pipe, cold foam is tested in 50mm-tube and 30 mm-tube. It was expected that water in the 30 mm-tube will migrate higher compared to the 50 mm. As the 30 mm is more compact (containing less air). From the result, shown in Figure 51, it can be seen that the different application is almost the same. The 30 mm-tube shows a quick water rise of 10cm at 8 minutes followed by 8,5 cm of the 50 mm-tube. Capillarity action was equal at 32 minutes. The cold foam inside the tubes is done by hand as compact as possible to prevent it contain air voids. Although, the distribution and networking of pores are very difficult to the define. For polymeric foams, open porous structures with high connectivity and pore sizes about or below 500 μm present the best performance in terms of absorption efficiency and absorption (Pinto et al., 2016). Therefore, this test concludes that the development of PU-based absorbent material should be based on a careful selection of the porous structure.

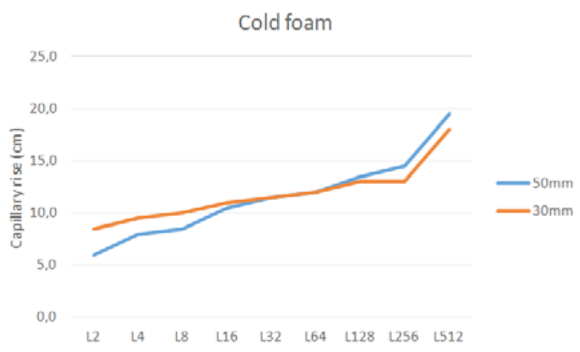


Figure 51: The WAP of the 50 mm-tube (blue) and the 30 mm-tube (orange).

Conclusions

Based on the results S-2 is selected and further evaluated in the efficient water system. Overall, it can be concluded that the yarn and the bonding weave are responsible for the main portion of the capillary rise (Chatterjee, 2013). The arrangement of open pores of the yarn can be considered as a bundle of capillary tubes with different effective diameters (Monaenkova, 2012). The open pores are formed within the fibres, between fibres in the yarns, and between yarns. So, the material porosity plays a significant role in the selection and not the diameter of the cord itself. The cords are found to be much better than polymeric foam. It may be due to the networking of pores. The S-2 consists of yarns upwards ordered whereas the random celled structure of PUR foam is irregularly arranged. The pores structure of the foam is complicated and difficult to quantify. Although, the capillary flow in a fabric is extensively studied.

Compared to other experiments, the results show a comparable result. Most materials tested achieved the minimum capillary rise of 25 cm. Although some materials from the literature passed 35 cm. According to Chatterjee (2013), vertical wicking in polyester material succeeds in reaching 1m with an increase in tension. A comparatively organic material, fine silt, water can migrate up to 1m. In conclusion, the determination of the effect of the porous structure of polymer fabrics or foams on their absorption performance is of significant importance for the optimal design of an efficient water system. The experimental library to compare the result is provided in Appendix E.4.

B I Further steps

Identification of best media for use in the capillary wick system should also be determined through laboratory experiments. Besides the water holding capacity (WHC) and water absorption pattern (WAP), parameters include bulk density and moisture release characteristics for each media. For determination of the bulk density, can be calculated as:

$$p_b = M_d/M_v \quad (3.2)$$

where p_b is bulk density (g/cm^3), M_d is the dry mass of media and M_v is the total volume of media. The total volume includes the internal pore volume. The bulk density of soil mainly depends on the compaction. Bulk density higher than 1.6 g/cm^3 tend to restrict root growth. Sand have relatively high bulk density since total pore space in the sand is less than silt or clay soils. Capillary rise occurs quickly in coarse sand, so to improve the uptake of water, the soil requires a fine-grained material. Moisture release characteristics of each media can be determined using special instruments to measure how much water is given off at a given temperature. The water absorption characteristics of the media is an important factor in the capillary wick system. The available water which is defined as an amount of water available for plant uptake and utilization. Future tests should suggest how many wicks might be needed for the system providing evaporative cooling.

In bringing all system elements together, evaluation of the materials and media need to be carried out and suitable plants need to be identified for providing evaporative cooling. Water flows through the wick material in the pipe and is conveyed vertically up until a porous layer is encountered. For the integration of the wick material into the pipe a pre-industrialized process must be analysed. Based on the accuracy of the pore size, the industrial process of extruded wick material into the tubes, might have an effect on the material capabilities. However, the pre-fabricated material is cost-effective. Therefore, collaboration with the construction industry (e.g. PVD) may provide new insights.

5.3 Proven concept

Reflected on the PoC, the final concept is detailed on its application, calculated and modelled on its capillary action. The feasibility of the design is analysed. The next step is to show the functionality of the capillary water system and to achieve the proven concept.

Based on the TRLs, the final concept reached level 4 to validate the component in laboratory environment. Currently TRL 3 is achieved, the laboratory studies validated analytical predictions of capillary action, a separated element of the technology. Thus, components are not yet integrated or representative. To succeed level 4, the system elements (capillary wicks, media and plants) have to be integrated to establish that they will work together. Further research to indicate the best media for use in the capillary wick system is already described in the previous section.

Moreover, the final concept proposes the storage of precipitation and transportation of water to increase evaporation, and thus potentially mitigating the UHI effects. The water system might be a promising solution to bridge the gap between indication of vulnerable locations and the customer's search for multifunctional water systems. To verify the UHI mitigation potential, tests must be performed regarding a prototype demonstration in a relevant environment (TRL 6). This prototype requires a mold to implement the extruded wicks into the Wavin AquaCell. To assess the potential effects on UHI, the uptake of the soil from the wicks and the vegetation cover should be modelled. Furthermore, the prototype should be tested in a greenhouse to calculate the potential to cool the surrounding air. If those tests do show remarkably larger evaporation, the PoC demonstrated the satisfying concept requirements. If those tests do not show the desired effect, other options are possible.

Based on the calculations in section 4.3.1, the system should at least include a 100L/m^2 water storage to feed around 16 (dry) days. The storage capacity of the AquaCell is approximately 400L/m^2. So, the storage capacity can be three times smaller to provide the desired functionality. In addition, to improve the transport of water and the capillary action this smaller storage tank can be installed closer to the surface. In this way, the wicks do not have to achieve the heigth from the bottom of the storage tank to the root zone. This alternative design is schematically visualized in Figure 52. The near-surface infiltration box can be connected to a deeper, larger installation to infiltrate and attenuate an overflow of rainwater. The alternative option manages a greater amount of rainwater. Apart from adapting the installation depth, the system can focus on integrating an pro-active, adaptive element to control the water storage level and water discharge according to predicted weather. Eventually, this will improve the robust and sustainable SWM solution.

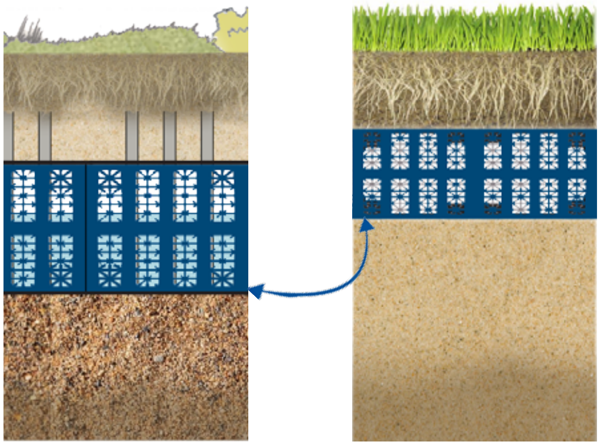


Figure 52: The second option

6. CONCLUSION & RECOMMENDATIONS

This chapter provides a reflection on the use of the customer profile in the design process of a feasible solution for Wavin to improve Storm Water Management (SWM). Afterwards, the final conclusions of the research are discussed and a number of recommendations for further research are presented.

6.1 Reflection on customer profiling

This research presents a customer profile to communicate the design vision and the SWM solution's anticipated effect on climate change. Since the scenarios including product strategies are broad and extensive, a structured and detailed customer profile is needed which takes the customer's needs into account during the design process.

The customer profile guides the scenario generation, idea generation and finally the conceptual idea. The explicit representation of the customer's understanding involves different elements that represents the collected information. The elements describe the current approach, trends, and in between what they are looking for in terms of adaptation measure. The profile was validated to make sure that the observations and interpretations are based on a shared perspective. The market research helps to understand the design context and gives an overview of all products and adaptations in which value is created. The characteristics of the problems and needs are mainly concerned about creating water storage facilities on surface level. In addition, the design game makes the patterns of value creation easily visible. It was found that a gap exists between the indication of vulnerable heat spots in urban areas and the practical solutions. Thus, solutions for a resilient, climate-adaptive city are needed next to managing storm water runoff.

Based on the customer understanding, and Wavin's interest, the final concept adds value to the customer. The design principle is based on blue-green roofs to provide a cooling effect in urban areas. From the user criteria, green roofs are less effective on surface level due to the height of the buildings. The final concept brings evaporative cooling to surface level of urban micro-climates. Besides evaporative cooling, customers can expect improvement of the water retention in the subsurface. Other potential pains are triggered according to water use during long periods of drought. The multifunctional water system uses a minimal amount of water to retain water for dry periods. So, the product system has potential in many areas in Europe. Climate change adaptation increases the demand for sustainable SWM solutions, the capillary water system addresses the important retentive subsurface, alleviate extreme weather and create essential green areas. The product system is an addition to the toolkit of climate-responsive designs in urban climate resilience.

6.2 Conclusion

The Storm Water Management (SWM) industry leaders like Wavin have to come up with innovative solutions to help stakeholders like municipalities in their leading role to achieve climate resilience in urban environments. Throughout this research, sustainable SWM solutions were elaborated on the challenges in urban climate resilience and the effectiveness of existing solutions, determining issues and alternatives in a process of stakeholder involvement. The result contributes to a climate-resilient city embedded in the urban design.

First, the sub-questions are discussed. Afterwards, the main research question is discussed.

1. Which trends have been researched in the context of temporary water storage, delay, and other (re)use, in the urban environment?

The urban water balance is becoming increasingly unbalanced due to the effects of urbanization and climate change. Intense precipitation shows an increasing trend, occurring with higher temperatures and longer periods of drought. During such circumstances, the city feels unpleasantly warm. In recent years, the challenges lie among creating a more natural approach to make the urban water cycle more robust. The trend towards a more natural approach highlights the use of micro-scale distributed techniques like natural buffering, infiltration, or delayed discharge to manage storm water of impervious surfaces in urban areas, and to address sewer overflow problems. It can be concluded that public areas play an important role to integrate the techniques. In new urban development and restructuring projects, cities can implement adaptation measures. Climate adaption focuses on sustainable SWM solutions as a means to solve the water challenges and mitigate the effects of heat and drought.

2. Which existing solutions have been researched in the context of temporary water storage, delay, and other (re)use, in the urban environment?

Wavin's current solutions manage excess rainwater effectively. Instead of below ground, consequence prevention, the above ground solutions incorporates local characteristics into the product design to facilitate a fully integrated system. Above ground solutions carefully tailored to its characteristics (neighbourhood level) can boost sustainability and reduce the risk of damage in terms of economic and human-health impact.

A large number of solutions for successful implementation have been identified from literature and observations. The existing solutions are categorized in six solution directions: 1) water transport; 2) collection and storage; 3) infiltration; 4) reuse; 5) resilience building, and 6) other. During the exploratory expert sessions, the existing solutions were assessed on effectiveness using a game technique. The game technique proved useful to start the dialogue and understand the users' experience. However, it was found that it is important how the cards are visually designed in order to support the dialogue and collaborative design work. After executing the sessions, Wavin expressed interest in incorporating the technique in its frequent meetings with municipalities. For further development of the gamified tool, it is important to consider the use of abstract or concrete visuals for the picture cards.

3. What are the lessons learned from currently existing solutions or trends in sustainable urban SWM?

Aligning theory and practice, a wide criteria to indicate effectiveness in above ground solutions can be distinguished. Results have shown that future solutions have to focus on multifunctional solutions to: 1) achieve the water challenges; 2) mitigate the effect of higher temperatures; and 3) provide added value. Focusing on multifunctional solutions can, in fact, provide added value. It was found that a small scale of the existing solutions is related to heat and drought impacts. According to water experts, the paved surface, which naturally results in higher temperatures, consist of compact subsurface soil. So, the capacity of the subsurface for retaining water is extremely limited. This insight provides focus on improving the retention capacity of the subsurface to alleviate higher temperatures. The product system aims to transport water from the subsurface to the surface resulting in a cooling effect.

4. Which of the identified solutions relevant for Wavin could be implemented or developed to improve sustainable storm water management?

Capillary action supports the conceptual idea about the evaporative cooling of green areas in the public space. Wavin provides solutions in water collection and temporary storage, and therefore the water transport system is easy to implement. The installation of infiltration boxes with water transport to the surface of lower green areas increase the evaporation rate. When comparing the final concept and customer profile, it should be noted that capillary rise is derived from the principle to create less maintenance for the customer. In order to gain a better understanding of the mechanism of capillary rise, different samples were tested. Recommendations were made on possible solutions to improve the capillary water system.

The conclusions of the sub-questions above contribute to answering the main research question:

> "Which solutions can be implemented or developed by Wavin to improve storm water management and minimize the effects of climate change in the present and in the future?"

In order to support Wavin in developing and implementing SWM solutions, a capillary water system using wick material was designed. From the laboratory tests, it appeared that wooden diffuser sticks did not work in contrast to the expectations. So, it can be concluded that the open pores formed within the fibres have to be very fine in order to optimise capillary rise. This is an important factor for the industrial production of the wicks. The material is not suited to be extruded but should be created on a very small scale. In the end, the effect in minimizing the heat absorption and reducing surface and air temperature (microclimate) should be determined. The efficient water use of storm water as cooling element will delay the shortages in dry-out events. In fact, the infiltration box should capture and store rainwater from an extra 1m2 paved surface. Therefore, the lower, green application is important to create a larger catchment area. In the future, more widespread applications can be developed along roads and sidewalks. At this stage, the final concept reached TRL 4 to validate the component in laboratory environment. Currently TRL 3 is achieved, the laboratory studies validated analytical predictions of capillary action, a separated element of the technology. In order to successfully implement the concept, there are both challenges for tests and local characteristics that need to be overcome.

6.3 Recommendations

There are several recommendations for further research on the design. They include recommendations for further tests as well as uncertainties in installation. How can the water system create a cooling effect in the urban environment? Can it be available for home owners as it demonstrates a remarkable effect? May the decision process be influenced to include green verges with or without the water system?

In order to improve the feasibility of this design, it could be argued that a reflection on the conceptual idea is desirable. In addition, an extra group of experts for the validation of the design fit. For example, the contractor was not involved but interpreted during the design process. An evaluation with a tangible model and experts may raise questions about the design constraints. Also, a business model to derive the cost price may influence the design. The costs (e.g. material and processes) are depending on the industrial process and material used. So, further research on its development, production, and testing should be carried out in order to define the investment of Wavin. This effect-oriented product could possibly bring to light further improvements on aligning the product design to the customer's need.

Another interesting option for further research is to continue the testing process of the concept using steps as defined in chapter 5:

- Evaluation of the wick materials – to select cords or other wick material (non-locally or new available)
- Identification and selection of suitable media – to support the uptake of the soil from the wicks and the plants
- Identification and selection of suitable plants – to integrate a potential rate of evaporation
- Integration of wick material into pipes – to maintain a pre-industrialized process

These separated system components validated in a relevant environment lead to:

- Integration of systems elements into prototype – to demonstrate that they work together in a relevant environment

BIBLIOGRAPHY

Ahiablame, L.M., Engel, B.A., & Chaubey, I. (2012). Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. Water Air & Soil Pollution, 223:4253-4273.

Barriopedro, D., Fischer, E., Luterbacher, J., Trigo, R., & Garcia-Herrera, R. (2011). The Hot Summer of 2010: Redrawing the Temperature Record Map of Europe. Science (332 (6026)), 220–224.

van den Besselaar, E.J.M., Klein Tank, A., & Buishand, T. (2013). Trends in European Precipitation Extremes over 1951–2010. International Journal of Climatology 33(12), 2682–2689. doi:10.1002/3619.

Bainbridge, David A. (2012). Wick Irrigation for Tree Establishment. Permanent Agriculture Resources, Holualoa, Hawaii.

Brandt, E., Messeter, J., Binder, T. (2008). Formatting Design Dialogues – Games and Participation. CoDesign – International Journal of CoCreation in Design and the Arts. 4(1), 51-66. Taylor & Francis, 2008.

Chatterjee, A., & Singh, P. (2013). Studies on Wicking Behaviour of Polyester Fabric. Hindawi Publishing Corporation. Journal of Textiles. Volume 2014, Article ID 379731, 11 pages. http://dx.doi.org/10.1155/2014/379731

Cirkel, D.G., Voortman, B.R., van Veen, T., Bartholomeus, R.P. (2018). Evaporation from (Blue-)Green Roofs: Assessing the Benefits of a Storage and Capillary Irrigation System Based on Measurements and Modeling. Water 2018, 10, 1253; doi:10.3390/w10091253.

Coutts, M., Tapper, N., Beringer, J., Loughnan, M., & Demuzere, M. (2013). Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. Progress in Physical Geography, 37(1), 2-28. doi:10.1177/0309133312461032.

Deltaplan. (2017). Deltaplan Ruimtelijke Adaptatie; maatregelen om Nederland klimaatbestendig en waterrobuust in te richten. The Hague: Ministry of Infrastructure and the Environment.

EEA. (2012). Urban adaption to climate change in Europe: Challenges and opportunities for cities together with supportive national and European policies. Copenhagen: European Environment Agency. Retrieved from https://www.eea.europa.eu/publications/urban-adaptation-to-climate-change/

EEA. (2017). Climate change, impacts and vulnerability in Europe 2016: An indicator-based report. Copenhagen: European Environment Agency. doi:10.2800/534806.

EPA (Environmental Protection Agency). (2008). Reducing Urban Heat Islands - Compendium of Strategies; United States Environmental Protection Agency, 2018.

EPA (Environmental Protection Agency). (2008). Trees and Vegetation. In: Reducing Urban Heat Islands: Compendium of Strategies. Retrieved from https://www.epa.gov/heat-islands/heat-island-compendium.

ESA. (2014). World Urbanization Prospects. New York: Department of Economic and Social Affairs, United Nations.

Estrada, F., Botzen, W.J.W., & Tol, R.S.J. (2017). A global economic assessment of city policies to reduce climate change impacts. Nature Climate Change 7, 403-406.

Fletcher, T., Shuster, W., Hunt, W., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J., Steen Mikkelsen, P., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. (2014). SUDS, LID, BMPs, WSUD and more - The evolution and application of terminology surrounding urban drainage. Urban Water Journal (12(7)), 525-542.

Hendriks, K., Snep, R., de Vries, B., & Brolsma, R. (2016). Groene daken in Tilburg; Operationele handvatten voor ontwikkeling van gemeentelijk beleid. Wageningen, Alterra Wageningen UR (University & Research centre), Alterra-rapport 2692. 62 blz.; 25 fig.; 3 tab.; 30 ref.

IPCC (International Panel Climate Change). (2007). Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability. IPCC Fourth Assessment Report: Climate Change 2007. Retrieved from https://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch8s8-2-1-1.html

Karagiannis, N., Karoglou, M., Bakolas, A., & Moropoulou, A. (2016). Building Materials Capillary Rise Coefficient: Concepts, Determination and Parameters Involved. In J.M.P.Q. Delgado (ed.), New Approaches to Building Pathology and Durability (pp 27-24). Building Pathology and Rehabilitation, vol 6. Springer, Singapore.

Klok, E.J., Jacobs, C.J.M., Kluck, J., Cortesão, J., & Lenzholzer, S. (2018). The cooling effect of small blue urban spaces is negligible. Poster presented at ICLEI - Resilient Cities 2018 Conference 26-28 April 2018, Bonn, Germany.

Kluck, J., Kleerekoper, L., Klok, E.J., Loeve, R., Bakker, W.J., Boogaard, F.C. (2017). De klimaatbestendige wijk: Onderzoek voor de praktijk. Hogeschool van Amsterdam, Onderzoeksprogramma Urban Technology, nummer 10. ISBN 978-94-92644-02-2.

Lambley, M. (2017, July 18). What is urban flooding and how does it affect us? Retrieved March 8, 2018, from Wavin Knowledge Centre: https://blog.wavin.co.uk/urban-flooding-affect-us/

Lee, C., So, I., Jeong, S, Huh, M. (2010). Application of Subirrigation Using Capillary Wick System to Pot Production. Journal of Agriculture & Life Science 44(3) pp.7-14.

Monaenkova, Daria. (2012). Elasto-capillarity in fibrous materials. All Dissertations. 965. https://tigerprints.clemson.edu/all_dissertations/965

NASA. (2012, October 28). Technology Readiness Level. Retrieved from https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html

Nielsen, J., & Sano, D. (1995). SunWeb: User Interface Design for Sun Microsystem's Internal Web. Computer Networks and ISDN Systems, 28(1&2): 179-188.

Olsthoorn, A.F.M., Kopinga, J., Tolkamp, G.W., van den Berg, C.A., & ter Braak, C.J.F. (2003). Effecten van vernatting in bossen, Conclusies en aanbevelingen voor praktijk en beleid. Expertisecentrum LNV, Ministerie van Landbouw, Natuurbeheer en Visserij.

Pioneering. (2018, May 17). Samenwerken aan klimaatbestendige steden, dorpen, wijken en gebouwen. Retrieved from http://www.pioneering.nl/bibliotheek/nieuws/839/samenwerken-aan-klimaatbestendige-steden-dorpen-wijken-en-gebouwen

Poleto, C., & Tassi, R. (2012). Sustainable Urban Drainage Systems: Drainage Systems. (M. S. Javaid, Ed.) Brazil: InTech. doi:10.5772/34491.

Purdue extension. (2017, September 22). Soil Basics: Capillary Rise. Retrieved from https://www.youtube.com/watch?v=5waNTa2b-yg&feature=youtu.be

Rajczak, J., Pall, P., & Schär, C. (2013). Projections of Extreme Precipitation Events in Regional Climate Simulations for Europe and the Alpine Region,". Journal of Geophysical Research: Atmospheres 118(9), 3610–3626. doi:10.1002/50297.

Rivela, B., Cuerda, I., Olivieri, F., Bedoya, C., Neila, J. (2013). Life Cycle Assessment for ecodesign of ecological roof made with Intemper TF ecological water-tank system. Materiales de Construcción Vol. 63, 309, 131-145 doi: 10.3989/mc.2012.02611

Scholz, M. (2013). Selecting Sustainable Drainage Structures Based on Ecosystem Service Variables Estimated by Different Stakeholder Groups. Water 2013, 5(4), 1741-1759.

Semananda, N.P.K., Ward, J.D., & Myers, B.R. (2018). A Semi-Systematic Review of Capillary Irrigation: The Benefits, Limitations, and Opportunities. Horticulturae 2018, 4, 23; doi:10.3390/horticulturae4030023

Sharabaty, T., Biguenet, F., Dupuis, D. & Viallier, P. (2008). Investigation on moisture transport through polyester/cotton fabrics. Indian Journal of Fibre & Textile Research Vol. 33, December 2008, pp. 419-425.

Shashua-Bar L., Erell E., Pearlmutter D. (2009). Water use considerations and cooling effects of urban landscape strategies in a hot dry region. The seventh International Conference on Urban Climate, 29 June - 3 July 2009, Yokohama, Japan.

Slingerland, J.D. (2012). Mitigation of the Urban Heat Island effect by using water and vegetation. Master's Thesis, Delft University of Technology, Delft, The Netherlands, 2012.

van Soesbergen G.A., van Wallenburg, C., van Lynden, K.R., van Lanen, H.A.J. (1986). De interpretatie van bodemkundige gegevens; systeem voor de geschiktheidsbeoordeling van gronden voor akkerbouw, weidebouw en bosbouw. Wageningen, Stichting voor Bodemkartering. Rapport 1967.

Solcerova, A., van Emmerik, T.H.M., Hilgersom, K.P., van de Ven, F.H.M., van de Giesen, N.C. (2018). Uchimizu: A Cool(ing) Tradition to Locally Decrease Air Temperature. Water 2018, 10(6), 741; https://doi.org/10.3390/w10060741.

Sörensen, J., Persson, A., Sternudd, C., Aspegren, H., Nilsson, J., Nordström, J., Jönsson, K., Mottaghi, M., Becker, P., Pilesjö, P., Larsson, R., Berndtsson, R., & Mobini, S. (2016). Re-Thinking Urban Flood Management—Time for a Regime Shift. Water 2016, 8(332), 1-15.

Stadswerk. (2016). Hittestress: een onderschat probleem. Retrieved 28 July 2018, from Openbare Ruimte.nu https://www.deopenbareruimte.nu/nieuws/hittestress-onderschat-probleem/

Stahre, P. (2008). Blue-green fingerprints in the city of Malmö, Sweden. Malmö: VA-Syd.

Swart, R., Biesbroek, R., Binnerup, S., Carter, T., Cowan, C., Henrichs, T., Loquen, S., Mela, H., Morecroft, M., Reese, M., & Rey, D. (2009). Europe Adapts to Climate Change: Comparing National Adaptation Strategies. Helsinki: Partnership for European Environmental Research: PEER Report No 1.

Thalen, J. & Garde, J. (2003). Capturing use: user involvement and participatory design. Advanced design methods for successful innovation (pp. 35-57). Design United, 2003.

Theeuwes, N. (2015). Urban heat : natural and anthropogenic factors influencing urban air temperatures. Wageningen University, Wageningen, 1-160.

Souchkov, V. (2017). TRIZ – Fundamentals [cursus]. Enschede: University of Twente.

Rovers, V., Bosch, P., Albers, R. (2014). Factsheet: Hittestress. TNO: CPC (Climate Proof Cities).

van de Ven, F.H.M. (2017, June 27). Wavin interviews urban stormwater expert Dr. Ir. Frans van de Ven, Part I & II . (G. v. Dijk, Interviewer).

Wavin. (2017, June 8). Urban Stormwater Management white paper: The role of urban stormwater management in building a sustainable climate-resilient city". Retrieved April 2018, from Wavin, Zwolle: https://www.wavin.com/en-en/-/media/Files/Urban-Stormwater-Management-Press-Release---Wavin_v2.ashx

Wesonga, J.M., Wainaina, C., Ombwara, F.K., Masinde, P.W., & Home, P.G. (2014). Wick Material and Media for Capillary Wick Based Irrigation System in Kenya. International Journal of Science and Research (IJSR), 3(4) pp.613-617.

Woltjer, J., & Al, N. (2007). Integrating Water Management and Spatial Planning. Journal of the American Planning Association, 73(2), 211-222. doi:10.1080/01944360708976154.

Xiong, J., Tian, Y., Wang, J., Liu, W., Chen, Q. (2017). Comparison of Coconut Coir, Rockwool, and Peat Cultivations for Tomato Production: Nutrient Balance, Plant Growth and Fruit Quality. Front. Plant Sci. 8:1327. doi: 10.3389/fpls.2017.01327

Zolina, O. (2012). Change in intense precipitation in Europe. Special Publication No.10, 97-120.