DEVELOPING A MONITORING NETWORK FOR WATERSTREET'S LIVING LAB

MSc Thesis
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DEVELOPING A MONITORING NETWORK FOR WATERSTREET'S LIVING LAB

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Preface

This thesis concludes my MSc in Water Management at the Technical University of Delft. It has been a long road since I started my thesis, but I am very happy to have been through it and gained all the useful knowledge from this experience. My love for water-related aspects of engineering started in the 2nd year of my Bachelor's and has grown ever since. Completing this thesis gave me much to think about on the future of water management in urban areas, which is especially important considering climate change. Except for water management, management of my thesis work has also been challenging but I am happy to have learned so much during this time. This will be a useful tool for any future work.

All the above would not be possible without the help of my supervisor, Martine Rutten. She was there for me through all the difficult parts of this work. I also thank Jeroen Langeveld and Katerina Varveri for their useful comments and recommendations. A special thanks to Emilie Buist for her contribution during my thesis as an intermediate between me and the study area of WaterStreet in the Green Village. She provided me with all the useful information and contacts needed for this work which was of very big importance due to remote working.

A special thanks to my family, my boyfriend my two friends Cornelia and Vivian, that have supported me from the time I was considering doing this master's until the end. Their support and help made this work easier. Lastly, I would like to dedicate this work to my opatje (my grandfather as I used to call him) that passed away during the time of my thesis.

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Abstract

Sustainable Urban Drainage Systems (SUDS) are useful tools to manage rainwater and reduce pollutants in urban environments. Their use, as sustainable solutions, can mitigate the effects of climate change and urbanization. The existence of different definitions of performance is one reason for delaying more implementation of SUDS. Deciding on the Key Performance Indicators (KPIs) is one of the objectives of this thesis. WaterStreet, the chosen study area, is a living lab that permits the implementation, presentation, and testing of newly designed SUDS with the goal of facilitating their entrance into the market. WaterStreet could benefit from using sensors to provide the KPIs and other indicators of performance, but the sensors already implemented do not achieve that objective fully. So, the objective of this thesis is, to **develop a comprehensive set of KPIs that describe the performance of SUDS and propose a monitoring network to measure the performance of SUDS implemented in WaterStreet**.

To achieve that objective, information on the study area's characteristics, like soil types, design of SUDS, and groundwater levels were gathered to find how water flows in, out, and around the study area including the SUDS. Additionally, the key stakeholders were determined with a stakeholder analysis, and literature was researched on the important indicators used to reflect the performance of SUDS for water quality and quantity. Interviews were performed to include the view of the key stakeholders on the indicators found in the literature. The two approaches explained above provide the data that need to be monitored on WaterStreet. Criteria for the quality of data that would be provided by the sensors are set, before concluding on suggestions. The suggested sensors and their limitations are based on results of published studies and reports.

Based on the findings of this thesis a distinction between the Key Performance Indicators (KPIs) and Indicators of Performance (IP) is made. In the first category, the indicators of overflowing volume, duration, and frequency are included along with rainfall and overflow from upstream drainage areas. In the second category the indicators, infiltration in the soil and through the first layer of SUDS, and storage in the soil and system are included. Both categories of indicators are suggested to be monitored in the study area of WaterStreet to increase the value of WaterStreet as a living lab. Indicators for water quality are not concluded due to the lack of information on the existing pollutants and their removal and remobilization mechanisms. Reduction of Total Suspended Solids (TSS) and Total Phosphorus (TP) are two possible indicators that are also considered as a proxy in Germany. Changes in pH and temperature are two indirect indicators that are found to affect the reduction and remobilization mechanisms and are therefore important to consider as well.

An acoustic disdrometer to measure rainfall, a sonar pulse sensor to measure groundwater levels, divers in an observation pipe in the system to measure the water level in the system and the infiltration in the soil, and lastly divers in a controlled volume downstream of the SUDS to measure the overflowing water downstream the SUDS, were the proposed sensors. The disdrometer and two of the sonar pulse sensors are already installed on WaterStreet while it is suggested to put divers in the individual systems and two more sonar pulse sensors. For the indicators, overflowing water from upstream and the rate of water entering the SUDS research on the runoff coefficient and the use of water balance are suggested, respectively.

An important consideration in this thesis is the characterization of hydraulic isolation from the top and bottom of the system, allowing the interpretation of the data from monitoring, to represent only one system's response. Suggestions to include a controlled volume to capture the overflow downstream of the SUDS and a drainpipe to ensure a drainage depth of 0.5 m, are made, to help ensure hydraulic isolation from top and bottom respectively. Based on this study, only half of the systems placed on WaterStreet are isolated, not considering the possibility that the groundwater table can get even higher resulting in even fewer systems isolated. Additionally, from analyzing the hydraulic response on the SUDS in WaterStreet, it was concluded that all 5 studied systems out of 8 total were being over-dimensioned, meaning that the storage in the SUDS would not be full even with rainfall of once in 100 years. From the same analysis, it was also concluded that the infiltration through the first layer is the prevalent overflowing mechanism of 3 out of 4 studies SUDS. Both the previous findings are important to realize a hydraulic response to rainfall proportionally to real implementations. This is an essential consideration from living labs because they try to bring lab and real implementation closer. Lastly, pollutants to be used as KPIs for water quality performance of SUDS should be researched more based on the principle of not shifting problems downstream.

1. Introduction

Climate change and urbanization, challenge water management in the city and one method to overcome the challenges is the use of sustainable practices (1). These practices try to bring back the natural hydraulic regime of the water cycle (2). Sustainable Urban Drainage Systems (SUDS) are practices that aim toward reducing stormwater runoff, peak flows, pollutant loads, retaining and infiltrating water, recharging the groundwater, and more (2). SUDS have been proven to be effective tools for stormwater management in city environments (1). Implementing SUDS comes with limitations. Limited understanding of how they perform, trust issues of both experts and citizens, and lack of legislation for performance indicators, are some of the limiting factors. An important step towards resolving most of the above limitations is to identify a list of comprehensive indicators (3), or Key Performance Indicators, that together will form an integrated measurable performance rate of SUDS.

Living labs, like the chosen study area of WaterStreet, aim to confront those limitations by testing and demonstrating new SUDS. WaterStreet is a physical living lab where researchers, developers, government bodies, and civilians meet and experiment, with the goal to research, evaluate and demonstrate new products that aim to better deal with rainwater in the city (4).

Both water quality and quantity aspects are considered in the research for the performance indicators because both are important aspects of SUDS design, as shown in Figure 1 (5). Biodiversity and amenity are excluded due to the time limitation of this work. The research on Key Performance Indicators follows that division.

A monitoring network is essential to gather data to reflect performance. To come up with a monitoring network, research on the study area, the systems implemented, their designed hydraulic response, and key performance indicators should be considered.

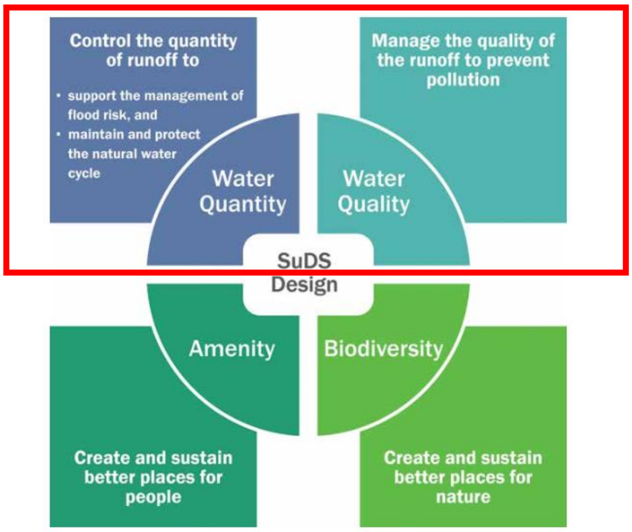

Figure 1 SUDS Design objectives from "The SUDS Manual". CIRIA is a research-driven and knowledge-distributing organization mainly acting in the United Kingdom.

1.1 Knowledge gaps- toward the objective

Several terms were found to reflect sustainable drainage solutions with the most popular of them being, Sustainable Urban Drainage Systems (SUDS), Best Management

Practices (BMP), Green infrastructure (GI), and Low Impact Developments (LID) (6). Given that the focus of WaterStreet is on a city environment and the solutions implemented there try to deal with retaining and draining water, within this thesis, the term Sustainable Urban Drainage Systems (SUDS) is used. Examples of those drainage solutions are green roofs, bioswales, rain gardens, permeable pavements, and storage facilities (2). The newly designed systems implemented on WaterStreet can be considered in the category of SUDS based on their designed response to rainwater.

Although SUDS is a very promising solution to resolve flooding, heat island effects, pollutants, and increase biodiversity and amenity in the city, they face many obstacles until actual implementation. In the research of Roy et al. (3), they conclude on the seven most important reasons, why SUDS are not implemented more by the water managers based on experiences in Australia and the United States. These are "1. uncertainties in performance and cost, 2. insufficient engineering standards and guidelines, 3. fragmented responsibilities, 4. lack of institutional capacity, 5. lack of legislative mandate, 6. lack of funding and effective market incentives, and 7. resistance to change."

Since 2008, when the research of Roy et al. (3) was published, much has been done to resolve the problems above, like the publication of "The SUDS manual" in 2015 or the report about "Guidance on the construction of SUDS" in 2017, both from CIRIA, a research and information association established in the UK (5) (7). The Environmental Protection Agency (EPA) established in the US has also published a report called "Urban Stormwater BMP Performance Monitoring" in 2009, stating several important pieces of information about how to monitor Best Management Practices or BMPs (8). Australia also come up with a guideline for the design of SUDS in 2017 (9). STOWA, the Foundation for Applied Water Research in the Netherlands published a report in 2007 called "Reporting the knowledge of design, construction, and management of SUDS" (10). Although many manuals on SUDS exist in several countries, translating the conclusions from one guideline to the next is difficult. Moreover, the main objective of SUDS differs per country due to the difference in the climate for example. It is therefore expected that the targets of performance and the definition of performance differ. Moreover, performance is differently defined for several stakeholders within the same country. The city planners, are focusing on the integration of the systems into the existing urban structures, while a resident focuses on if the system does "keep their feet dry". So, it is important to first define what reflects the performance of SUDS and then provide a network of sensors to collect the indicators that define it.

Identifying and agreeing on a list of indicators (3), or Key Performance Indicators, could provide the common ground for stakeholders to assess and compare the performance of SUDS. It can also result in better cooperation and understanding between stakeholders leading further to more useful standards to help allocate responsibilities. Monitoring those indicators, can update the design of SUDS, understand the overall cost of a system and help build a better case to request funding for new systems. As discussed above different stakeholders define performance differently. This is because they are focusing on the different functions of SUDS.

Although much research is done on what affects the performance of SUDS (5), (10), (11), (8), (9), a dedicated and established list of indicators that reflect the performance of water quality or quantity was not found. Focusing on the case of the Netherlands and in STOWAs report about drainage systems for rainwater of 2007 (10), guidelines, in the form of advice, are set for SUDS along with examples of implemented systems. These guidelines can be used to select important water quantity indicators but stakeholders are not obligated to consider them.

Among the water quantity, amenity, and biodiversity functions, SUDS are also used to reduce the pollutants that are carried away in the rainwater (5). In the report of STOWA (10) mentioned above, much is said about water quantity but not quality. Although much is known about, which pollutants can originate in the rainwater and if they are harmful or not, deriving the pollutants that can also be used as performance indicators for SUDS is difficult to conclude (12). The effect of the system on the pollutant concentration and the interaction of the pollutant with its surroundings can differ per pollutant. That increases the complexity of removal processes and the selection of the pollutants that can be used as Key performance indicators.

Continuous or systematic monitoring that provides all the components of the hydraulic response of SUDS, would contribute additional knowledge on how the systems interact with the environment they are implemented and collect the needed indicators that define their performance. Although WaterStreet provides important results from demonstrating and experimenting with the systems in short periods, a preliminary review of the existing sensors concluded that not all the needed information is gathered based on the objective to capture water quantity and quality indicators that reflect the performance of SUDS overall. Moreover, the regulated environment and the existence of new systems, create ideal conditions and opportunities for a more extensive and systematic monitoring network than the current one. So, the choice of WaterStreet as a study area for this thesis is motivated by the increase of value that the monitoring could provide to WaterStreet's SUDS and the fact that the current sensors are not able to provide all the indicators needed to reflect the performance of SUDS.

1.2 Research aim

Based on the need to identify key performance indicators for both the water quality and quantity functions of SUDS, and the realization that WaterStreet has the potential to gather that information, the aim of this thesis was formulated.

<u>The main objective of this thesis:</u>

Develop a comprehensive set of KPIs that describe the performance of SUDS and propose a monitoring network to measure the performance of SUDS implemented in WaterStreet.

1.3 Research questions

To achieve the objective of this thesis the next questions were answered:

Table 1 Research questions and sub-questions to achieve the main objective. The colors link the questions to the approach of the research shown in Figure 2. The section that includes the answer to the questions can be found in the last column.

Main question	Sub Questions	Section of this report connected to the question.
A. How do the systems implemented in WaterStreet respond to rainfall?	1. How does the scheme of the water balance look like?	4.1.1 & 4.1.2
	2. How are the systems designed to respond?	
	3. How do the surroundings of the system affect its performance?	4.1.3

	4. What indicators describe the performance of SUDS in WaterStreet based on their response to rainfall?	4.1.4
B. What would be a comprehensive set of KPIs that describe the performance of SUDS?	1. What important indicators are mentioned in the literature?	4.2.1 + 4.2.2
	2. Who are the key stakeholders in implementing SUDS?	4.2.3
	3. What is the key stakeholders' view on important indicators and how do they relate to indicators found in literature?	4.2.4
	4. What is the chosen comprehensive set of KPIs that describe the performance of SUDS?	4.2.5 + 4.2.6
C. What are the chosen indicators to be monitored in WaterStreet?		4.3
D. What sensors are suggested for the collection of the data that reflect the indicators?	1. What should be the criteria for the quality of data?	3.3.1 & 4.4
	2. What data are already monitored in WaterStreet?	2.8
	3. What are the suggested sensors?	4.4
E. How does the monitoring network of WaterStreet look like?		4.5
F. What could be a useful recommendation for the future implementation of SUDS?		6

1.4 Research design

To achieve the objective of this thesis, the approach shown in Figure 2, was followed. The colors show the integration of two steps into one, and in this way, the last step includes the results from all the previous ones.

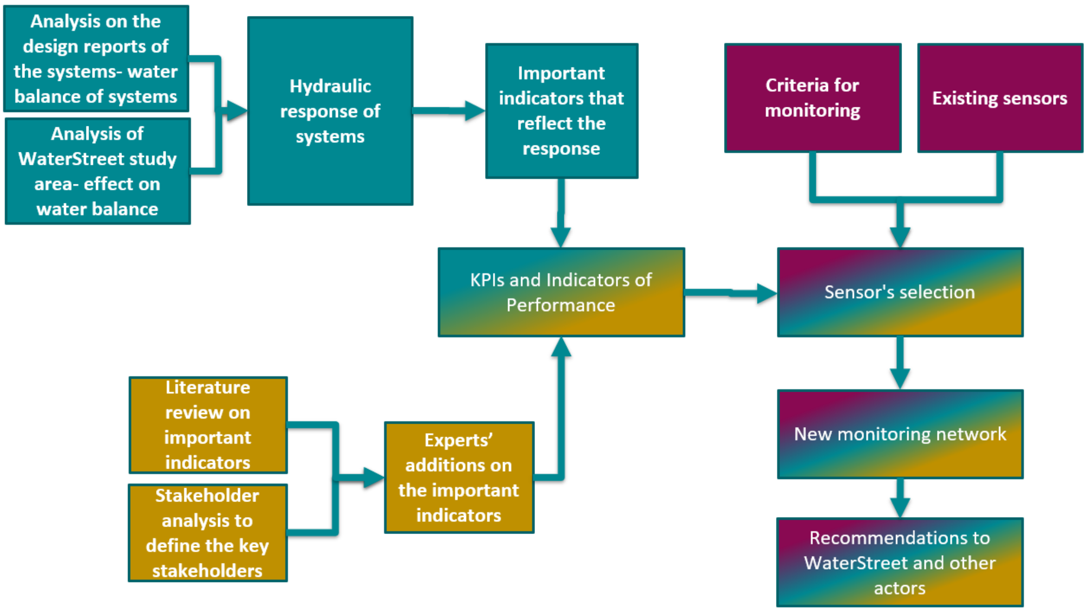

Figure 2 Research approach. Three main lines of research are indicated in different colors. The colors are mixed where the results of the previous research are used.

Following Figure 2, to conclude the data that should be gathered with the monitoring network two main approaches were followed. The first (in yellow) was to identify the set of KPIs with the help of literature and experts, and the second (in blue) was to understand the way water flows in the study area of WaterStreet to define the hydraulic response of SUDS and the interaction of SUDS with the study area. The results of these two approaches were then combined (blue and yellow combination) to come up with the data that need to be monitored. Lastly, after defining the criteria (in purple) for the monitoring network and considering the existing sensors, the selection of the sensors was possible. The new monitoring network was the collection of the sensors placed on the terrain. Based on the findings and challenges of this research recommendations were provided for WaterStreet and other actors that implement SUDS in order to monitor and interpret the results from monitoring the performance of SUDS.

1.5 Scope- Definitions - Tools

The scope of this thesis was limited to the WaterStreet study area and the systems that were implemented until January 2021. To select the performance indicators the focus was drawn to the needs in the Netherlands. This means that the indicators chosen, respond to the needs of the stakeholders that are active in the Netherlands. This focus was chosen because WaterStreet is in, Delft which is in the Netherlands.

The hydraulic response was limited in the conditions of rainfall. This would mean that the conditions of snow, ice, hail, and mist were excluded. It is suggested in the future to research how to address those conditions because they are expected and can provide a different response than rainfall. A focus on rainfall conditions was chosen to support the cause of the systems on WaterStreet to manage the rainwater (13).

To better understand the following chapters the next terms were defined for this thesis.

SUDS are the new Sustainable Urban Drainage systems implemented on WaterStreet terrain. The SUDS implemented on WaterStreet are dealing only with rainwater from the roofs and streets and manage the pollutants that are carried with the overflow. Functions related to amenity and biodiversity are not considered in this research because the focus is on the hydraulic response.

Hydraulic response of SUDS on WaterStreet is the collection of fluxes and storages within the system that change in time (for example, infiltration or available storage in the system).

Hydraulic isolation from the top of the system is evident when two systems that are not designed to work in collaboration in this study area, are eventually affecting each other by sharing a drainage area. That sharing of drainage area affects the water stress of the downstream based on the performance of the upstream system.

Hydraulic isolation from the bottom of the system and in the soil is evident when two systems that are not designed to work in collaboration in this study area, are eventually affecting each other when groundwater enters one and the next. This is evident especially when the groundwater table is high. When that happens, the downstream system is directly linked to the performance of the upstream one.

A monitoring network is the sum of sensors and tests to measure the data that collectively capture the hydraulic response of the SUDS implemented in WaterStreet.

Key Performance Indicator (KPI) is a quantitative, measure of achievement to indicate if a SUDS is working successfully towards dealing with the quantity and quality of rainwater in the city. Indirect indicators like the cost of technology and maintenance, for example, are not considered because they are regarded as the result of a system that does not perform properly.

The tools used to provide the schematics of this thesis were the architectural program, ArchiCAD 23. This program was selected because of its availability and at the same time was able to draw the scaled figures. Moreover, PowerPoint and python programming interface was used to present and analyze data.

2. Study area

To introduce the study area, first, the objectives of WaterStreet are presented which are a guideline for this thesis. Secondly, information on the location and the physical boundaries of the study area are shown. Within these boundaries, the terrain, soil types, and water levels in the canal and ground were analyzed. Schematizing the terrain was important to visualize the interaction of the systems from overflowing water, while soil types and water levels in the canal and ground were important to realize the groundwater flow from the SUDS to the canal. Lastly, a first preview of the SUDS implemented on WaterStreet is shown, along with the existing monitoring set-up.

2.1 About WaterStreet

WaterStreet is a collaboration between Delfland Water Board, VPdelta, and The Green Village. It is located on The Green Village site and has developed a living lab focused on researching new products that aim to better deal with rainwater in the city (13). This site allows developers to assess their innovations without the involvement of the public or government, helping them reduce the financial risk and revealing problems and limitations before going to the pilot phase (Figure 3). WaterStreet implements the hop, step, and jump or triple jump approach (Figure 3) (13) to make the transfer toward full-scale implementation in the Market easier.

Figure 3 The hop, step, and jump approach to help SUDS go to the pilot phase, implemented by WaterStreet. WaterStreet is the study area of this thesis where new drainage systems are implemented demonstrated and tested.

2.2 Location

WaterStreet is located in South Holland and on the campus of the Technical University of Delft (Figure 4). This thesis focused on this area and its physical characteristics. This is relevant when implementing the same systems in different locations. Then the results of this thesis cannot be applied without first considering the existing characteristics of the area. In that context, this thesis can be used as a guideline on what to look for, before implementing a similar monitoring network in different areas. One example is the prevalent geology, which can play a significant role in SUDS selection and performance. In different regions, geology can be significantly different resulting in different types of SUDS being implemented.

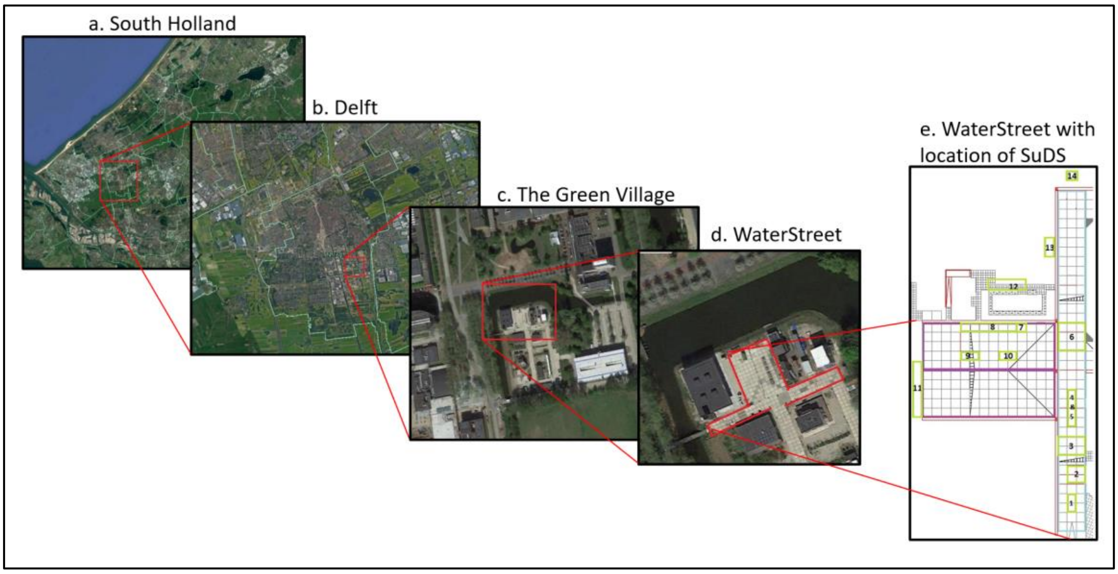

Figure 4 Google maps snapshots. Zooming in the WaterStreet study area located in Delft, the Netherlands.

2.3 Boundaries of thesis

The physical boundaries for this thesis were set at the boundaries of the WaterStreet as shown in Figure 5 in black color. WaterStreet area corresponds to 1028 m2, a small percent of the total area of The Green Village. Overall, 144 m2 (36 tiles of 4m2 each), out of the total 1028 m2 are covered with SUDS that aim to deal with the rainwater on WaterStreet in a sustainable way.

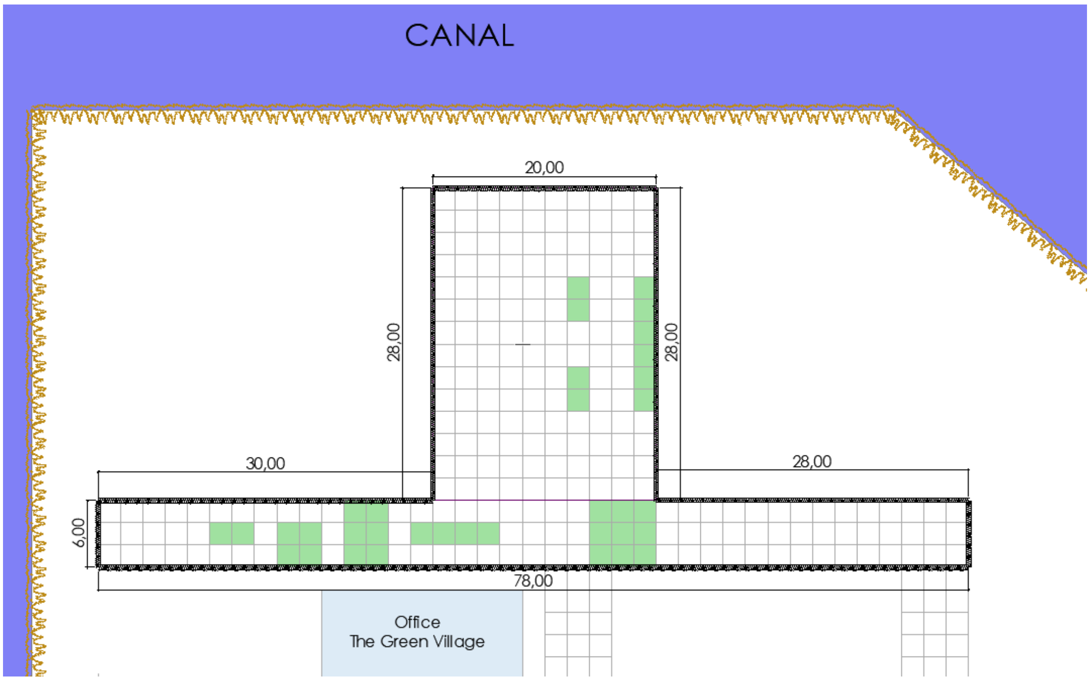

Figure 5 Boundaries of study area indicated with black colored line and location of the SUDS on the study area indicated in green. Dimensions of the study area can be seen also along with the location of the Offices in the Green Village and the canal surrounding it.

Outside these boundaries, the surface water in the canal, the groundwater flow to the canal, and the surface flow around the study area were considered in this thesis.

On the vertical axis, the boundary was set around 5 meters above the pavement and 4.50 m until the bottom of the canal. The depth of the canal is 2.4 m (14). This is the natural area where most of the hydraulic processes of the SUDS are active.

Within the boundaries of the study area, 2 sections can be distinguished, outside and inside (Figure 6) of the system. The section inside the system can then be divided into two sub-sections, the saturated and unsaturated zone. The section outside the system can also be divided into two subsections, above the ground level, and in the soil until the canal. This division was useful for the water balance analysis of the SUDS.

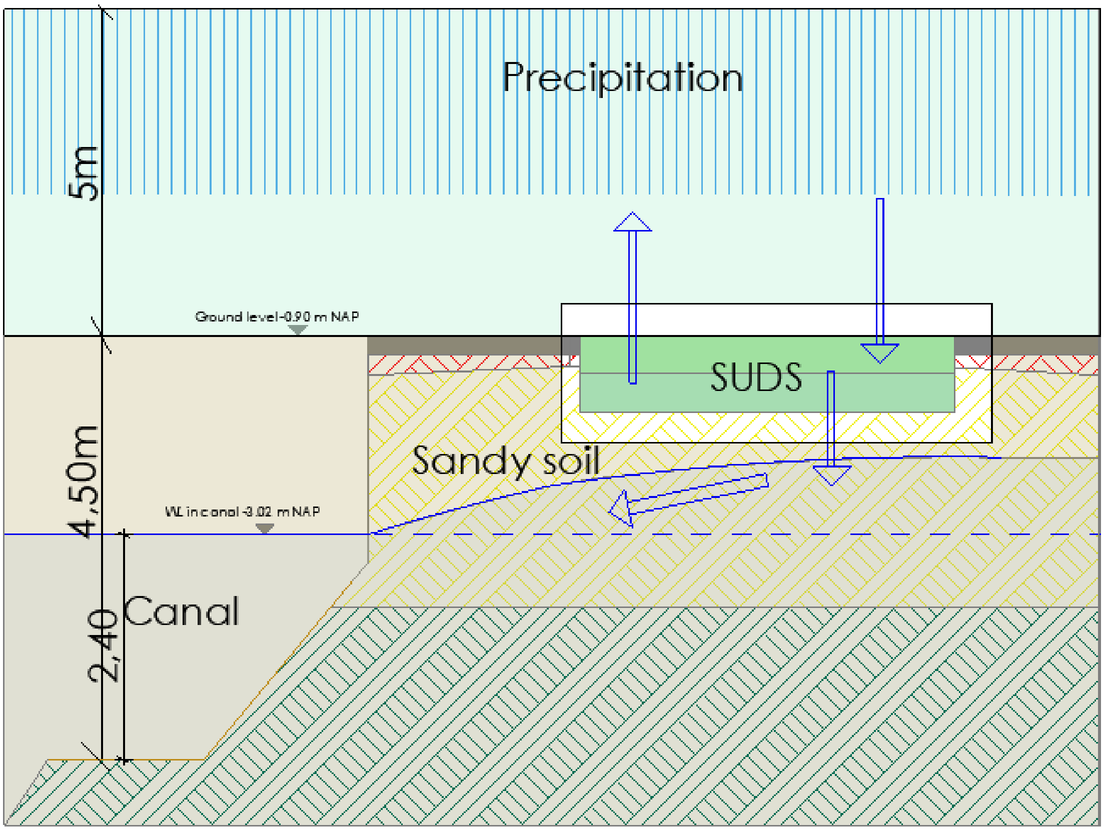

Figure 6 Reference cross-section of the study area. Two sections are identified, outside the system with blue and grey colors and inside the system without coloring. Inflows or precipitation, outflows to the ground, or evapotranspiration are represented with arrows while depth information on the terrain is presented in this picture like the depth of the canal and the maintained water level of the canal.

2.4 Terrain and main direction of water on and around the study area

Paved terrain

The terrain consists of SUDS tiles and concrete non-permeable tiles with dimensions of 2 m x 2m. The non-permeable tiles in Figure 7 are shown with white color while the SUDS with green. The water that precipitates on the terrain follows the slope and is directed toward the storm sewer that is located on the sides of the terrain and is shown with red lines in Figure 7.

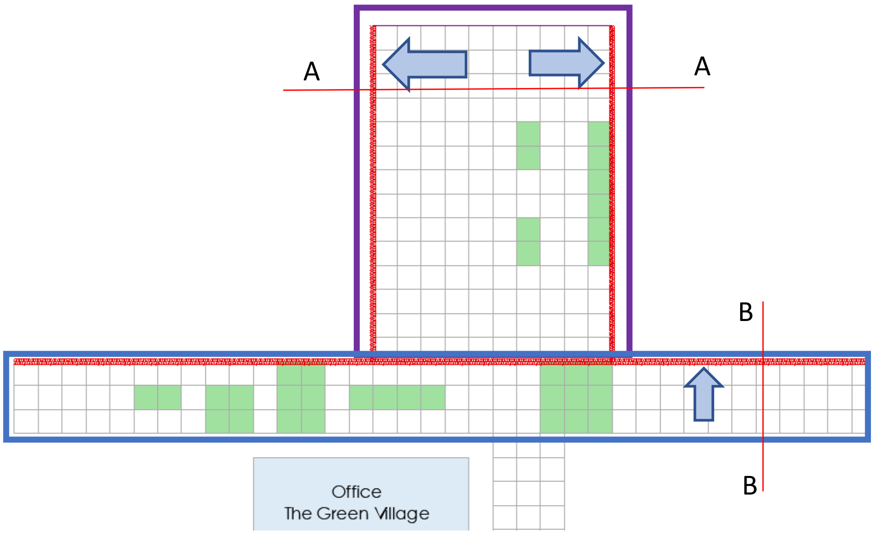

Figure 7 Study area with the Storm water sewer system indicated with the red line. White are the non-permeable tiles and green the SUDS. The square area overflows to the sides, east and west part of the figure while the path overflows to the north part. The main flows on the terrain can be seen with the blue arrows. The cross-section A and B are relevant to the next figures.

From a hydraulic point of view, the study area can be divided into two main sections based on the slopes of the terrain, the first outlined with blue and here called path area, and the second with the purple or square area shown in Figure 7. To indicate the water flow on the tiles, the slopes of the terrain were calculated based on technical reports [1].

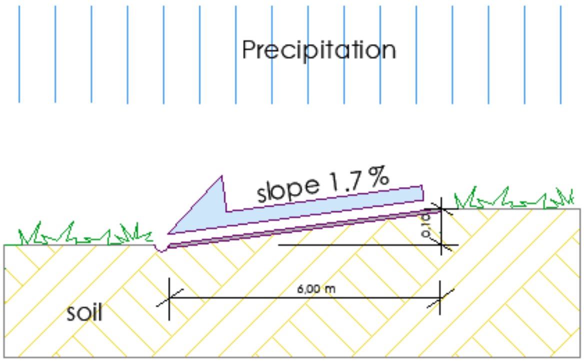

Figure 8 Cross-section B-B vertical to the pathway or blue section. Indicating the slope of the terrain and the direction of the overflowing water.

In the first section or the blue section, the slope was calculated at 1.7 %, and the water is directed from the right to the left as shown on the cross-section B-B (Figure 8). The location of the cross-section is shown with the red line in the top view (Figure 7).

Regarding the second section, shown in Figure 9 the average slope from the center of the area to the sites as shown on the cross-section A-A was calculated at 1.1%. The location of the cross-section is shown with the red line in the top view of the purple section (Figure 7).

[1] The technical reports were provided by Ms. Emilie Buist, Project manager Water Innovations in WaterStreet

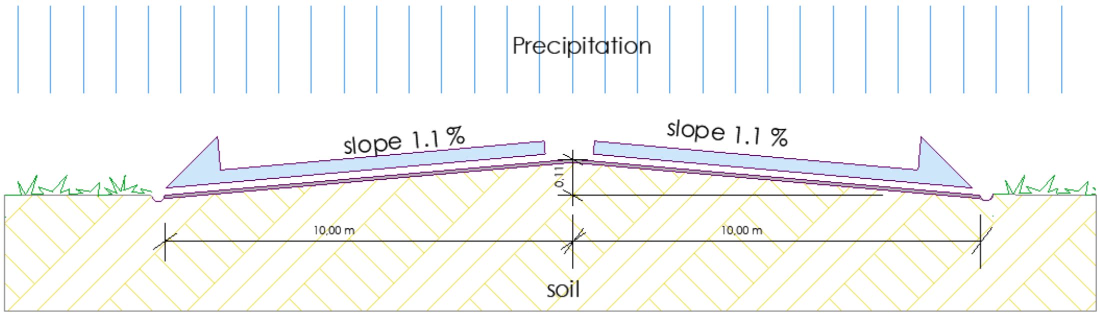

Figure 9 Cross-section A-A vertical to the square or purple section indicating the slope of the terrain and the direction of the overflowing water.

__Unpaved terrain outside the study area__

To get a first understanding of how the water moves outside the study area the AHN (Actual Height of Netherlands) map of the Netherlands was used (14). This is useful because the water that overflows from the surrounding area to the study area might have to be processed by SUDS. The actual height data collected for the surrounding area can be seen in Figure 10.

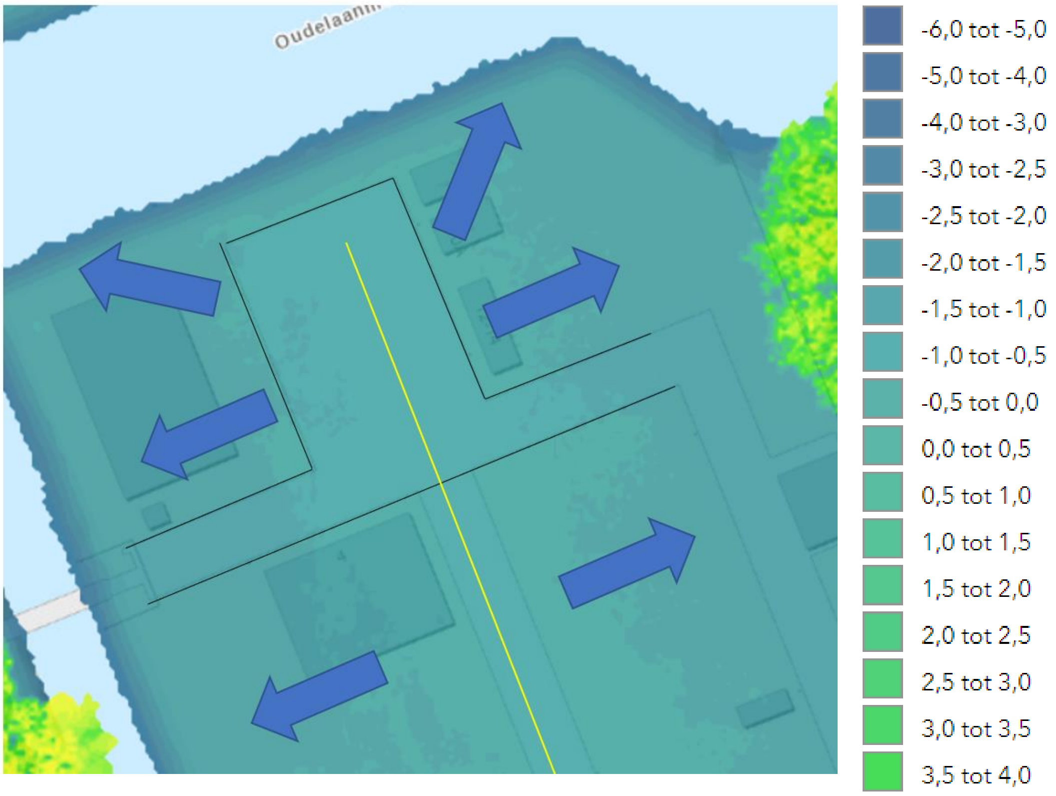

Figure 10 Snapshot of the surroundings of the study area with the corresponding legend from the Actual Height repository of the Netherlands. The colors indicate the actual height at a location and the lighter the blue color is, the higher the elevation is the higher the elevation. The yellow line indicates the watershed divide of the two watersheds in the east and west of the figure. The blue arrows indicate the preferential flow path of the precipitated water when falling on the soil surrounding the study area indicated by the black line.

The overall flow of surface water on and around the study area was realized by integrating the direction of flow surrounding the study area, shown in Figure 10, and the direction of flow on the study area, shown in Figure 7. The integrated flows can be seen in

Figure 11. From the figure below it can be concluded that based on the slopes of the paved study area and the slopes of the surrounding area no water enters the paved area from the surroundings. Therefore, the study area works as an isolated section.

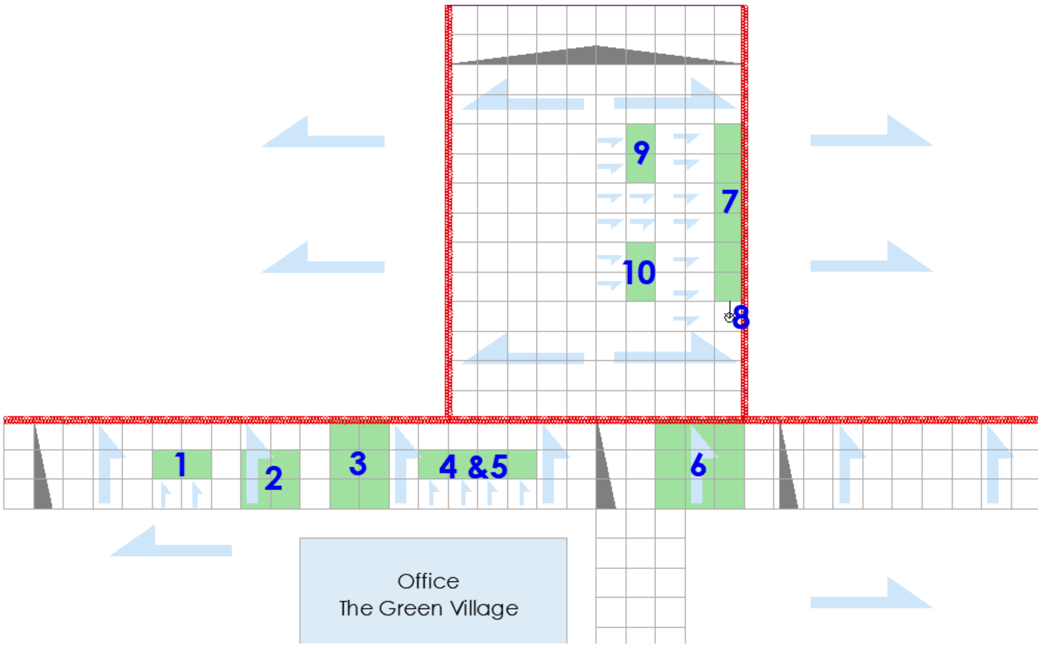

Figure 11 Surface water direction based on the paved and unpaved terrain and its elevations. With blue arrows, the main direction of water can be seen along with the location and identification of the systems in the study area.

2.5 Soil types

Sandy and moderately fine is the characterization of soil type given from the boring tests done until the depth of 2.90m from the ground level (15). The boring data were put together to make the soil cross-section C-C at the location shown in Figure 12. Moreover, the dimensions of the systems that the cross-section intersects were gathered to identify the exact soil that surrounds them. This information is important because the water that is stored in the system will later infiltrate the unsaturated area surrounding the system and the rate of infiltration is strongly related to the type of soil. Sandy -moderate fine soil is the prevalent soil type surrounding the systems as shown in the cross-section C-C (Figure 13). The same layering was observed in the study area.

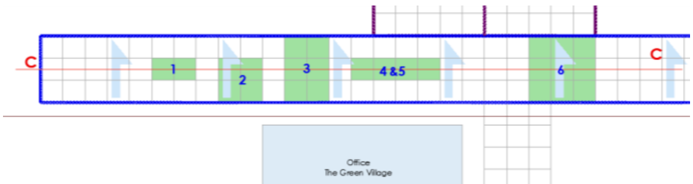

Figure 12 Location of the cross-section C-C for the presentation of soil type.

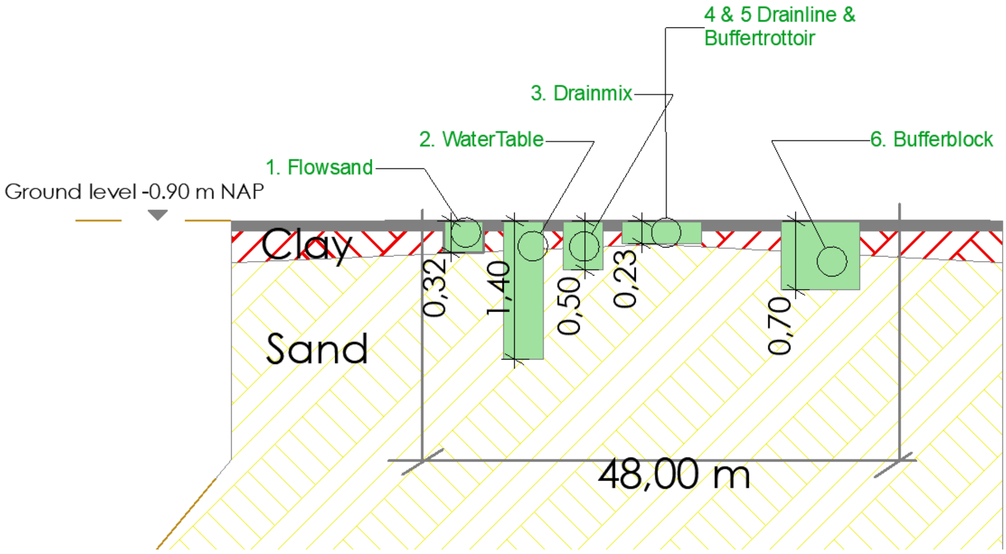

Figure 13 Cross-section C-C of the soil type at the location of the SUDS along with the Blue or pathway section. Prevalent is the sand type under the SUDS.

The type of soil around the systems is important because a type of soil that easily permits water to flow through it is considered good for draining the water stored in the system. Saturated hydraulic conductivity is one important parameter for groundwater flow according to Darcy's law. Some indicative values for the hydraulic conductivity of Sandy clays are 10^{-9} to 10^{-8} m/sec, for the very fine sand 10^{-6} to 10^{-5} m/sec, and for fine sand 10^{-5} to 10^{-4} m/sec (16). After the analysis of the boring data shown above the prevalent soil of The Green Village is moderate fine sand. Based on the literature and assuming that in the study area average fine sand is expected, the saturated hydraulic conductivity of that sand can be assumed to be around 5.5×10^{-5} m/sec (16).

2.6 Water level in canal and ground

Groundwater's hydraulic gradient is an important parameter for solving the groundwater flow according to Darcy's law. The water levels in the ground are closely monitored in two locations (PB01 & PB02) close to the study area. From those two observation wells, the groundwater table under the path area was realized but not under the square area. Therefore, the cross-section of only the path section can be seen. Although the water level of the canal around the study area is not monitored, it is controlled and maintained by the Delfland Waterboard at -3.02 m NAP. This water level is not constant since there is a need for circulation of the water in the canals for water quality reasons so the level might vary over time.

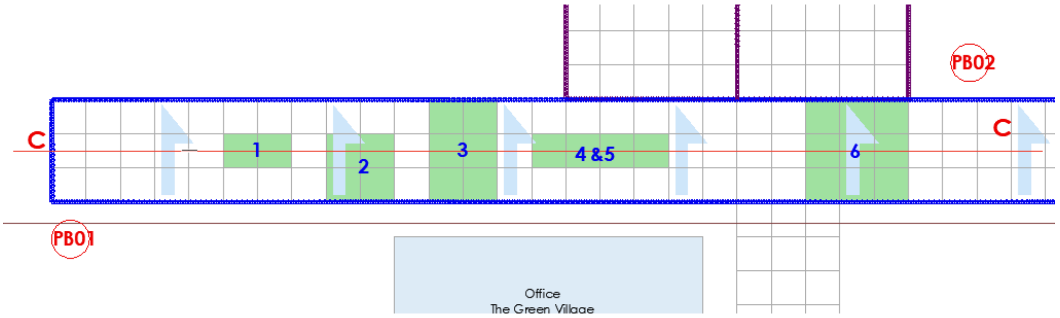

Figure 14 Top view of the pathway section with the locations of the groundwater wells identified with a red circle including the name of the well. PB01 and PB02 are the two wells close to the study area.

An analysis of the groundwater levels collected in the field (PB01 & PB02) shows the average groundwater levels per month for the two locations indicated in Figure 14. The monthly average levels were calculated and plotted from hourly data taken between June 2019 and March 2021. As seen in Figure 15 the groundwater levels in the PB02 location were constantly higher than the PB01. That is expected as water is directed towards the canal that has a lower maintained water level, thus creating the gradient towards it.

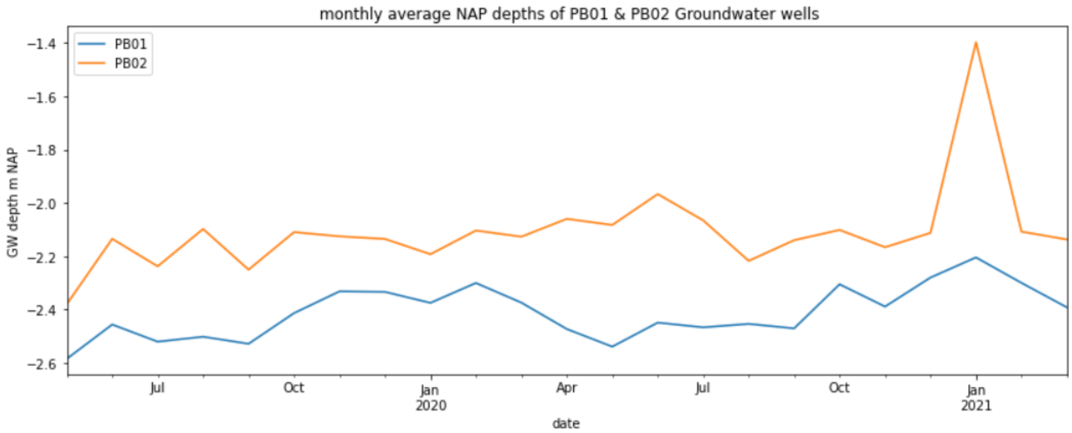

Figure 15 Monthly average groundwater levels in m NAP for wells PB01 & BP02. The cross-section of the groundwater flow can be realized from these measurements.

From the analysis of the water levels in the canal and ground, a cross-section of the path area was realized (Figure 16) at locations C-C (Figure 14). The exact ground levels and canal water levels can differ per location and time so the hydraulic gradient might be different than this figure. For presentational reasons, the following cross-section (Figure 16) was created. An average groundwater level of -2.11m NAP at the PB02 location and -2.41 m NAP at the location PB01, were used.

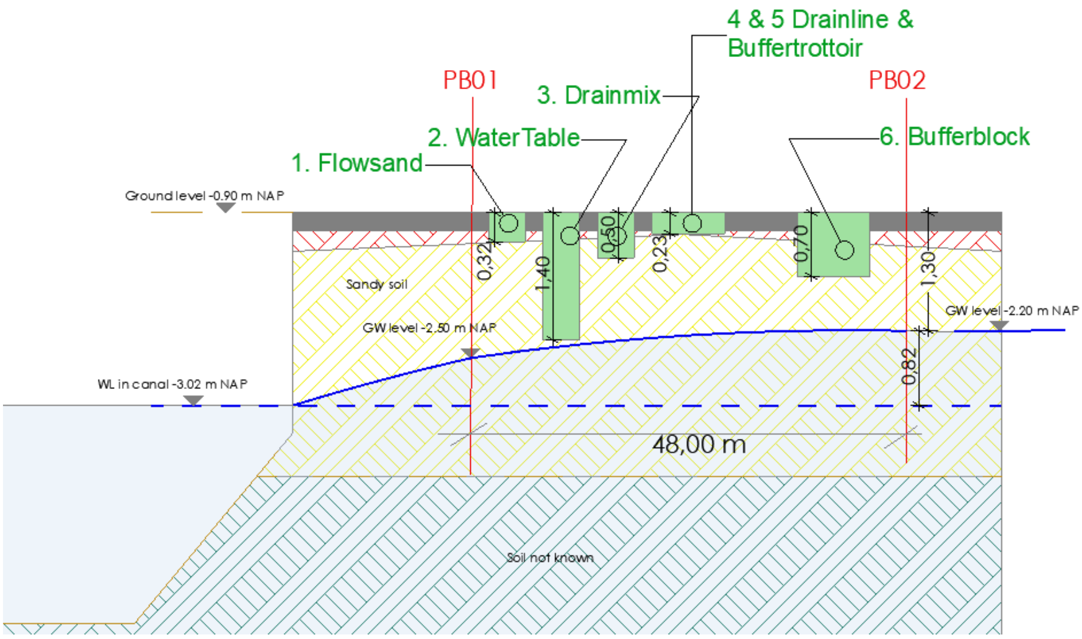

Figure 16 Cross-section C-C with the water levels in the ground and canal including the SUDS.

2.7 Systems on WaterStreet

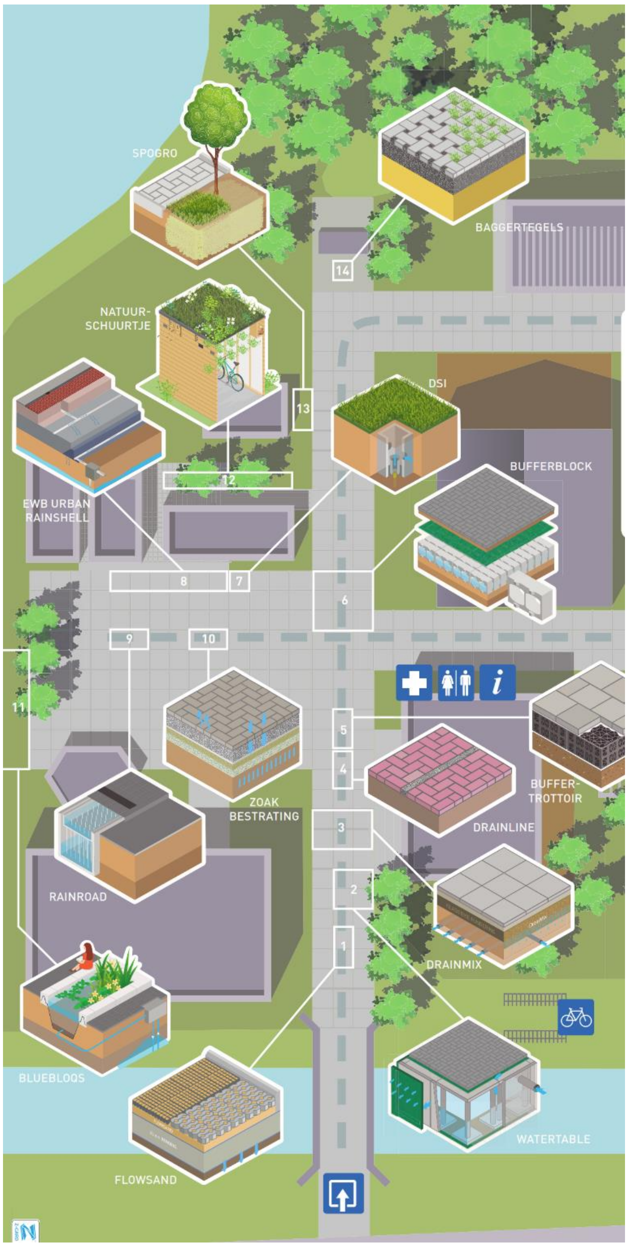

Figure 17 WaterStreet, the study area of this thesis, illustrations of the systems on the terrain provided by the Green Village.

Regarding WaterStreet's SUDS, 14 new systems are implemented. They are shown in Figure 17 with a corresponding number. The new systems are designed with new materials and methods that help respond to the stormwater in different ways (17). For example, URBANRAINSHELL [8] has considered a mix of minerals and shells that together help infiltration and pollutant removal of the stormwater. SPOGRO [13] uses recycled Rockwool from greenhouse horticulture to increase the buffering capacity of the soil. BLUEBLOQS [11] is a system that consists of a retention facility, a Biofilter treatment, and storage in the subsurface that work in combination.

Some systems work in combination and are considered as one in this thesis. For example, in the case of SUDS DRAINLINE [4], and BUFFERTROTTOIR [5]. DRAINLINE [4] is put on top of the storage created in the BUFFERTROTTOIR [5] to enhance the infiltration rate and store the water quickly. Moreover, WATERTABLE[2] and BLUEBLOQS [11] can relieve the water that has to be managed by the storm sewer, by collecting and storing part of the water and letting it infiltrate naturally. Lastly, the system called URBANRAINSHELL & DSI [7&8] is the only one to consider water quality reduction based on a shell material that is considered to reduce car pollutants.

Although all the systems are part of WaterStreet, not all of them were studied due to the way the systems respond to rainwater as well as the choice of the boundaries of this thesis. Consistency in the selection of SUDS leads to consistency in the realization of the water balance. The next systems were excluded from this thesis: BLUEBLOQS [11], NATUURSCHUURTJE [12], SPOGRO [13], and BAGGERTEGELS [14], and the motivation can be found next:

1. With regard to BLUEBLOQS [11], this system is not chosen because it collects the water from the storm sewer to reuse it in the buildings of The Green Village, while all other SUDS in this study area are connected to the groundwater.
2. NATUURSCHUURTJE [12], was not chosen because its main objective is to increase the ecological value of green roofs, which is different from the main objective to manage rainwater of the other systems.
3. Concerning SPOGRO [13], it is located outside the boundary area set for this thesis. It is located on the bare soil area, and it has no definitive boundaries itself to be able to place the sensors like the other systems.
4. Finally, BAGGERTEGELS [14], as SPOGRO is located outside the boundaries of this thesis. Moreover, it is a system that has as main objective to reuse dredging material in the construction of permeable tiles and does not provide storage of water under the tiles.

In conclusion, the systems that were analyzed further in this thesis are, FLOWSAND [1], WATERTABLE [2], DRAINMIX [3], DRAINLINE – BUFFERTROTTOIR [4&5], BUFFERBLOCK [6], URBANRAINSHELL & DSI [7&8], RAINROAD [9], and ZOAK BESTRATING [10]. The objectives of these systems, concerning this thesis, are to first manage the rainwater and reduce the surface temperature, and the pollutants loads, which are inside the boundaries of the study area and contribute to the recharge of groundwater.

2.8 Existing monitoring network

In the preliminary review for this thesis, research was performed on the existing monitoring network to validate the need for the objective of this thesis. The sensor's type and location were provided by WaterStreet[2]. The available sensors on WaterStreet are measuring rain, wind, temperature, humidity, and groundwater levels. These are relevant to this work though more data are gathered in the study area like room temperatures. In Figure 18, the overview of The Green Village is shown. With red dots are the locations of the known sensors and Table 2 shows the relevant information they provide as well as the names of the sensors. Most of the sensors monitor for around two years as seen in the table. This can be an important limitation for the use of the data so far because they cannot provide the full variability of the data they collect within this time frame. The effect of extreme droughts on the groundwater table or rainfalls might not have been captured in this data set for example.

[2] Information on the sensors were provided by Joep van der Weijden that is the data manager of the Green Village

Table 2 Existing available sensors on WaterStreet. Information on the type of measurement, units, sensor name, and duration of measuring. This table was created with information until April 2021. Since then, more sensors might have been installed not included in this table.

		sensor name	Start of measuring	measurment	units	type of measure
WEATHER STATION	location 1	dayRain	15/09/2020 - currently	day rain	mm	FLOAT
		windSpeed		wind speed	m/s	FLOAT
		outHumidity		outside relative humidity	%	FLOAT
		windSpeed10		10 minute average wind speed	m/s	FLOAT
		dewpoint		dew point	°C	FLOAT
		stormRain		storm rain	mm	FLOAT
		heatindex		heat index	°C	FLOAT
		rainRate		rain rate	mm/hour	FLOAT
		windDir		wind direction	degrees	FLOAT
		inTemp		inside temperature	°C	FLOAT
		barometer		pressure	mb	FLOAT
		outTemp		outside temperature	°C	FLOAT
		inHumidity		inside relative humidity	%	FLOAT
		windchill		wind chill	°C	FLOAT
KNMI	location 2	micro rain radar	09/11/2020 - currently	precipitation	mm	every 10 seconds
Ground water	**location 3**	LEVELLOG PB01	16/05/2019 - currently	Ground water level	m	hourly
	location 4	LEVELLOG PB02				
	location 5	LEVELLOG PB03				

Figure 18 Locations of the sensors on WaterStreet, the study area. The groundwater sensors, weather station, and KNMI station location can be seen in this figure. These sensors are the ones found until April 2021.

3. Methodology

3.1 Systems on WaterStreet hydraulic response

Based on the research questions posed in this thesis this section provides the methodologies used to answer the main question:

A. How do the systems implement in WaterStreet respond to rainfall?

By answering the sub-questions below:

1. What does the scheme of the water balance look like?
2. How are the systems designed to respond?
3. How do the surroundings of the system affect their performance?
4. What indicators describe the performance of SUDS in WaterStreet based on their response to rainfall?

Figure 19 provides the approach used to answer the above questions. First, the design of the systems was analyzed based on the design reports and schemes, provided by The Green Village and research on the internet on the individual systems. Parallel to that, the characteristics of the study area were obtained and analyzed, like the placement of the systems, soil types, terrain slope, and groundwater level observations. Both analyses combined revealed the hydraulic response of the systems and their interaction with the study area. Water balance schemes were sketched including fluxes and storages. Both fluxes and storages could be considered important indicators that reflect the hydraulic response of SUDS. Additionally, a graphic representation of the hydraulic response was made based on the design of the systems, to illustrate the condition of maximum response. Lastly, the fluxes and storages included in the water balance, considering the characteristics of the study area and the graphical representation of the hydraulic response, revealed the important indicators that reflect the response of WaterStreets SUDS to rainwater.

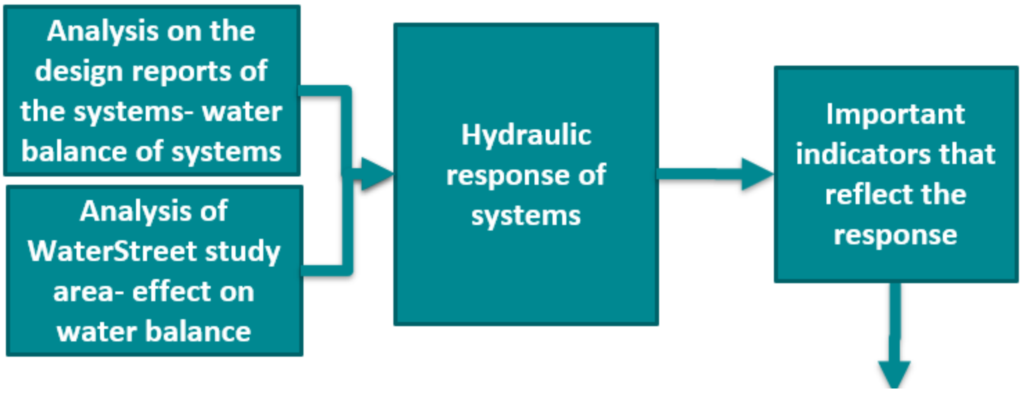

Figure 19 Approach used to get the hydraulic response of the system on WaterStreet.

3.1.1 Data collection of the SUDS on WaterStreet

The methodologies used to collect the data for the design of SUDS and the study area of WaterStreet were:

1. Connecting with developers of the SUDS through Emilie Buist, Project manager of Water Innovations working for VPdelta.
2. Research on published literature for the specific SUDS.
3. Visual inspection of the SUDS in April 2021.

Table 3 provides the list of personal communications that provided the dimensions of the SUDS.

Table 3 Sources of length, width, location, and depth for the individual systems implemented on WaterStreet.

System's name [code]	Source of information	
	Occupying area (length * width)	**Depth**
FLOWSAND [1]	The locations, length, and width of all the systems were provided by Ms. Emilie Buist, personal communication, January 28, 2021	The depth was provided by the developer of the system through Ms. Emilie Buist (personal communication, February 09, 2021)
WATERTABLE [2]		The depth was provided by the developer of the system through Ms. Emilie Buist (personal communication, May 10, 2021)
DRAINMIX [3]		The depth was provided by the developer of the system through Ms. Emilie Buist (personal communication, February 09, 2021)
DRAINLINE & BUFFERTROTTOIR [4&5]		The depth was provided by the developer of the system through Ms. Emilie Buist (personal communication, May 10, 2021)
BUFFERBLOCK		The depth was found in the research of RAAK "The sponge city" (18)
URBANRAINSHELL & DSI [7&8]		The depth was found in the research of RAAK "The sponge city" (18)
RAINROAD [9]		The depth was provided by the developer of the system through Ms. Emilie Buist (personal communication, February 09, 2021)
ZOAK BESTRATING [10]		The depth of that systems was not obtained during the time of this work.

One limitation that this part of the research faced, was that the systems are in an early stage of innovation. For some of the systems, for example, developers are still making changes to the design, like RAINROAD (Dorus Vlierboom, personal communication, 17 May 2021). Based on the scope of this thesis the systems are considered in their condition in April 2021 as they were at the visual inspection.

3.1.2 Water balance scheme

The water balance schemes include buckets, representing the storages, and arrows representing the fluxes. On the water balance, the volumes of water stored or flowing through can be seen. Water balance schemes were sketched for all the systems on WaterStreet. Combining all the systems with their fluxes and storages provided a reference water balance for the SUDS in the study area. Based on the reference water balance the equations that accompany the water balance are provided.

Important literature for the schematics of the water balance has been the study of RAAK, called "De infiltrerende stad" (18) or" The sponge city". The goal of the "drained city" was to increase the knowledge of the infiltration systems practice by testing and analyzing infiltration systems. Some of the infiltration systems analyzed in this program are implemented on WaterStreet. Validation and update of the sketched water balance per system were possible during the visual inspection in April of 2021. Then, several of the fluxes and storages were included or excluded from the individual water balance of the SUDS. One example was that the system BUFFERBLOCK is designed to promote infiltration through a permeable material, but on WaterStreet also a drain was placed to let water enter the system. That meant that the incoming water can not only flow through a permeable material but also through a drain, while that realization was not clear in the design report of that system.

3.1.2 Hydraulic response graph (HRG)

To understand the condition of maximum response of the SUDS under rainfall, the literature of van de Ven (19) was used. The dimensioning curve of infiltration trenches, one type of SUDS, was the most important tool used in the literature of van de Ven. Based on the design of the SUDS in WaterStreet a new graph was developed to represent their hydraulic response called Hydraulic Response Graph (HRG). HGRs are plotted for the SUDS on WaterStreet after the introduction of the equations and the presentation of a reference HRG.

The Hydraulic response graph was first sketched to reveal the additional value that it could provide to the understanding of the hydraulic response of SUDS. Then, based on the dimensions of the systems and assumptions on runoff coefficients and infiltration capacity of the soil and permeable layer, the graph was plotted for 5 out of 8 systems on WaterStreet. Plotting the HRG for the individual systems showed the expected response of the SUDS in WaterStreet for a given rainfall intensity and duration. Based on the findings some fluxes and storages can be considered insignificant for the hydraulic response while others were considered more important.

A simpler version of that graph was found in the literature of van de Ven, (2016) (19 p. 287), where this graph is used to design infiltration trenches and is therefore called the dimensioning curve. That methodology originates from Sweden (19). The graph provided in the literature assumed that the paved area has a runoff coefficient equal to 1 and the unpaved 0. They also assumed that the infiltration to the soil from the system is equally distributed in the walls of the infiltration trench and that the groundwater table is at all times lower than 0.5 m from the bottom of the infiltration trench. The graph illustrates the distribution of the water volumes given a certain supply of water entering the SUDS and two different infiltration rates (q_1 &q_2) which can be seen in Figure 20. If the infiltration rate is q_1 then the needed volume to be stored in a SUDS is d_1. If the infiltration is smaller, as seen with line q_2, then more volume should be provided to store the same water supply. The steeper the slope of q line, the more water infiltrates the soil and less needs to be stored in the system.

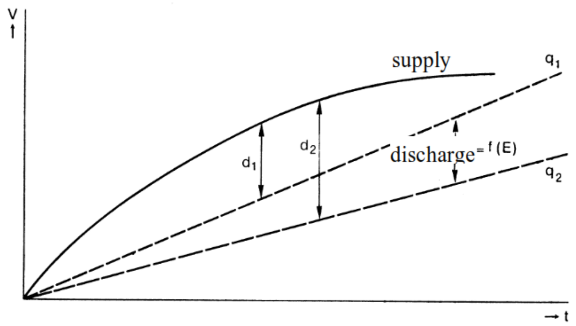

Figure 20 Dimensioning curve used in Sweden to design infiltration trenches (19 p. 287). Infiltration trenches can be considered in the category of SUDS.

The same principles were considered for the SUDS in WaterStreet with the addition of a second straight line like q_1 or q_2 representing the infiltration through the permeable layer. Two q lines were therefore included, one for the infiltration through the first layer and one through the soil. Additionally, considering that the systems implemented in WaterStreet are already designed, the storage in the SUDS is already provided, meaning that the infiltration in the soil is enhanced with the available storage. To include that graphically the line representing infiltration in the soil was shifted upwards by the maximum volume provided, to illustrate the effect of the storage on the distribution of volumes. The reason why the line representing the soil is shifted upwards is that there is buffer storage provided, the infiltration in the soil still provides the emptying rate of the water stored.

3.1.3 Systems interaction with surroundings

To conclude the effect of the study area on the hydraulic response of the systems, first, the terrain's slope, soil type under the systems, and groundwater levels were analyzed. The results of that research can be found in section "2. Study area".

First, the slopes of the paved and unpaved terrain with the addition of the SUDS on it provided the interaction of the SUDS from the top. This would mean that the incoming water to a downstream system is affected by the performance of the upstream. The groundwater levels were gathered to provide the maximum, average, and minimum observed levels. The addition of the SUDS on the cross-section considering their actual depths provided the interaction of the SUDS from the bottom. This would mean that the groundwater enters one system and then the next one downstream. Some systems are permeable from the bottom and some are not. This could change the interaction from the bottom, therefore the design of the SUDS was researched for that parameter as well.

The overall understanding of the water flows on, around and under the SUDS and the possibility of sharing the same upstream drainage area resulted in a list of SUDS that were hydraulically isolated from the top and bottom and together with their water balance scheme provided the hydraulic response of the SUDS. The knowledge of hydraulic isolation was useful for the design of the monitoring network and data interpretation.

3.2 Key Performance Indicators for SUDS

Based on the research questions posed in this thesis this section provides the methodologies used to answer the main question:

B. What would be a comprehensive set of KPIs that describe the performance of SUDS?

By answering the sub-questions below:

1. What important indicators are mentioned in the literature?
2. Who are the key stakeholders in implementing SUDS?
3. What is the key stakeholders' view on important indicators and how do they relate to indicators found in literature?
4. What is the chosen comprehensive set of KPIs that describe the performance of SUDS?

Based on the last sub-question (B4), the next question arises that is:

C. What are the chosen indicators to be monitored in WaterStreet?

To answer that last question the results of all the prior sections are used and the needed indicators to be monitored are highlighted.

Figure 21 provides the approach considered to answer the first main question of this section which is to provide a comprehensive set of KPIs for water quantity and quality. As shown in Figure 21, literature was firstly researched on what important indicators are considered to reflect the water quantity and quality performance of SUDS. This section answers the first question of the approach. Parallel to that, also the key stakeholders were defined that validated and updated the findings from the literature. This part of the research answers the 2nd and 3rd sub-question of the first main question. The key stakeholders were defined with an actor's analysis and stakeholder analysis, while their view on the important indicators was asked in interviews. The findings from the literature validated and updated with the help of key stakeholders are put in parallel, to answer the last sub-question of this section.

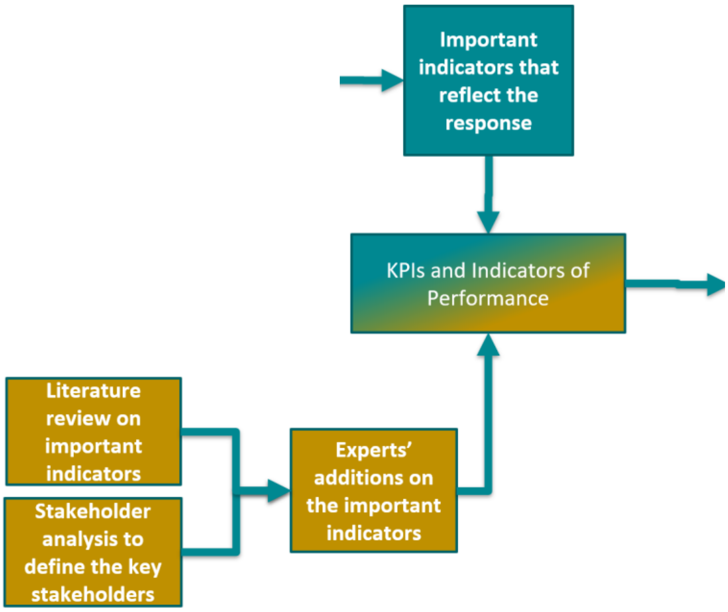

Figure 21 Approach used to conclude the needed KPIs for the performance of SUDS to manage water quality and quantity.

3.2.1 Water quantity indicators found in the literature

A focus on Dutch literature was decided based on the scope of this thesis. Research on the internet for published guidelines and reports regarding the assessment of SUDS performance in the management of water quantity was performed. The findings presented in this thesis were based on reports of STOWA, RIONED, Municipality of Amsterdam, CIRIA, and COP- community of practice waterinfiltrerende verharding. The most important findings for water quantity Performance Indicators were considered from STOWA (10) and Kennisbank of RIONED (20). RIONED is a Dutch organization for urban water management with the mission to bring people, state, and water together, be a knowledge center about water management, be included in political decisions, and bring together regional and national water management strategies (21). While STOWA is the center of expertise of the Waterboards in the Netherlands with the mission "to develop, collect, distribute and implement applied knowledge, essential for an effective and efficient water management" (22). Moreover, CIRIA is a "Construction Industry Research and Information Association, a neutral, independent and not-for-profit body" (23), that provided a useful report called, "The SUDS manual" (24).

3.2.2 Water quality indicators found in the literature

Water quality KPIs were also considered in this thesis even if the design of most systems implemented in WaterStreet did not have the objective to reduce pollutants. Only the system URBANRAINSHELL has considered that objective in the design. Although that was the case for the rest of WaterStreet's SUDS, that does not mean they do not provide a reduction of pollutant loads in the water while entering and exiting the system. The reduction of pollutants is achieved due to their absorption in the materials used to design the SUDS, even if the objective of the design was not that. This means that reduction is also achieved but not in such a controlled manner as it would be in a SUDS designed to reduce the pollutants loads. The approach chosen to determine the key performance indicators was to first identify what pollutants could be found in the study area and then consider their reduction mechanisms.

To identify the important pollutants that may be found, report number 5 published in 2020 by STOWA (25) was used, called "De Feiten over Kwaliteit van afstromend regewater, Database kwaliteit afstromend hemelwater" (Translation: "Facts about quality issues of overflowing rainwater, Database of water quality of overflowing water"). The goal of this report was to present the rainwater quality in urban areas and therefore useful in this thesis. The pollutants found in this report should be addressed to be reduced. One way to manage that is with the use of SUDS.

The priority list for the Netherlands was found in the STOWA report which already considers the EU DIRECTIVE 2000/60/EC, the observed water quality issues in the Netherlands (eutrophication, hygiene security, and groundwater quality), and the pollutants' ability to bind with particles. The priority pollutants further used for this thesis were the ones measured with an average concentration higher than the Annual Average Environmental Quality Standard (JG-MKN) and the pollutants for which no limit is set yet but were still considered in the priority list for the Netherlands. These can be found in Table 4 and referenced in the STOWA (25).

Table 4 Measured concentration of priority pollutants in the Netherlands compared with the annual average environmental standard. The standard concentration suggests no harmful effects on the environment. Based on those standards all pollutants except Anthracene are considered on the priority list of this thesis because they are measured with higher concentrations.

Priority list for the Netherlands	**Average measured concentration in overflowing water from streets and roofs in residential areas**	**Annual Average Environmental Quality Standard (JG-MKN)**
Cadmium (Cd)	0.18 μg/L	0.08-0.25 μg/L
Copper (Cu)	21 μg/L	2.4 μg/L
Mercury (Hg)	0.026 μg/L	0.00007 μg/L
Lead (Pb)	21 μg/L	1.2 μg/L
Nickel (Ni)	4.1 μg/L	4 μg/L
Zink (Zn)	144 μg/L	7.8 μg/L
Anthracene	0.0076 μg/L	0.1 μg/L
Benzo(a)pyrene	0.048 μg/L	0.00017 μg/L
Mineral oils	102 μg/L	-
Chemical Oxygen Demand (COD)	36 mg O/L	-
Total phosphorus (TP)	0.30 mg P/L	-
N- Kjeldahl (Organic N + ammonium)	2.1 mg N/L	-

Nitrate (NO3)	1.5 mg N/L	-
Total Suspended Solids (TSS)	38 mg/L	-
E. coli	2.4 *10^4 /100ml	-

The list above is a first indication of the harmful priority pollutants that could be encountered in the study area. Not all of them could be reduced when in contact with a SUDS. The research of Dierkes et al. (12) was used to limit that list considering that parameter.

The research of Dierkes et al. (12) provided the key pollutants used as a guideline for the water quality performance assessment of SUDS in 6 countries, the UK, Germany, The Netherlands, Australia, New Zeeland, and Canada. In that report, the reduction mechanism and the conditions that affect those mechanisms are also mentioned, like absorption and the change of pH, respectively. Additionally, the research of Li et al. (26) and Huber et al. (27) was used to define the conditions surrounding the systems that affect the reduction mechanisms. Lastly to define the absorption capacity of several pollutants on TSS the research of Galfi (28) was used for the biological pollutants, the research of Nasrabadi et al. (29) for the nutrient pollution, the research of Orrono et al. (30) Yao et al. (31) for heavy metal pollutants, the research of Glaser et al. (32) for PAHs, and Napier et al. (33) for the TPHs.

3.2.3 Key stakeholders

To include the key stakeholders' view, on the indicators list defined in the literature, first, the key stakeholders were defined to be asked. To conclude the key stakeholders the next steps were taken, based on the guidelines for the Actor and Network analysis course of TU Delft (34).

1. Conclude the list of actors by creating an actor's map.
   - Problem identification
   - Inventory of the actors involved.
   - Indicate the interdependencies of the actors.
   - Draft actor's map.
   - Validating the draft map in meetings and interviews.
   - Concluding actor's map.
2. Conclude on the power and interest of the list of actors from the map.
   - Send a questionnaire to score the actors.
   - Ask additionally if any other actors are missing from the list.
   - Make a power interest grid of the actors included in the map.
3. Select the most powerful and interested as key stakeholders based on the power interest grid.

1. Conclude the list of actors by creating an actor's map

The problem identification follows this research objective which is to define the Key Performance Indicators (KPIs) to be monitored on WaterStreet. Although the main problem of the actor's map was to define the actors that would benefit and need the monitoring data in order to ask them for additional indicators.

First, based on the literature of van de Ven (19) and attending research community meetings called "climate cafe" (35), a first draft of the actors and their interdependencies was created. A list of the climate cafe meetings followed can be seen below in Table 5.

Table 5 Attended Climate Cafe meetings. In these meetings, several topics of focus are discussed. Information on the actors involved in implementing Urban drainage systems was drawn from these meetings and the draft map could be made.

Date of climate cafe meeting	The focus of the meeting	Presenters
2/04/2021	Water quality monitoring Climate scan introduction	Sydney Stax Floris Boogaard
9/04/2021	Living labs	Emilie Buist Piet Zijlstra
16/04/2021	Biodiversity	Merlijn Andriesse
7/05/2021	Deltares Klimaatbestendige Stad Toolbox	Marco Hoogvliet
4/06/2021	Infiltration Transport (IT) sewers monitoring	Erik Laurenzen

One limitation chosen for the actor's map was to not involve more than 3 levels (34) of actors. That meant that actors that are connected to the defined problem owner in more than 3 steps were not included in this map. This was done to avoid a chaotic map that could provide more complexity than problem-solving. The maximum level of the problem was defined by the boundaries of this thesis to work in the Dutch environment that constrained the map to 3 steps.

To validate and make additions to the draft actors map the meetings shown in Table 6, were performed. The participants of the meetings were relevant to the topic of SUDS, as suggested by the guideline used for this stakeholder analysis (34). The requirements for the group participants were their availability and their involvement in the field of sustainable urban drainage systems in the Netherlands. In that context, the main groups that were targeted in this research were developers of sustainable urban drainage systems, municipality employees, academics, and students of urban water management-related studies. After the validation, the actors included in the questionnaire were concluded.

Table 6 Interviews conducted to validate the Actor's map with the importance of the chosen interviewee and their profession. Different professions are represented in this table.

Date	Interviewee	Profession	Importance
21/5/2021	Lennart Droppert	Student and municipality employee	Municipality employee
3/6/2021	Jip Gravenberch	Master Student of Water Management	The thesis work on improving the monitoring of vegetated permeable pavements
3/6/2021	Vlierboom DAJ (Dorus)	Master Student of Water Management and Movares internship	Working on upgrading RAINROAD, one of the systems on WaterStreet
3/6/2021	Abe Feenstra	Master Student of Water Management and Field Factors internship	Field Factors is the developer of BLUEBLOQS implemented on WaterStreet
11/6/2021	Participants of climate cafe meeting general (recorded)	Academics, municipality employees, consultancy employees, and students	
	Floris Boogaard	Academic	Active involvement in field testing SUDS
	Sidney Stax	Municipality employee	Biologist and environmental city manager
	Frits Ogg	Municipality employee	educated citizen
	Antal Zuurman	Senior consultant urban water & climate adaptation	Working at RIONED

6/7/2021	Emilie Buist	Project manager Water Innovations working for VPdelta	Managing the water innovations implemented on WaterStreet

2. Conclude on the power and interest of the list of actors

After drawing the final actors' map a questionnaire about the power and interest of the actors was conducted in the Google Forms interface. This method provided easy access and quick response to the questions for the participants of the questionnaire. The questionnaire asked the participants to score the 11 concluded actors from the actor's map from 1 to 10, based on how powerful or interested they are in implementing sustainable urban drainage systems, with 1 being low power or interest and 10 being high power or interest. Also, two open questions were posed asking the participants if they know any other important actors missing from the list. That question provided extra feedback on the actor's map created in the previous steps. An overview of the questionnaire can be seen in Appendix C- Questionnaire's participants and preview. The feedback from the power and interest questionnaire was gathered to make the power interest grid and conclude on the most interested and powerful stakeholders. The power interest grid was made with the average scores given to the actors. Additionally, box plots were made to see the variety of responses per actor and power or interest.

Representatives of the most interested and powerful stakeholders resulting from the methodology were interviewed to validate the list of KPIs from the literature. The choice to include the view of the key stakeholders that were the most interested and powerful limited the research to them but was essential to keep the duration of this thesis within the needed time.

3.2.4 Key stakeholders' view on the findings from the literature

To increase the value of the list concluded from the literature, interviews were conducted with representatives of key stakeholders, concluded from the stakeholder analysis. The list of interviewees can be seen in Table 7 along with the reasoning for including them in this research.

Table 7 Interviews conducted with stakeholders about their view on the performance of SUDS. Additionally, information on the significance of the interviewee and the date of the interview can be seen.

Profession of interviewee	Name of interviewee	Significance of interviewee	Date of interview
Internship at Amsterdam Rainproof - City of Amsterdam	Charlie Jurjus	helping in the creating of the tool for measuring the key indicators for the "Hemelwaterverordening Amsterdam", the regional regulation about water management of private terrains	18/11/2021
Project manager Water Innovations bij VPdelta, Innovation & Impact Centre, TU Delft	Emilie Buist	Representing the study area's systems based on her experience and contact with the developers	26/11/2021
TU Delft master student	Brahmanand Goerdat	Doing his thesis on "Mainstreaming process of SUDS in different sized municipalities"	3/12/2021
An employee of Nijmegen municipality	Sidney Stax	City Manager Water & Sewerage	16/12/2021

3.3 Selection of sensors

Based on the research questions posed in this thesis this section provides the methodologies used to answer the main questions:

D. What sensors are suggested for the collection of the data that reflect the indicators?

By answering the sub-questions below:

1. What should be the criteria for the quality of data?
2. What data are already monitored in WaterStreet?
3. What are the suggested sensors?

To select the most appropriate sensors, the data provided should help calculate the indicators concluded from both the hydraulic response and the validated literature. That list can be found in Section 4.3 Indicators to be monitored on WaterStreet.

Hard criteria or requirements for the sensors, that will collect that data, were set before the selection. The division of the criteria into hard and soft requirements was necessary due to the time limitations of this thesis. Additionally, the existing sensors were considered. These are provided in the section, 2.8 Existing monitoring network, and assessed based on the same hard criteria. The choice of the sensors was based on literature findings due to working remotely. Figure 22 shows the approach explained above in a schematic view.

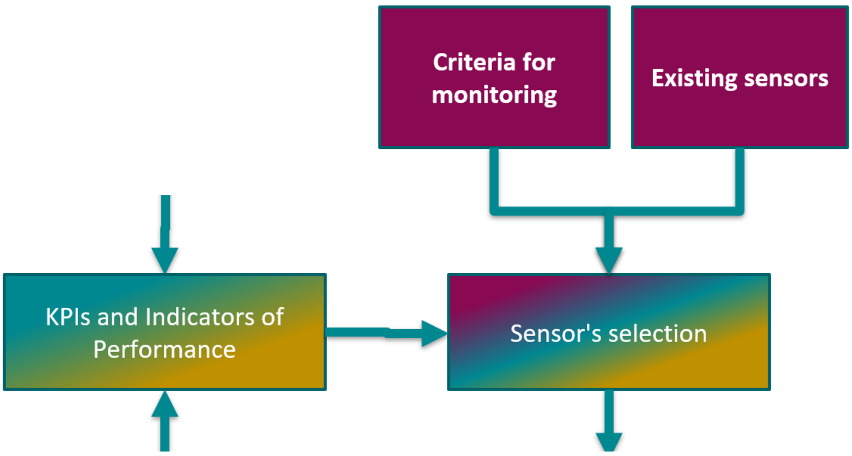

Figure 22 Approach used to select the sensors needed. Criteria are set after defining the data that should be gathered.

3.3.1 Criteria for monitoring

Criteria

To set the list of hard and soft requirements or criteria for the sensors, research on the Google search engine was performed [3]. That list was validated with the help of the

[3] The research used the terms “criteria for sensors”, “selection criteria for sensors”, “criteria for sensors for suds” and “choosing the right sensor”.

supervisor of this thesis[4]. Both the above methodologies provided a list of requirements that then were divided into categories of hard and soft.

First to make the criteria clearer a definition of them was needed.

- **Periodicity** is the time difference between two measurements of the sensor. This time difference in the measurements should be smaller than the temporal scale of the parameter, else the periodicity of the response will not be captured. Therefore, to define the needed periodicity the choice of temporal scale of the indicators was important.
- **The range** is the difference between the maximum and minimum values of the measurements. The sensor should be able to capture the smallest and biggest value that could be encountered based on historical data and other research in literature.
- **Precision** is the random error of the measurements provided by a sensor. The precision of the sensor should be smaller than the minimum difference of measurement that should be able to be distinguished with the sensor.
- **Accuracy** is the systematic error of the measurements provided by a sensor and can be calibrated.
- **Available space for the sensor** is the physical area that the sensor should have beforehand to be placed.
- Regarding the **distance between the sensor and the system,** the sensors will not be put in direct contact with the system like the rain gauge.
- **Cost criterium** is the cost of the sensor without the possible equipment needed to support it.
- Regarding the **availability of power** in the study area for the sensor, the WaterStreet study area provides many power outages in a dense grid.
- Regarding the **data collection, display and distribution,** Green Village has a platform provided by Grafana Labs (36) that provides the data collected in all the areas in real-time. Part of the Green Village is WaterStreet and on this platform, for example, the rainfall data are already provided. According to Joep van der Weijden (personal communication, July 23, 2021), the data manager for WaterStreet, it is possible to include more data to be displayed on this platform like the measurements of the SUDS on WaterStreet.
- About **important environmental aspects** like mist or high temperatures, for example, a maintenance schedule should be made to regularly check the condition of the sensors.

From the criteria above the most important ones were chosen to be Periodicity, Precision, and Range, and are called hard requirements. These were the criteria to guide the selection of the sensors. The rest or soft, criteria were considered as additional data provided for the monitoring network. The reasoning behind the inclusion of the criteria in the hard or soft category is indicated in Table 8. The selection of sensors shown in this work

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[4] To validate that list and to select the most appropriate for this thesis, the knowledge of one of my thesis supervisors, Dr. Katerina Varveri, was used (personal communication, September 28th, 2021). Her additions were valuable because she is experienced with doing experiments on permeable pavements.

was based on the characteristics of the study area so this does not mean that the same criteria should always be considered most important in different study areas.

Table 8 Division of hard and soft criteria with reasoning.

Criterium	Hard	Soft	Reasoning
Periodicity	√		The chosen sensor should be able to catch the periodicity of the hydraulic response, so it is essential to choose based on that criterium.
Range	√		The chosen sensor should be able to catch the expected values of the data collected. If not, then part of the data set will not be gathered.
Precision	√		Given the definition of the criterium, precision is the random error that cannot easily be discarded from the data set, so it is essential to use a sensor that provides high precision information.
Accuracy		√	Given the definition of Accuracy provided in this thesis, accuracy is the systematic error and hence can more easily be managed in the data set provided, given that calibration is done.
Available space for the sensor		√	The study area of WaterStreet provides the space for the sensors to be put since it is a living lab with the purpose to present and learn how new SUDS perform.
distance between the sensor and the system		√	The maximum distance in the study area is around 50m. This distance is not significant for the sensors that measure from a distance of the system. Other sensors will be put on the system or next to it. These sensors will provide data for only one of the systems.
Cost		√	The cost will be considered in the way that the existing sensors will be analyzed first and have a priority for selection if they comply with the hard requirements. Overall, the cost of the sensors is important but not as important as collecting the needed information to achieve the objective of the living lab to help accelerate SUDS to a bigger scale.
Power supply		√	The study area of WaterStreet provides an abundance of power supply sockets for the sensors or other equipment.
data collection, display, and distribution		√	The study area of WaterStreet already has a data platform that could be expanded to include the data provided by the new monitoring network (Joep van der Weijden (personal communication, July 23, 2021),
Environmental aspects		√	For the application of this monitoring network, it will be essential to conclude a maintenance scheme. Given the information provided in this thesis the needed task of the maintenance will be easier decided.

<u>Limiting values for criteria</u>

Setting limiting values for the hard criteria of the sensors required nonlinear research. A first limit was defined from literature, then based on the limitations of the sensors in the market the value could change. For example, the least expected rainfall on the terrain is zero rainfall depth, but monitoring rainfall depth in the order smaller than one millimeter with a tipping bucket for example provides errors and therefore a higher, lower limit for the range of rainfall is reconsidered based on the limitations of the sensor. This methodology was used for all the hard criteria but only the end results can be seen in this thesis not to consistency and to reduce the complexity of the results.

For the periodicity criterium of monitoring as well as the number of sensors per indicator, research on the temporal and spatial scales of the indicators was performed. First, the research of Hellmers and Fröhle (2017) (6) was used as a guideline. In their research, they integrated local scale drainage measures (1-100m^2) in meso scale (1-10km^2) catchment modelling, and they provided a summarising list of indicators and their spatial and temporal scales. Then the boundaries of the study area were considered to limit the spatial scale where needed. This meant that, if the scale from the literature of one indicator was greater than the provided area in this study area, then the minimum of the two would be considered. One example is groundwater storage. The spatial variability of groundwater recharge is considered in the reviewed literature to be in the order of km^2 while the study area is around 1000 m^2. This means that for the groundwater spatial scale the limit would the second. The chosen spatial and temporal scales based on the above methodology are provided in Table 9, per indicator.

Table 9 Water quantity indicators and relevant spatial and temporal scales considered for the study area. The spatial scale was limited by the actual boundaries of the study area and systems while a range of temporal scales is given based on literature. These scales are important to consider the number of sensors per indicator and the periodicity of the measurements for the monitoring network.

Indicators	spatial scale	temporal scale
Rainfall depth (i)	1000 m2	min-hour
Overflowing surface water to the system from the upstream drainage area (O_1) & Overflowing surface water from the system to downstream ($O_{2.1}$)	4m2	sec-min
Infiltration rate of the permeable first layer of the system or through the drain ($i_{2.1}$)	4m2	sec-min
Water in the SUDS ($S_{2.2}$)	4m2	min-hour
Infiltration rate in the soil ($i_{2.2}$)	4m2	min-hour
Groundwater levels (s3)	1000m2	days-weeks

Table 9 also highlights the indicators that need to be represented with one observation per system on the terrain or if one observation can be used for the whole study area.

For the range, criterium literature was reasserted to provide the maximum and minimum values that could be measured. For the precision criterium, the limitations were considered based on the time scale of the indicators provided by that data after asking "what is the minimum difference that is needed to be distinguished with the sensor?".

3.3.2 Sensors

To find the sensors that will collect the data needed, studies of monitoring SUDS and the guidelines for monitoring from CIRIA (23) were used. The objective was to be able to collect the data of the needed quality based on the limits of the criteria set. So, the data quality reported in the literature was the target for the review. Due to the time limitation of this study, there was not extensive research on all the available sensors in the market per data needed and no actual implementation of the sensors to define the feasibility of the suggestions.

Where the connection between the data provided by the monitoring network and the needed indicators was not direct, equations were needed. A review of Verruijt (1970) (16) was used to provide the groundwater levels between two observations made in the field. The rational method to provide the overflowing water from the upstream drainage area was also used. And lastly, water mass balance was used to provide the indicators of infiltration in the system and the soil based on the observations of water level.

4. Results

4.1 Systems on WaterStreet hydraulic response

4.1.1 Hydraulic response of reference SUDS

4.1.1.1 Water balance scheme

For the water balance scheme, the study area can be divided into four sections, the upstream drainage area, the SUDS area, the downstream area, and the ground under the SUDS. In the SUDS area, first, the permeable upper layer can be found, and then the storage area underneath it. The sections are schematized in Figure 23. Every section of the water balance is constrained by an equation connecting the inflows, outflows, and storages. These can be found in Table 10.

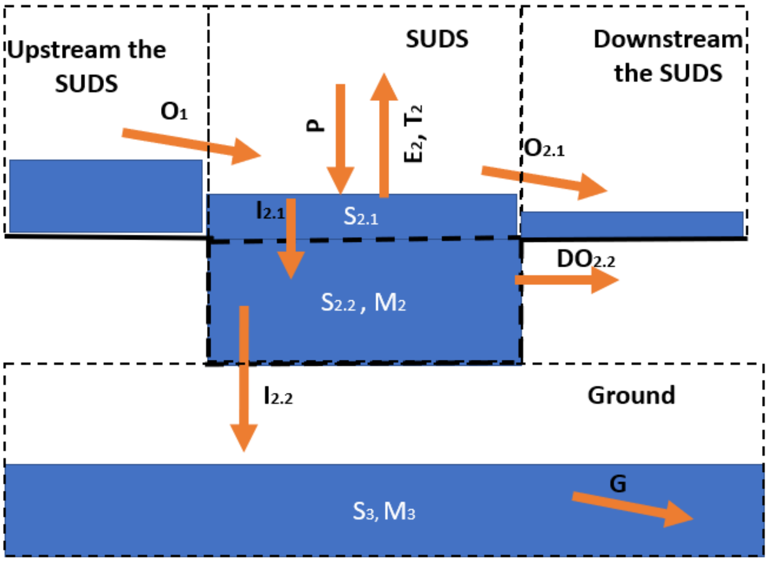
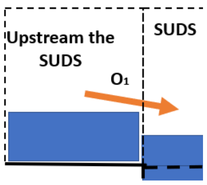
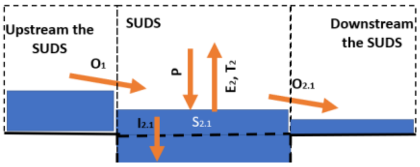
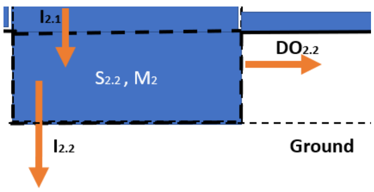
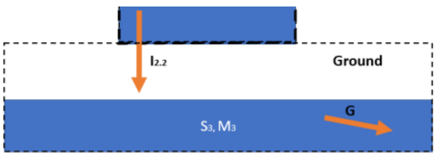


Figure 23 Water Balance scheme. P: Precipitation, E: Evaporation, T: Transpiration, S: Storage of water, O: Surface Overflow, M: Soil Moisture, DO: Drain overflow, G: groundwater flow. The upstream area is indicated with the number 1. In the SUDS section, the first part indicates the permeable first layer of the system and the second indicates the area in the SUDS. $O_{2.1}$ is the surface overflow from the system to the downstream section, while $DO_{2.2}$ is the drain overflow from the system. $I_{2.1}$ is the infiltration through the permeable material to the system and $I_{2.2}$ is the infiltration through the subsoil to the groundwater. $S_{2.1}$ is the storage in and on the system's tiles while $S_{2.2}$ is the storage in the system. The last section is the ground area where the groundwater table can be found and the storage S_3 is measured in units of ground water table rise.

Table 10 Water balance sections with equation per section and narration.

Section	Water balance Scheme	Water balance equation	Water balance equation explained
Upstream drainage area		$\boldsymbol{O_1} = C_{upstream} * i * A_{upstream}$	The volume of water that precipitates on the upstream terrain ($i * A_{upstream}$) partly overflows from the SUDS area (O_1). $C_{upstream}$: is the runoff coefficient of the upstream area. i: is the rainfall depth

SUDS system sections		$P + \mathbf{O_1} = E_2 + T_2 + \mathbf{I_{2.1}} + O_{2.1} + dS_{2.1}/dt$	The volume of water that precipitates on the SUDS ($P = i * A_{occupying}$) and overflows from upstream (O_1), partly enters the system ($I_{2.1}$), partly evaporates (E_2), and transpires (T_2) or ponds on the tile ($S_{2.1}$) and partly overflows downstream ($O_{2.1}$).
		$\mathbf{I_{2.1}} = \mathbf{I_{2.2}} + DO_{2.2} + dS_{2.2}/dt + dM_2/dt$	The volume of water that enters the system ($I_{2.1}$), partly overflows through a drain ($DO_{2.2}$) or gets infiltrated in the soil under the system ($I_{2.2}$) and part is stored in the system ($S_{2.1}$) or stored as moisture (M_2).
The ground under the system section		$\mathbf{I_{2.2}} = G + dS_3/dt + dM_3/dt$	The volume of water that enters the soil under the system ($I_{2.2}$) partly flows to the canal (G) and partly gets stored in the aquifer (S_3) or stored as soil moisture (M_3).

4.1.1.2 Hydraulic response graph

The water balance in Figure 23 can provide a static graphical representation of the fluxes and storages within their boundaries but it fails to reflect the dimension of time in the response of the system. For that reason, a **hydraulic response graph (HRG)** is developed, that can be seen in Figure 24.

The hydraulic response graph (RHG) includes one curve for the supplied volume of water (curve V_w) provided by the Depth Duration Frequency curve (DDF) of rainfalls with a specific return period, one line representing the infiltration in the soil (line $I_{2.2}$) that is shifted vertically upwards and equal to the volume that can be stored ($S_{2.2}$max) in the SUDS (line B), and one last line representing the volume of water that can infiltrate through the first layer (line $I_{2.1}$). Under and between the lines the volumes are distributed based on the incoming water, the available storage in the SUDS, and the slopes of the lines $I_{2.2}$, B, and $I_{2.1}$. The water that cannot infiltrate through the permeable material fast enough has to overflow downstream ($O_{2.1}$) and if the storage in the SUDS is full then overflow through the drain ($DO_{2.2}$) is activated if the design of the SUDS includes it.

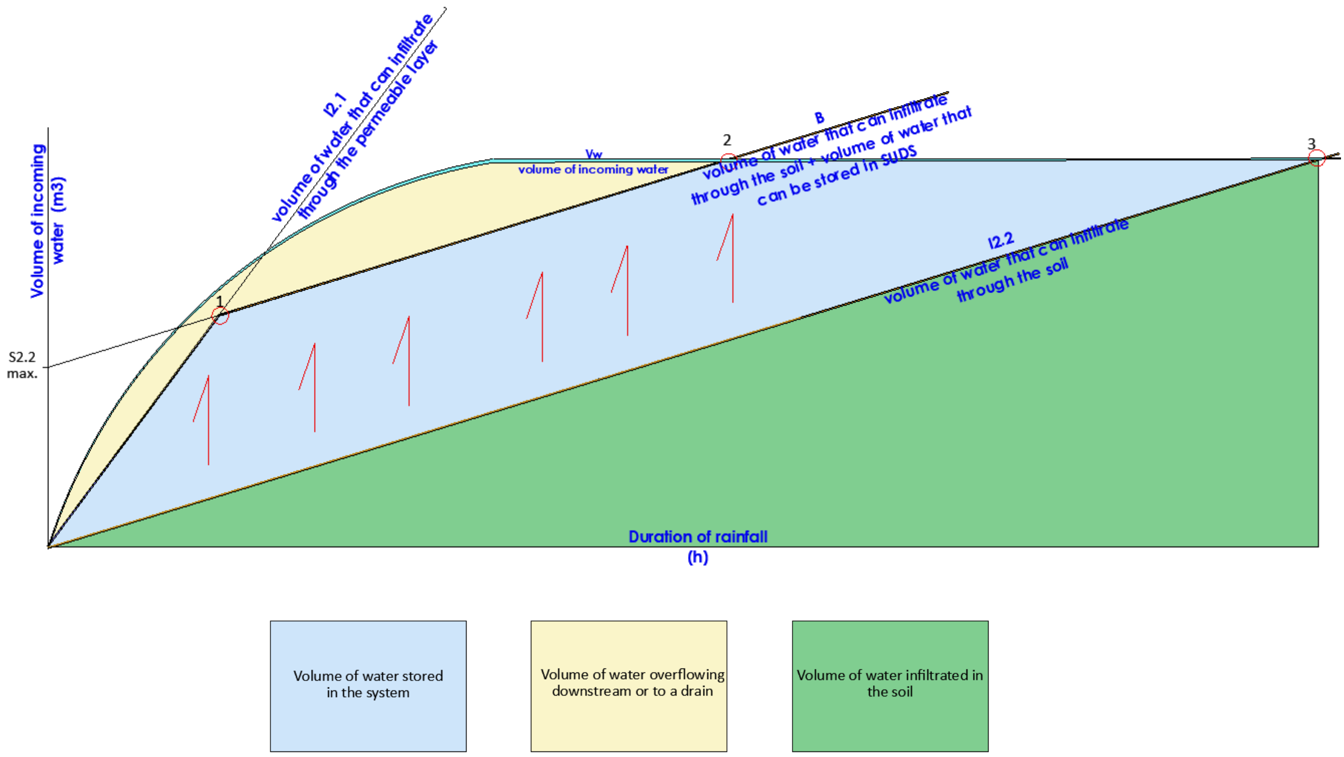


Figure 24 SUDS hydraulic response graph. Curve V_w reflects the incoming volume of water while line $I_{2.2}$ is the infiltrating water in the soil, line B is the infiltrating water in the soil plus the water stored in the system, and line $I_{2.1}$ is the infiltrating water through the 1st permeable material.

The hydraulic response of the systems under a certain return period of rainfall and for an event of a certain duration is reflected by this graph. If the subsoil has a lower infiltration rate distributed on the infiltration surface ($i_{2.2}$), then the slope of lines $I_{2.2}$ and B will be smaller leading to less water directed to the soil (green), and more water stored in the system (blue). If the infiltration rate of the 1st layer of the system distributed on the surface ($i_{2.1}$) is reduced, due to clogging for example, then the slope of line $I_{2.1}$ will decrease leading to more volume of overflowing water. If the incoming rainfall has a smaller return period (i is smaller), then the light blue line will be lower, and less volume of overflow will occur. Lastly, if the provided storage for water is bigger, then line B should be shifted more upwards leading to less overflow.

Point 1 represents the condition that the provided storage is full and the overflowing water downstream the system is not only due to the maximum infiltration through the permeable layer but also due to the provided storage in the SUDS being filled. Point 2 represents the condition of rainfall that has a big duration and gives the system the time to empty quicker than the incoming volume of water, so overflow stops. Lastly, point 3, indicates the condition that the duration of rainfall is even bigger giving the soil the time to drain the water without the need for the SUDS.

Collecting the indicators of rainfall depth (i), and infiltration rate distributed on the 1st layer ($i_{2.1}$) and in the soil ($i_{2.2}$), the water level in the system ($s_{2.2}$), along with the overflow can help plot the HRG more accurately.

4.1.2 Hydraulic response of SUDS on WaterStreet

4.1.2.1 Water balance scheme

Based on how the systems on WaterStreet are designed to respond to rainwater and the hydraulic parameters of the water balance, several parameters were excluded from the water balance of the individual system. The fluxes and storages included in the water balance shown in Figure 23 are found at least once in the design of the systems on WaterStreet. A water balance scheme, for every system, is included in this research and can be viewed per system, in Appendix A- Systems design and water balance. Table 11 summarizes the results of this research.

Table 11 Summary of dimensions and drainage and occupying surfaces per system on WaterStreet. Additionally, for every SUDS the fluxes and storages of their water balance are listed. In case the drainage area varies based on the performance of another system a question mark indicates the fact. If a piece of information was not found during the time of this thesis, then it is indicated.

#	**Name of system**	**$A_{Occupying}$ (m2)**	**Depth (m)**	**$A_{upstream}$ (m2)**	**$A_{upstream}$/ $A_{Occupying}$**	**Precipitation (P)**	**Storage on tile ($S_{2.1}$)**	**Storage in tiles ($S_{2.1}$)**	**Overflow ($O_{2.1}$)**	**Evaporation (E_2)**	**Inflow through the drain ($I_{2.1}$)**	**Inflow through the permeable layer in the system ($I_{2.1}$)**	**Soil moisture in SUDS (M_2)**	**Storage in SUDS ($S_{2.2}$)**	**Pipe Outflow ($DO_{2.2}$)**	**Infiltration in soil ($I_{2.2}$)**	**Soil moisture in the soil (M_3)**	**Storage in the aquifer (S_3)**
1	FLOWSAND	8	0.32	8	1	√	√		√	√		√	√	√		√	√	√
2	WATERTABLE	16	1.40	252	15.75	√	√		√		√			√		√	√	√
3	DRAINMIX	24	0.50	?	-	√	√		√			√	√	√	√	√	√	√
4& 5	DRAINLINE & BUFFERTROTTOIR	16	0.23	16	1	√	√		√					√		√	√	√
6	BUFFERBLOCK	36	0.70	0	0	√	√		√		√	√		√		√	√	√
7 & 8	URBANRAINSHELL & DSI	24	0.85	64+?	2.66	√	√		√			√	√	√	√			√
9	RAINROAD	8	1.18	8	1	√	√	√	√	√		√		√		√	√	√
10	ZOAK BESTRATING	8	Not found	8	1	√	√	√	√	√		√	√	√		√	√	√

Table 11 shows that all systems collect the precipitated water and store it in either an open container or in a soil matrix material and drain the water to the aquifer, either through the soil or directly to the deeper aquifer, like the system URBANRAINSHELL & DSI. Only the system RAINROAD and ZOAK BESTRATING include storage in the permeable tiles and according to Dorus Vlierboom (personal communication, 17 May 2021) who works to upgrade the first system, RAINROAD failed to do so. Only two systems include an overflow drain in the SUDS. This means that for most systems infiltration in the soil is considered the main way that the system can empty. One additional observation was that WATERTABLE lets water enter the storage area only through a drain, BUFFERBLOCK through both, a permeable layer and a drain while all the other systems let water enter only through the first permeable layer.

4.1.2.2 Hydraulic Response Graph (HRG) of SUDS in WaterStreet

Table 12 explains the parameters and equations used to create the HRG. The parameters indicated in bold can be defined based on the dimensions of the system and the parameters in red are suggested to be monitored. Table 12 also shows the relationship between the volume of water that infiltrates in the SUDS or the soil, and the water depth along the infiltration surface. Additionally, it shows the connection between the precipitated water depth and the volume of water in the system. Assumptions were appropriate for the infiltration rate in the soil and permeable material as well as runoff coefficients and porosity of the SUDS that had soil mixture in them. These are also considered limiting factors of this research further experimentation to reduce the assumptions are suggested at the end of this thesis.

Table 12 Equations used to plot the lines that make the Hydraulic response Graph.

Parameters of the graph		Equation	Parameters of the equation
$i(t)$	Estimated rainfall depth (m/h)	$i(t) = \exp[2.559 + 0.318 \cdot \ln(t)] \cdot \{1+(0.312 - 0.025 \cdot \ln(t)) \cdot [1-\{-\ln(1-T^{-1})\}^{-0.163}]/(-0.163)\}$ (37)	t: duration of rainfall (h) T: return period of rainfall (here T=100 years)
V_w(m3)	Volume of incoming water	$V_w = [O_1 + P] \cdot t$	$O1 = C_{upstream} \cdot i(t) \cdot A_{upstream}$ $P = i(t) \cdot \mathbf{A_{occupying}}$ t: duration of rainfall (h)
$I_{2.1}$(m3)	The volume of water that infiltrates through the 1st layer	$I_{2.1} = \mathbf{A_{occupying}} \cdot i_{2.1} \cdot t$	$A_{occupying}$: occupying area of the SUDS where infiltration of the permeable 1st layer can occur (m2) $i_{2.1}$: infiltration rate distributed on the first layer (m/h) t: duration of rainfall (h)
$S_{2.2}$max (m3)	The maximum volume of water that can be stored in the system	$S_{2.2}max = \mathbf{V} \cdot \varepsilon$	V: is the total volume of the system (V= $\mathbf{A_{occupying}}$ * **depth** of system) ε: 0.3 for soil mixture in the system or 1 for open storage
B(m3)	The volume of water that infiltrates the soil plus the maximum volume that can be stored in the system	$B = S_{2.2}max + I_{2.2}$	
$I_{2.2}$(m3)	The volume of water that infiltrates the soil	$I_{2.2} = \mathbf{A_{walls}} \cdot i_{2.2} \cdot t$	$\mathbf{A_{walls}}$: walls of the SUDS where infiltration to the soil occurs (m2) $i_{2.2}$: infiltration rate distributed on the walls of the SUDS (m/h) t: duration of rainfall (h)

The next assumptions are made to plot the HRG of the systems on WaterStreet:

1. To plot the incoming volume of water (V_w) the DDF curve of rainfalls with a return period T=100 years is used (5). The choice for the return period of the design rainfall is supported by the water quantity standards provided by the CIRIA report (5) and provides more intense rainfalls than the once in 10 years rainfall suggested in the report of STOWA, the Dutch Foundation for Applied Water Research (10).
2. The runoff coefficient of the drainage areas upstream to the SUDS is assumed to be 1, given that the drainage areas are only non-permeable pavement based on the study area characteristics. This would provide a small overestimation of the overflow and infiltration in the SUDS but not a significant one, given that the coefficient of the pavements is often assumed around 0.9.
3. It is also assumed that there are no losses from the rainwater that falls on the SUDS. This means that all the rainfall falling on the occupying area is provided for the calculation of the incoming water to the SUDS. A part of that can then be infiltrated and stored or overflowed downstream. This provides an

overestimation of the incoming water that should be addressed further but is not in the scope of this thesis.

4. Infiltration rate distributed on and flowing through the soil under the WaterStreet of maximum $i_{2.2}$= 5.5*10^{-5} m/sec for a sandy and moderate fine soil (16) is assumed.
5. Infiltration rate distributed on and flowing through the permeable material $i_{2.1}$= 200mm/hour. This is around the average of the infiltrations found in the research of Boogaard et al. (38) for permeable pavements in the Netherlands.
6. The surface of infiltration to the soil (A_{walls}) is assumed to be 25% of the walls around and under the SUDS. This can also be considered as a safety measure included to account for the condition of the system being clogged. A safety factor for the dimension of the SUDS is also used in the literature of van de Ven (19).
7. When soil mixture is present in the SUDS then a porosity of ε=0.3 is assumed while when there is no soil ε=1.
8. In the case of the SUDS WATERTABLE, which lets the water enter through a drain and not a permeable material, line $I_{2.2}$ is not plotted because no infiltration surface is found. This means that all the incoming water enters the system without being delayed by the permeable material.
9. It is assumed that the groundwater level is not closer than 0.50 m from the bottom of the SUDS. This initial assumption was taken from the dimensioning curve provided by the literature. This is found not to be true at all times in the study area and should be addressed further.

The HRG was plotted for 5 out of 8 SUDS of WaterStreet. The HRG of the systems, DRAINMIX [2] and RAINSHELL & DSI [7&8] were not plotted because the upstream drainage area connected to those systems is affected by the performance of other systems on the terrain. Additionally, the HRG of the system ZOAK BESTRATING [10] was also not plotted because the depth of the system was not found during this thesis as specified in Table 3. The depth of the system affects both the surface of infiltration in the soil and the available volume that can be stored in the SUDS. Both are important parameters of the equations to plot the HRG. Based on the equations given in Table 12, the HRG of SUDS FLOWSAND [1], DRAINLINE& BUFFERTROTTOIR [4&5], WATERTABLE [2], BUFFERBLOCK [6], and RAINROAD [10] were plotted and seen in Figure 25.

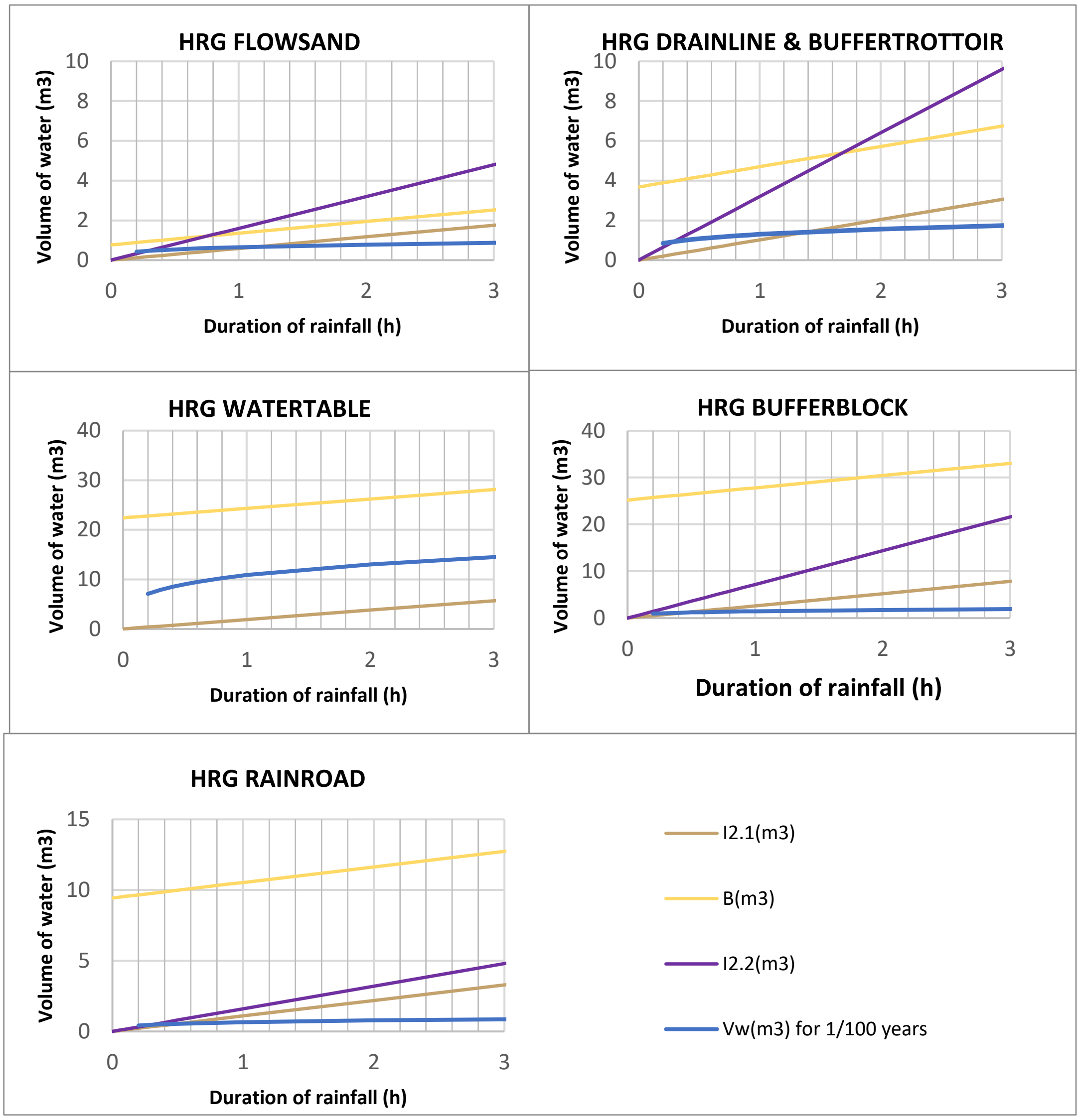


Figure 25 HRG plots of systems FLOWSAND [1], DRAINLINE& BUFFERTROTTOIR [4&5], WATERTABLE [2], BUFFERBLOCK [6] and RAINROAD [10]. The legend on the bottom and right art of the figure indicates the colors used to represent the different lines of the HRG. The plot of incoming volume of water is limited to 15 minutes. This is because the observation data that provided the parameters of the equations for the calculations of the rainfall intensities were not more frequent than 15 minutes (37).

From Figure 25 it can be concluded that the SUDS FLOWSAND [1], DRAINLINE& BUFFERTROTTOIR [4&5], WATERTABLE [2], BUFFERBLOCK [6], and RAINROAD [10] are not expected to be full during rainfalls with a return period of once in 100 years. This can be seen on the HRG because B line, representing both the infiltrated and stored water in the SUDS, is at all durations higher than the incoming water (V_w). The systems could be filed if the infiltration in the system is higher to let the water enter and be stored in the SUDS. This is true in the higher duration rainfalls but still, the storage does not fill because line B is always higher than the incoming water. For small duration rainfalls occurring once in 100 years, the limiting factor for the hydraulic response of the systems FLOWSAND [1], DRAINLINE& BUFFERTROTTOIR [4&5], and RAINROAD [10] is found to be the infiltration capacity ($i_{2.1}$) of the permeable layer, because the line $I_{2.1}$ intersect V_w. For the system BUFFERBLOCK [6] the limiting factor is only the infiltration in the soil. This means that the incoming volume of water can infiltrate fast enough through the 1st layer but not through the soil so it should be stored in it to be able to drain. For the system WATERTABLE [2], the water is entering the system through a drain meaning that the limiting factor of a permeable material does not exist.

The prevalent mechanism of overflow could be either the infiltration through the permeable material or the storage not being enough with the first one being true for most of the systems analyzed in this thesis. This means that for rainfall occurring once in 100 years, the overflow will occur due to the maximum infiltration through the permeable material reached but the storage under it will not be full.

Plotting the HRG for rainfalls of once in 10 years, suggested in the 20th report published by the Dutch Foundation for Applied Water Research (10), resulted that for the most frequent rainfall events the systems in WaterStreet are not expected to overflow because the water enters the SUDS fast enough and there is also enough storage that is not filed based on the HRG. The plots are not presented in this thesis as they do not provide any additional information.

The systems are not expected to be filled considering that the ratio of permeable to upstream drainage area achieved in the study area is much higher than in real implementations. The highest ratio shown in Table 11 was found to be 1/15.75 while the smallest suggested by literature was around 1/30 (39). This means that the SUDS in WaterStreet should collect water from a bigger upstream drainage area than achieved now for the SUDS to be full. Without the storage being a limiting factor to the hydraulic response only the infiltration through the permeable material is considered a limitation that is also acting first.

4.1.3 System's interaction with surroundings

The systems analyzed in this thesis are already implemented in the study area. This results in an interaction of the system with its surroundings above, around, and under. If the performance of the upstream system affects the stress posed to the downstream, then the interpretation of the measured response of the second should consider the performance of the first.

Overall concluding interaction with surroundings

Table 13 summarizes the hydraulic isolation from the top and bottom of the systems on WaterStreet. The data used to provide the hydraulic isolation shown in Table 13 are constrained by the time frame of this thesis. For example, the observed groundwater levels that provide the interaction from the bottom of the systems could rise even more than what is observed until May 2021, when the groundwater levels were analyzed. This could reveal an interaction between more systems than the ones indicated in the table.

Table 13 Summary of individual SUDS analysis indicating their hydraulic isolation from the top or bottom.

#	Name	Hydraulic isolation top	Hydraulic isolation bottom
1	FLOWSAND	Yes	Yes
2	WATERTABLE	Yes	No
3	DRAINMIX	No	Yes
4& 5	DRAINLINE & BUFFERTROTTOIR	Yes	Yes
6	BUFFERBLOCK	Yes	No
7 & 8	URBANRAINSHELL & DSI	No	Yes
9	RAINROAD	Yes	Yes

10	ZOAK BESTRATING	Yes	Yes

Concluding from the above table systems FLOWSAND [1], DRAINLINE & BURRERTROTTOIR [4&5], RAINROAD [9], and ZOAK BESTRATING [10] are the systems that are hydraulically isolated from both the top and bottom.

The results of hydraulic isolation in Table 13 are based on design reports of the terrain's slope and monitoring of the groundwater levels for a certain period. Both results can be false if slopes alter due to subsidence of the terrain or if groundwater levels are higher. For those reasons, it is suggested to validate the slopes of the terrain and monitored the groundwater table. Alternatively, to manage the groundwater table, drainage pipes could be installed. Ensuring hydraulic isolation of the systems is important because monitoring a combined performance would not be of high value, since the systems that are implemented in WaterStreet are not likely to be put together in real implementations.

<u>Interaction above the system- hydraulic isolation from the top</u>

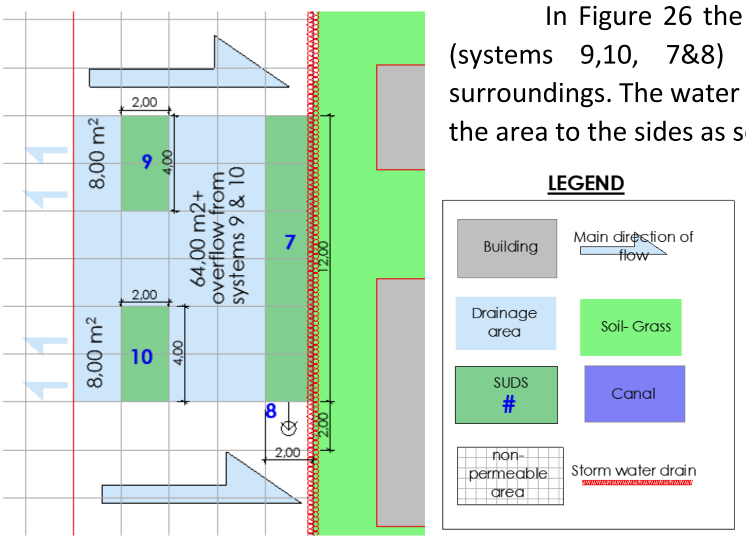


Figure 26 Upstream drainage and occupying areas of the systems on the square area of WaterStreet. The main direction of the flow can also be seen with blue arrows and the exact drainage area calculation. The different contents of this figure are identified in the legend provided.

In Figure 26 the systems on the square area (systems 9,10, 7&8) can be seen with their surroundings. The water is directed from the center of the area to the sides as seen with the blue arrows and towards the red line that is the storm sewer. The draining area to systems 9 and 10 is equal to 8 m2. Regarding system 7&8, the amount of water draining to them is affected by the performance of the systems upstream (9 and 10). This means that the total water that has to be managed by that system is the amount falling on the upstream 64 m2 area, plus the amount of water that does not infiltrate the systems upstream. From this observation it can be concluded that system 7&8 is not isolated hydraulicly from the top. Systems 9 and 10 on the other hand have a distinctive upstream drainage area above them and due to the direction of the flow in the terrain the systems are hydraulicly isolated from the top.

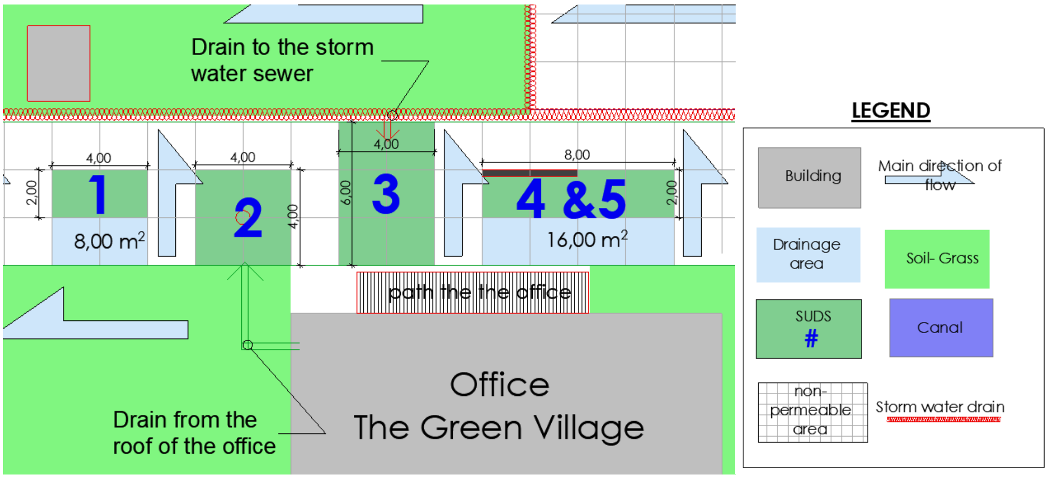


Figure 27 Upstream drainage and occupying areas of the systems on the west part of the path area of WaterStreet. The main direction of the flow can also be seen as the exact drainage area calculation. The different contents of this figure are identified in the legend provided.

Figure 27 shows the systems located on the west part of the path area, the upstream drainage areas per system, the main direction of flow on the paved and unpaved terrain, and the structures surrounding them. The storm sewer can be seen with red lines and the main direction of the water on the paved terrain is shown with the blue arrows. Starting from system 1 the upstream draining area is calculated at 8 m2 and it is hydraulicly isolated from the top due to the flow direction on the soil and paved terrain around it. System 2 as seen in Figure 27, collects the water from the roof of the office building of The Green Village, corresponding to a 252 m2 surface, and is hydraulically isolated from the top due to the main direction of the flow. System 3 is connected to the storm sewer and water can enter from there; this affects the amount of water that has to be managed by system 3. Additionally, the storm sewer is connected with another system that is not included in this research, making system 3 interact with that system. That explains why system 3 is not hydraulically isolated from the top.

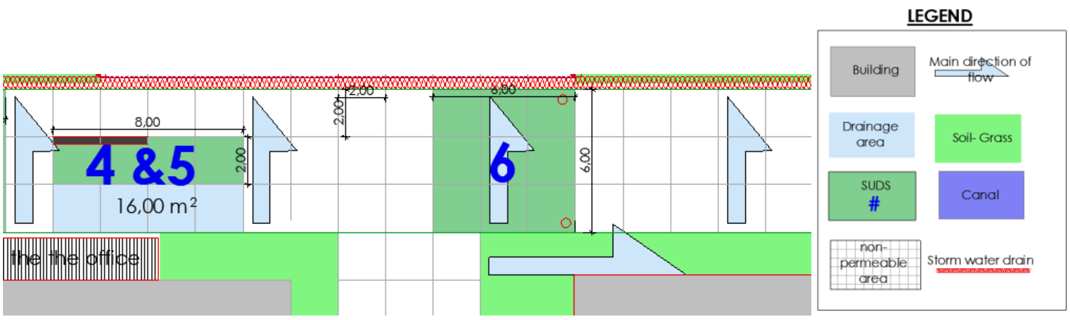


Figure 28 Upstream drainage and occupying areas of the systems on the east part of the path area of WaterStreet. The main direction of the flow can also be seen as the exact drainage area calculation. The different contents of this figure are identified in the legend provided.

Figure 28 shows that system 4&5 has an upstream drainage area, equal to 16 m2, and is hydraulicly isolated from the top due to the main direction of the flow in the unpaved and paved terrain. Lastly, the system with the number 6 does not have an upstream drainage area and only collects the water that falls on the occupying area of the system. Moreover, the main direction of flow on the unpaved and paved terrain isolates system 6 from the top.

Interaction under and around the system - hydraulic isolation from the bottom

Next, regarding the flow of water under and surrounding the system, the groundwater flow was analyzed in both vertical and horizontal directions. The vertical direction is straightforward as water can move downwards due to gravity or upwards due to capillarity. Since the systems are placed next to each other and not on top of one another, interaction in the vertical direction is not expected. The groundwater on the other hand can get high enough and enter one system and then the next.

Figure 29 schematizes the groundwater streamlines (bleu) assuming that the systems are recharging groundwater wells with the same recharge discharge. This assumption was made because the effect of SUDS on the groundwater table is similar to the effects of a recharge well. Both SUDS and recharge wells are found to be used to recharge aquifers (40) (41). Also, this assumption could be made for the purposes of this figure, which was to present the main direction of the horizontal flow and not provide numerical information. More on the equations used to plot the streamlines and contour lines of the groundwater flow due to the recharge wells can be found in Appendix F – Groundwater simulation.

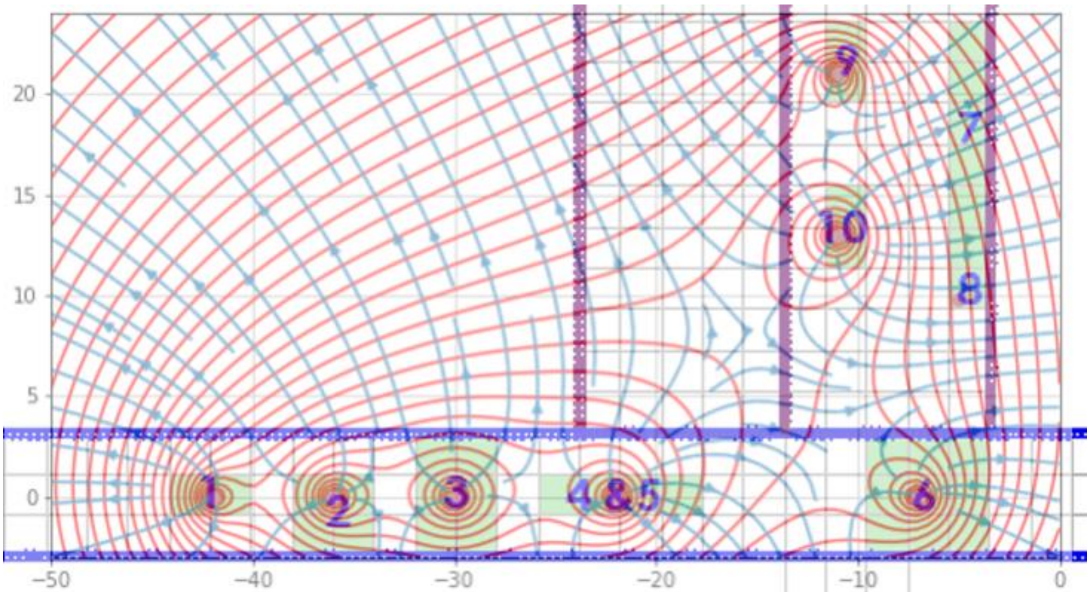


Figure 29 Top view of the horizontal groundwater streamlines (blue) and contour lines (red). The SUDS are placed in the study area, and they are assumed to act on the groundwater table in the same way as a recharge well. Based on that assumption the streamlines and contour lines are plotted.

Figure 29 shows that in the path area the groundwater flow is directed toward the canal on the west side of the figure while for the square area towards the east. This could mean that systems 9 and 10 would affect system 7&8, but the design of the last system shows that a non-permeable geotextile is installed between the soil surrounding the system isolating system 7&8 from the surrounding soil and the ground water table rising.

On the other hand, based on the design characteristics of the systems in the path area, it is found that the geotextile between the system and the surrounding soil is permeable. So, the groundwater can enter the system as shown in Figure 30 where the maximum groundwater level is realized with red. The groundwater levels in Figure 30 were based on the groundwater level information from the two observation wells, PB01 and

PB02. Further information on this can be found in section 2.6 Water level in canal and ground.

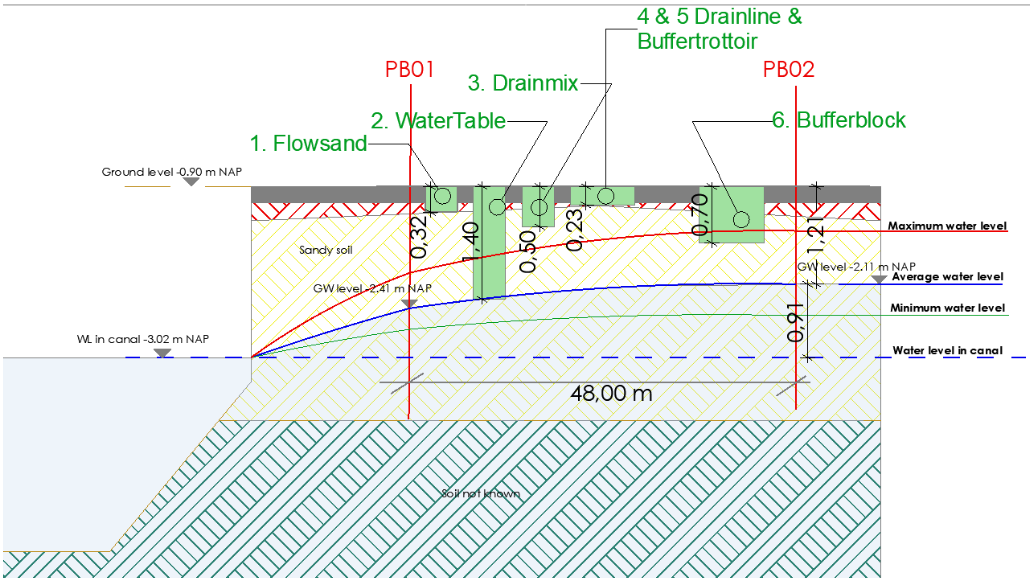


Figure 30 Vertical cross-section in the middle and parallel to the path area showing the interaction of the systems due to maximum groundwater levels observed.

With regards to high groundwater and understanding the depths of the systems, BUFFERBLOCK and WATERTABLE are connected and affect each other. It can be the case that in the future the groundwater levels are even higher and then more systems could be connected from under and around. Considering that the data represent two years, it can be assumed that the maximum water levels shown in Figure 30 are a good representation of the seasonal variation. On the other hand, in the future considering climate change pushes for extremities to become more extreme, it could be that the groundwater level exceeds the maximum groundwater level observed until May 2021.

Based on the above we could anticipate an event that which would lead all the systems being under the groundwater table. This could be avoided with groundwater control. In the literature of STOWA (10), it is suggested to always ensure a drainage depth between the bottom of the system and the groundwater level of 0.5 m. Considering the system with the biggest depth is WATERTABLE, the groundwater drainage depth should at least be 1.20 m (the depth of WATERTABLE) plus 0.5m, so a depth of 1.70 m from the ground surface level. Perforated drainage pipes can help achieve that objective, ensuring the proper drainage depth for the systems helping them not to interact from the bottom. A representation of the cross-section can be seen in Figure 31. A design process of the drainage pipes can be found in the literature of Van De Ven (2016) (19 p. 146).

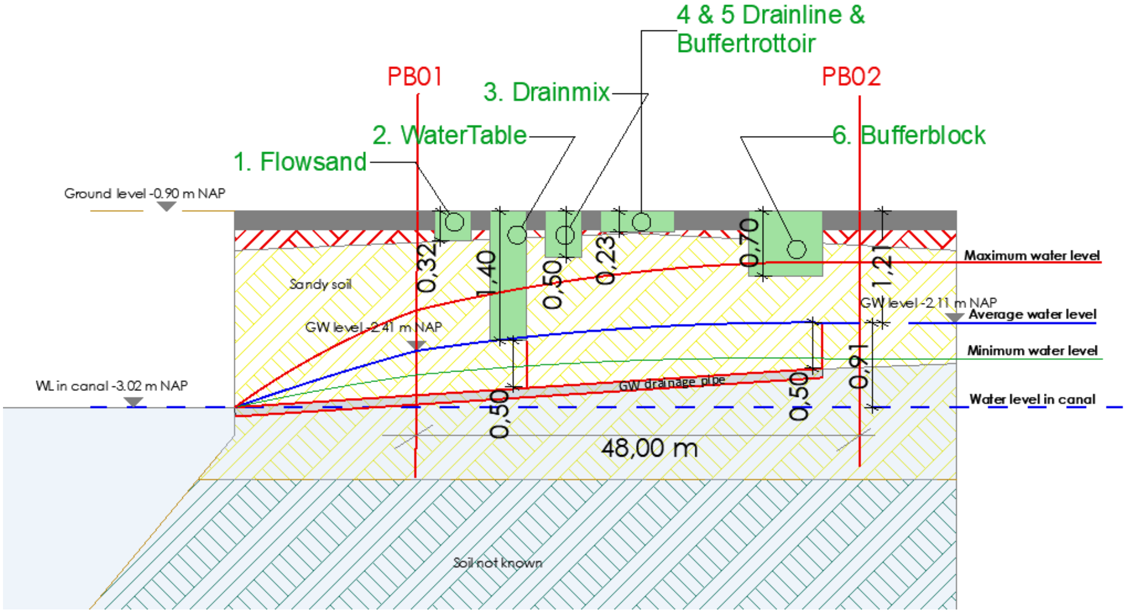


Figure 31 Cross-section of path area with groundwater management to ensure hydraulic isolation from the bottom. The goal was to at least provide a 0.5m distance between the deepest system (WATERTABLE) and the groundwater level. This is achieved by a GW drainage pipe.

4.1.4 Concluded important indicators

Considering the water balance of the systems, the hydraulic response graphs (HRG), and the interaction of the implemented systems with their surroundings or with each other, the next important indicators were concluded along with the individual significance:

Symbol	Name	Significance
s_3	groundwater levels	Assure hydraulic isolation from the bottom Indicate if the storage under the system is saturated
$i_{2.2}$	Infiltration rate in the soil	Construction of the HRG Indicates how fast the water enters the soil Indicate the amount of water that recharges the ground
$S_{2.2}$	Water in the SUDS (S2.2)	Construction of the HRG Indicate the buffer capacity in the SUDS
$i_{2.1}$	the infiltration rate of the permeable first layer of the system or through the drain	Construction of the HRG Indicates how fast the water enters the system
O_1	overflowing surface water to the system from the upstream drainage area	Construction of the HRG Stress that causes the system to respond
$O_{2.1}$	overflowing surface water from the system to downstream	the amount of water that overflows is a concern for the residents
i	Rainfall depth during a time period	Construction of the HRG Stress that causes the system to respond

The list above does not include all indicators from the water balance in Figure 23. Starting with the soil moisture in the subsoil (M_3) and system (M_2), they are considered secondary indicators to monitor because if these parameters are at a maximum, the system has still a storage capacity to respond to rainwater. Subsoil moisture (M_3) for example is already at maximum when the groundwater starts to get saturated. Lastly, the groundwater flow (G) is a response to the rise of the groundwater table (s_3). The main focus has been placed on the SUDS behavior, so the groundwater flow is not in the scope of this work.

The overflow from SUDS to the storm sewer ($DO_{2.2}$) is also not included based on the findings of section 4.1.2 Hydraulic response of SUDS on WaterStreet . The reason behind this, is that the systems provide large storage that a rainfall with a return period of once in

100 years is not sufficient to fill them considering that the water can enter the SUDS. The $DO_{2.2}$ flux is activated when the systems are full thus the chance of that is slim considering the rainfalls until once in 100 years. Lastly, evaporation, transpiration, and intercepted water from and on the SUDS are assumed to be limited considering the other fluxes in the water balance. This suggests an overestimation of the incoming water to the SUDS that should be considered when interpreting the result. It is also suggested to perform rainfall simulation experiments to provide a runoff coefficient of the SUDS area under different conditions.

The concluding water balance for the SUDS in WaterStreet can be seen in Figure 32.

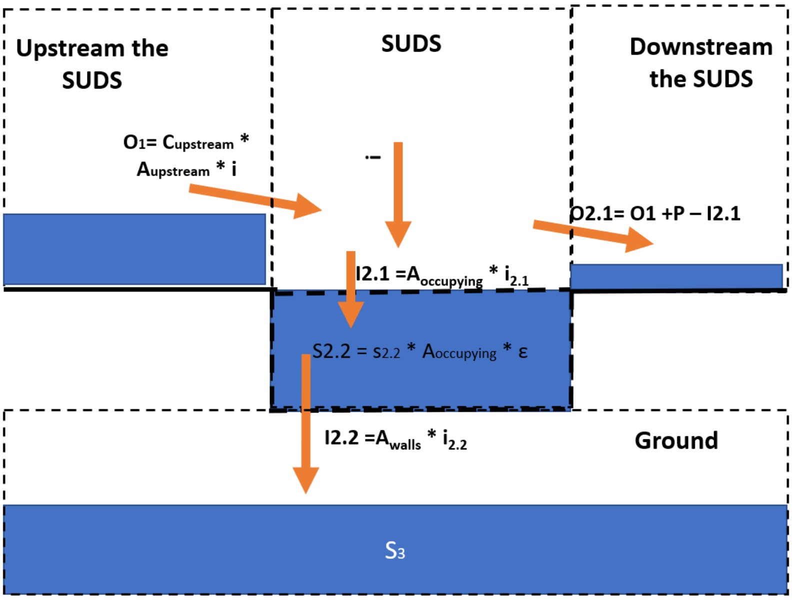


Figure 32 Water balance for SUDS with the concluded important indicators that can provide the fluxes and storages of the water balance with the dedicated equations shown in the figure.

4.2 Key performance indicators for SUDS

4.2.1 Water quantity indicators found in the literature

The literature review was aimed at indicators for systems similar to WaterStreet. The findings were focused on including only indicators that are directly connected to water quantity. So, for example, the cost is not considered a performance indicator because the high cost is connected to a water quantity indicator not performing sufficiently. This choice was made to enable a direct connection between the water balance components and the sensors needed.

Table 12 summarizes the results of the literature review. The infiltration capacity of the permeable material was found to be an important factor to assess the performance of SUDS. Most of them also considered the conditions surrounding the system, like the soil hydraulic conductivity and the groundwater table. Additionally, no overall common view on the important indicators was found, increasing the need for an integrated list of indicators that can be the common ground for stakeholders.

Table 14 Summary of literature review on the important indicators considered by several actors. The actors considered were mostly organizations of knowledge collection and distribution regarding urban drainage systems. 4 out of 5 sources are active in the Netherlands because of the location of the study area of this thesis.

Source	Organization of source	Significance of source	Important indicators mentioned	Reference
STOWA	Independent organization- projects are supervised by regional water managers – funding from water boards, provinces, and other members	Centre of expertise of Dutch Waterboards	• the infiltration capacity of the permeable tile • groundwater level • overflowing frequency of the system • emptying time of the system • hydraulic conductivity of surrounding soil	(10)
RIONED	Independent organization – funding from members of the organization that are among other municipalities, ministries, and businesses	Dutch organization for urban water management	• the time that water can stay ponded on streets • infiltration capacity	(42)
Municipality of Amsterdam	Administrative subdivision of government in a region	The municipality of Amsterdam has already set storing and infiltration regulations for landowners to reduce the water flown to the wastewater sewerage system.	• available storage in the system • emptying time • the volume of water directed to the public wastewater sewerage system	(43)
CIRIA	Neutral, independent, and non-profit body- funded by members	Construction Industry Research and Information Association	• hydraulic conductivity of surrounding soil • the infiltration capacity of the permeable tile • Available storage in the system	(7 p. 151)
COP- community of practice waterinfiltrerende verharding	Organizations established by RIONED and STOWA- members are municipalities, Amsterdam University of Applied Sciences, Aquafin, and RIONED.	Distribute knowledge on permeable pavements community of educated citizens	• the infiltration capacity of the permeable tile • groundwater level • overflowing frequency of the system • emptying time of the system • hydraulic conductivity of surrounding soil	(44)

It is also observed that in the literature of STOWA, ROINED, and the municipality of Amsterdam, no alignment of the important indicators was found, which is important because all of them are active within the Dutch region. This is supported by law enforcement in the Netherlands. The legislation in the Netherlands, called "Wet milieubeheer" includes article 10.32a, which gives the municipality the power to set rules for rainwater management in their region. They suggest including both storing or infiltration facilities to reduce the water flown to the combined sewerage system (45). This article gives a degree of freedom to the water managers of the regions to decide on their performance indicators based on the objectives they set. This does not help the cooperation between stakeholders that work in several regions, because they have to adapt to the objectives and performance indicators set by every region. This method, although gives the freedom for a case-specific solution, it loses the added values of a more universal definition of performance for SUDS.

Based on the literature above the next indicators were considered important:

- the infiltration capacity of the permeable tile
- groundwater level
- overflowing frequency of the system
- emptying time of the system
- hydraulic conductivity of surrounding soil (K)
- the time that water can stay ponded on streets
- available storage in the system
- the volume of water directed to the public wastewater sewerage system

4.2.2 Water quality indicators found in the literature

Water quality is an important indicator for SUDS systems because of the principle of not shifting problems downstream. Although it is essential to regulate and monitor the pollutants originating in urban environments, not all of them can be reduced when entering an urban drainage system given the design of SUDS in WaterStreet. The ones that can be considered Key Performance Indicators are also the ones that can be trapped in the SUDS and hence reduced in the effluent.

The efficiency of pollutant removal of SUDS varies based on the pollutant, the composition of the media, and the environmental condition of the study area. High efficiencies are found for the Total Suspended Solids (TSS) reduction (50%-90%) while lower is recorded for the total phosphorus (30% - 60%) and nitrogen (10% - 40%) (12). It is important to define which of the pollutants can be considered as water quality key performance indicators like TSS and which are important indicators. Different pollutant reduction strategies, like source control, can be considered for the reduction of the non-key water quality performance indicators for SUDS.

The second column of Table 15 shows the priority pollutants considered in this thesis and presented in section 3.2.2 Water quality indicators found in the literature. The priority pollutants are the ones considered to be measured in overflowing water of residential areas with a concentration higher than the environmental standards. The last column provides the Key pollutants based on the research of Dierkes et al. (12). Based on their research these key pollutants are included in the testing protocols of 6 countries, the UK, Germany, The Netherlands, Australia, New Zeeland, and Canada. The pollutants that are found in both columns are considered to be the first estimation of the Key Performance Indicators in this thesis. This is because the intersection of the two columns provides both the pollutants that can be found in significant concentrations based on environmental standards (25) and at the same time the pollutants are able to be trapped in a SUDS. The pollutants are listed in categories to organize the results.

Table 15 Important pollutants found in the Dutch overflowing water (column 1) and indicators used as performance indicators for SUDS in the UK, Germany, The Netherlands, Australia, New Zeeland, and Canada (column 2). The integration of both columns provides the pollutants that are both found and regulated by SUDS.

Category of pollutant	Priority pollutant in overflowing water from streets and roofs in residential areas (25)	Water quality performance indicators for SUDS (12)
Heavy metals	Cadmium (Cd)	Cadmium (Cd)
	Copper (Cu)	Copper (Cu)
	Mercury (Hg)	
	Lead (Pb)	Lead (Pb)
	Nickel (Ni)	
	Zink (Zn)	Zink (Zn)
PAH & TPH	Benzo(a)pyrene (PAH)	
	Mineral oils (PAH & TPH)	
		Total petroleum hydrocarbons (TPH)
Nutrient pollutants	Chemical Oxygen Demand (COD)	
	Total phosphorus (TP)	Total phosphorus (TP)
	N- Kjeldahl (Organic N + ammonium)	Total Nitrogen (TN)
	Nitrate (NO3)	

Inorganic materials	Total Suspended Solids (TSS)	Total Suspended Solids (TSS)
Biological pollutant	E. coli	

Considering Table 15, the compounds, Mercury, Nickel, Benzo(a)pyrene, Mineral oils, COD, N- Kjeldahl (Organic N + ammonium), Nitrate (NO3), and E.coli are included in the list of priority pollutants but not as pollutants to be included in the testing protocols of the 6 countries considered and therefore not key performance indicators.

TSS is considered for Germany the most important indicator of water quality performance of SUDS based on its ability to capture pollutants and get trapped in SUDS. Total Suspended Solids (TSS) are waterborne particles that exceed 2 microns in size and contain inorganic materials, algae, and bacteria (46). Smaller-sized solids are considered to be dissolved in water. The particles greater than 2 microns can then be divided into classes based on literature clay-very fine silt (<8 µm), fine silt (8–16 µm), medium silt (16–32 µm), coarse silt (32–63 µm) and sand (>63 µm) (47). In the research of Orroño et al., they found that Cadmium (Cd), Copper (Cu), Nickel (Ni), and Zink (Zn) are mostly bound to clay soils while Lead (Pb) is found mostly in silt (30). The sand was the fraction with the least concentration of metals bound on it. This means the focus should be on the smaller fractions of Suspended Solids. Clay exhibits a high absorbing capacity due to its high surface area compared to sand particles. The moving mechanisms of the TSS are related to the turbidity of the water. If the water reduces velocity, then more solid particles can be deposited in a SUDS and hence less TSS can be found in the effluent along with the pollutants that are bound to it. Changes in the pH, Temperature, and concentration of deicing salts (sodium chloride (27)) can remobilize pollutants in the water. This means that the pollutant gets detached from the solid deposited in the SUDS, dissolves in the water, and exits the SUDS. For example, Cadmium, Lead, and Zink is significantly mobilized in acidic conditions (48).

The ability of Total Suspended Solids (TSS) to absorb heavy metals gives the motivation to use TSS as a proxy for the reduction of all the heavy metals found on site (31), PAHs (32), and TPHs (33). The biological pollutant, E. coli, can also be trapped on TSS (28), so again the reduction of TSS can be used as a proxy for the reduction of E. coli. For the Nutrient pollutants on the other hand, although they are attached to TSS (29), the effect of SUDS on reducing their concentration is not so high (12). The above is also in line with the German guideline to consider TSS as the “authoritative evaluation” parameter for SUDS and consider also including Total phosphorus in the future (12).

Based on the above and following the German guideline, the reduction of TSS in the effluent of the SUDS could be used as a water quality performance indicator for SUDS along with the reduction efficiency of total phosphorus.

4.2.3 Key stakeholders

This section summarizes the results from the stakeholder analysis that revealed the most important stakeholders to be considered as key stakeholders. To conduct that, a questionnaire was sent on 17/06/2021 to 68 candidates asking them to score for power and interest in the concluded stakeholders from the actor’s map.

For the actor’s map, the following structure was used (34). In the middle of the map, the problem owner is located while other actors are put around it. The actors can affect the problem in both positive and negative ways as long as they are linked to the implementation of SUDS. The interdependencies of the actors were schematized with arrows. On the arrows, information on the relationship between two actors is shown. The validated actor's map can be found in Figure 33 while the relevant interdepends and their characteristics can be found in Appendix B- Actors .

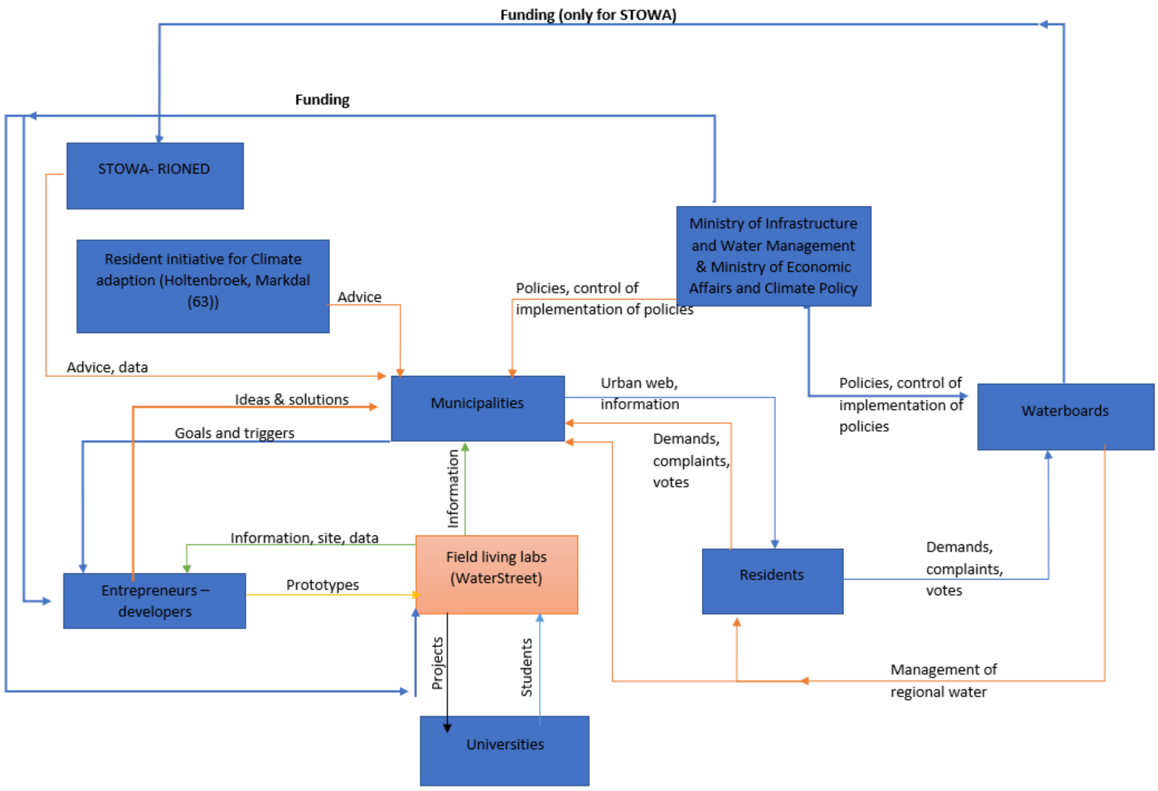


Figure 33 Actor's map to the problem of implementing SUDS. With red color is the problem owner and blue the actors that play a role in implementing SUDS in the Netherlands. The arrows indicate the connection between the actors and above the arrows the relevant interdependencies are mentioned.

From Figure 33 it is visible that although the problem owner to provide the KPIs, is Water Street, the actor with the most arrows, or the most interdependencies is the municipality. This does not come as a surprise because the municipalities in the Netherlands are one of the most important actors that implement SUDS as they are in charge of managing groundwater in urban areas drainage of wastewater and excess rainwater through the sewer systems based on the Water Act of Netherlands (article 3.5 & 3.6) (49). So even though WaterStreet can play a significant role in providing the KPIs, if the municipalities decide that the system does not comply with requirements they consider important it might not be implemented. This strengthens the need for WaterStreet to gather the key performance indicators with a monitoring network considering the most important actors.

The list of actors from the actor's map was included in the questionnaire. The duration of the questionnaire was chosen to be extended until the beginning of September, due to the summer break. Based on the response of 17 candidates shown in Table 29 in Appendix C- Questionnaire, the power-interest grid was plotted from the average score given to the actor. The power–interest grid concluded from the responses can be seen in Figure 34.

According to the responses to the questionnaire, municipalities are the most powerful actors when implementing SUDS while the developers are the most interested this is attributed to the average score given to a stakeholder for their power and interest as plotted to make the power-interest grid shown in Figure 34.

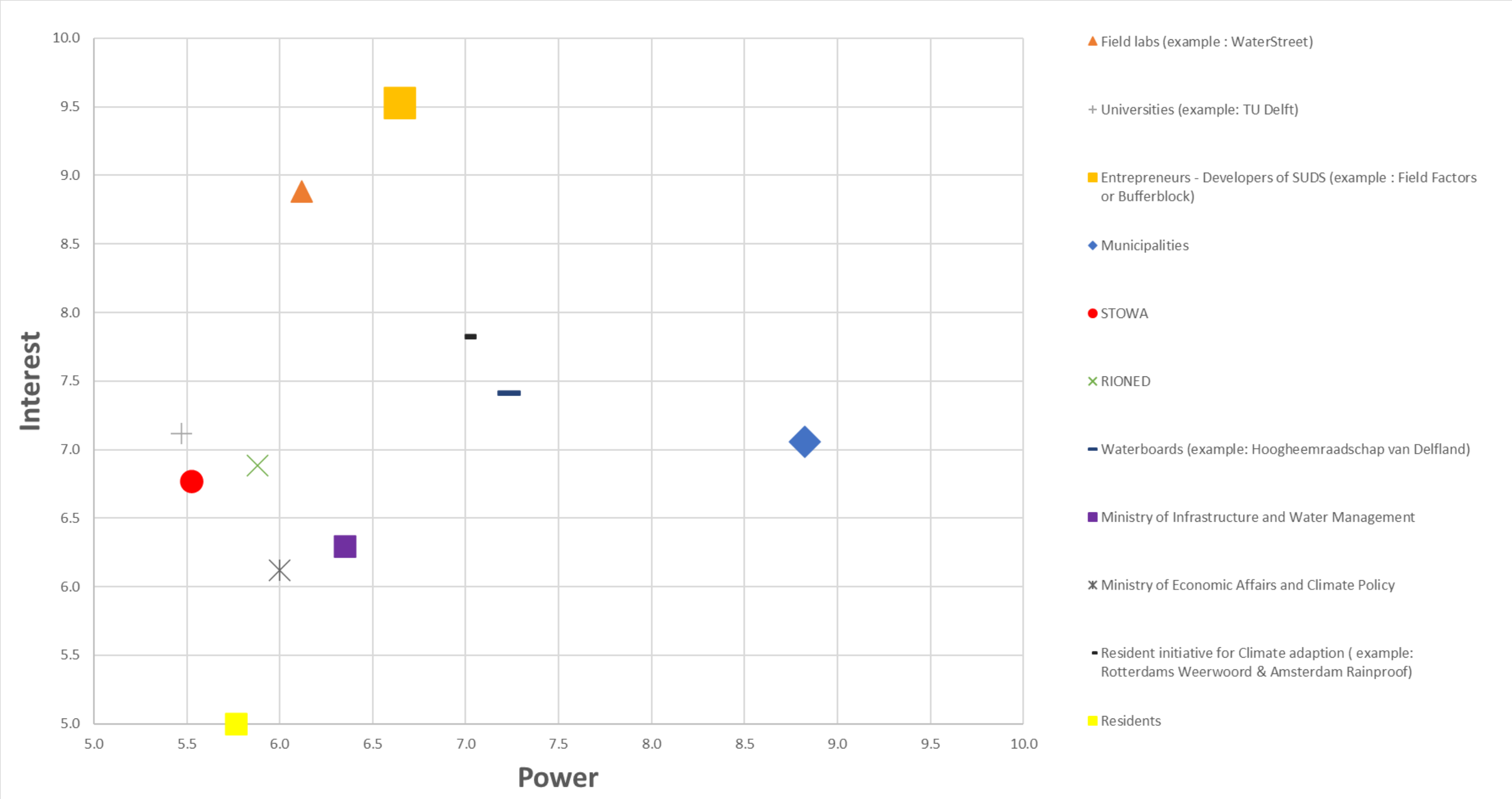


Figure 34 Power - Interest of actors for implementing SUDS. The horizontal axis indicates the average Power that an actor has while the vertical, the interest. From this figure, the relevant power and interest of every actor can be identified. All the average scores given for both power and interest were above 5 so the axis was shortened to focus on the results.

The respondents for the power interest questionnaire were in total 17, with the professions, students, academics, developers, municipality employees, citizens, consultants, and WaterStreet employees. Although the participants represent many different groups involved in SUDS implementation, the number of responses was not high considering that the questionnaire was sent to 68 possible candidates. Due to that limitation, data analysis of the scores for the different stakeholders was performed.

The average score cannot represent the variation between the responses. To visualize the deviation in responses boxplots were plotted. These can be seen in Appendix D- Box plots of the results of the questionnaire. The boxplots provided relative agreement on the scores of the actors and strengthen the average result. The highest deviation between the responses of both power and interest was found for the actor “residents”. The smallest deviation of the scores for the power of the actors was found for the actor “field labs”. The smallest deviation for the interest was found for the actor “entrepreneurs”. In that context for the case of power the actor “Residents” was the most conflicting one while the most agreement was observed for the actor “Field Labs” like WaterStreet, although the highest scored actor for the power was the “Municipalities”. Regarding the interest to implement SUDS systems the “Developers” did not only score the highest but also the variation of the sample was the lowers. This means that there is a good agreement among the candidates for the high score. Again, the “Residents” had the biggest variety in scores.

Considering that the most powerful and interested stakeholders were municipalities and developers, this research focuses on them to provide validation for the list of important indicators provided by literature.

4.2.4 Stakeholders’ view on water quantity indicators

Developers and Municipalities were the two main stakeholders concluded from the stakeholder analysis section (4.2.3 Key stakeholders). Based on that finding, interviews were conducted to validate and make additions to the list of performance indicators concluded from the reviewed literature (4.2.1 Water quantity indicators found in the literature). The responses from the individual interviews are shown in Appendix E – Interview results of key stakeholders and a combination of them can be seen in the list below:

- the infiltration capacity of the permeable tile
- overflowing frequency of the system
- emptying time of the system
- the infiltration capacity of surrounding soil and soil types
- the time that water can stay ponded on streets
- available storage in the system
- the volume of water directed to the public wastewater sewerage system
- **The return period of the design rainfall**

The interviews validated the list of indicators from literature for water quantity with the addition of the return period of the design rainfall chosen for the systems.

In the performed interviews there was no mention of water quality indicators to act as key performance indicators. This means that all the interviewees considered the water quantity objective of SUDS as the most important. That might be true in some cases, but the addition of water quality indicators is important and should not be forgotten because of the principle of not shifting problems downstream, like water pollutants.

An interesting result drawn from the interviews was that the performance of SUDS did not have a universal definition among them because they were mainly defining it on the spot based on their experience. Only the interviewee, Charlie Jurjus could provide a constructed definition of the performance of SUDS based on the 3 important indicators to reflect the performance of SUDS set by the municipality of Amsterdam. This regional legislation on the performance of SUDS is called “Hemelwaterverordening” and is active since 10 May 2021 (50). Understanding what different stakeholders expect from SUDS could help their cooperation. More interviews with diverse actors are needed to draw a dedicated answer to what indicators, different stakeholders consider important although this was not done in this thesis due to time limitations.

4.2.5 Water quantity Key performance indicators for SUDS

The objective of this section was to combine the previous results concluded in section 4.1.4 Concluded important indicators, and section 4.2.1 Water quantity indicators, shown in Table 16. After combining the results, a list of water quantity key performance indicators was developed that will be the focus of a SUDS monitoring network.

Table 16 Concluding important indicators from water balance analysis of SUDS and from literature and interviews with key stakeholders. The indicators have been put in parallel where they are considered to be relevant to each other.

Concluding important indicators from section 4.1.4 Concluded important indicators based on the hydraulic response of SUDS on WaterStreet	**Concluding important indicators from section 4.2.1 Water quantity indicators, based on literature and interviews**
groundwater levels (s_3)	groundwater levels
Infiltration rate in the soil ($i_{2.2}$)	the infiltration capacity of surrounding soil and soil types
Water in the SUDS ($S_{2.2}$)	available storage in the system
the infiltration rate of the permeable first layer of the system or through the drain ($i_{2.1}$)	the infiltration capacity of the permeable tile
overflowing surface water to the system from the upstream drainage area (O_1)	
overflowing surface water from the system to downstream ($O_{2.1}$)	
Rainfall depth during a time period (i)	The return period of the design rainfall
	the volume of water directed to the combined sewer
	overflowing frequency of the system
	emptying time of the system
	the time that water can stay ponded on streets

From Table 16 it is evident that the concluded important indicators are not the same. Stakeholders focused more on the overflowing condition by including more indicators that reflect that, like the overflowing frequency and emptying time.

Based on Table 16, a categorization of the indicators is revealed. The first category includes the indicators that stress the system and lead to the performance of SUDS (category A), the second includes the indicators that help create the performance (category B1 & B2) and the last category includes the indicators that are connected to the response in overflow condition (category C). The three categories with representative indicators can be seen in Figure 35.

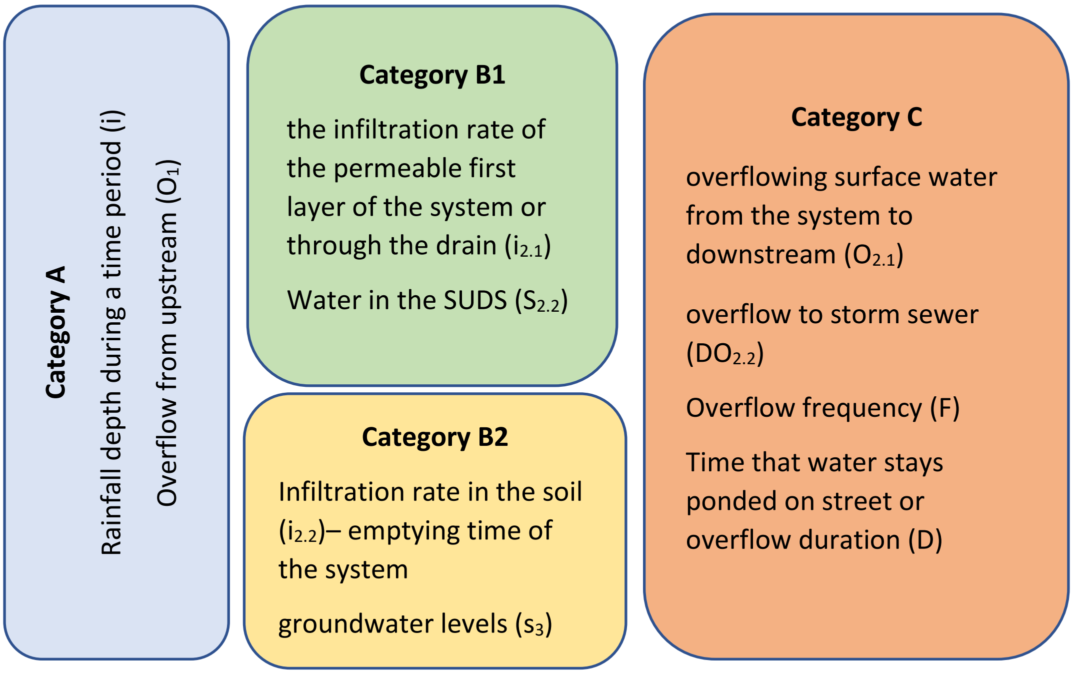


Figure 35 Categorization of important indicators. With blue are the indicators of stress, leading to SUDS performance (category A), green and yellow are the indicators of performance that lead to overflow, (category B1 and B2) and the red category included the indicators that reveal overflow (category C).

One of the objectives of SUDS on WaterStreet is to manage the stormwater in order not to overflow in urban areas. Also, based on the interviews performed, stakeholders are focused on keeping the residents' feet dry. So, one way to assess the performance of SUDS is to use the four indicators in the last category as key performance indicators. For overflow to occur rainfall water should stress the system so an important indicator to include in the KPIs list is also the incoming volume due to rainfall.

Based on the above motivation the chosen key performance indicators are:

1. Duration of overflow (D)
2. Frequency of overflow (F)
3. Overflowing rate ($O_{2.1}$ & $DO_{2.2}$)
4. Rainfall depth (i) and water from upstream (O_1)

Regarding water quantity, SUDS have also the objective to recharge the aquifer. To support that objective and realize more about the reason for the hydraulic response of SUDS, the addition of the indicators in category B2 should be considered for the monitoring network. The selected Key Performance Indicators should not be considered more important than the ones in category B. They just represent better the responses of the stakeholders that took part in the interviews done for this thesis. The indicators in category B are just as important because they are the ones that help create the performance and are therefore called indicators of performance. A distinction between the two categories is evident and the division between them can be seen in Table 17.

Table 17 Chosen Key performance indicators and indicators of performance based on the findings and assumptions of this thesis.

Key performance indicators (KPIs)	**Indicators of performance (IP)**
Duration of overflow (D)	Infiltration rate of the first layer ($i_{2.1}$)
Frequency of overflow (F)	Water in the SUDS ($S_{2.2}$)

Overflowing rate ($O_{2.1}$ & $DO_{2.2}$)	Infiltration rate in the soil ($i_{2.2}$)
Rainfall depth (i) and overflowing rate from upstream (O_1)	Groundwater levels (s_3)

4.2.6 Possible Water Quality key performance indicators for SUDS

Following the German guideline, the possible Key Performance Indicator for pollutant reduction of SUDS are Total Suspended Solids (TSS) and Total Phosphorus (TP). The first can be used as a proxy for heavy metals, PAHs, TPHs, and E. coli reduction and TP could be used as a proxy for the Nutrient pollutants. Additionally, pH and temperature of the ground water are important regulators of the reduction mechanisms and therefore also indicators to monitor.

Laboratory tests are needed to validate the existence of the priority pollutants in the study area and their initial concentration in the overflowing water on the surface. If the concentration of the pollutants is above the Annual Average Environmental Quality Standard (JG-MKN) (25) then the pollutant should be considered for monitoring. Using Total Suspended Solids (TSS) reduction as a proxy for both heavy metal, PAHs, and TPHs reduction should be done with caution. It might be the case, for example, that those suspended solids are originating from construction work on the site with no pollutants attached to them. So, if a reduction of TSS is found to occur it does not necessarily mean that there is a reduction in pollutants. Moreover, it is advised to test the influence of temperature and pH change on the absorption mechanism of the priority pollutants (26).

4.3 Indicators to be monitored on WaterStreet

The monitoring network's objective can either support the Key Performance Indicators or additionally the Indicators of Performance. There is an added value for the monitoring network to target both lists of indicators. If for example overflow is found to happen due to reduced infiltration of the soil ($I_{2.2}$), that indicates that management of the subsoil is needed before implementing more SUDS. If the infiltration in the system ($I_{2.1}$) is the main cause of overflow, maintenance might be needed to clean the permeable tiles. To provide all that data, sensors are needed, which increases the cost of SUDS research. This could be a motivation to only provide the Key performance indicators of a system and not add the indicators of performance.

Given the objective of the study area to provide additional information and research to support the upscale of the SUDS, both the KPIs and Indicators of performance should be monitored in WaterStreet. This list can be seen in Table 18 among the units used for them.

Table 18 Data to be monitored based on the objective of the monitoring network to provide the performance of the SUDS in WaterStreet to rainwater management. The units of the required indicators to be monitored are also included.

Key performance indicators (KPIs) & Indicators of performance (IP)	**Units of the indicator**
Duration of overflow (D)	Unit of time
Frequency of overflow (F)	Times per unit of time
Overflowing rate ($O_{2.1}$)	Unit of volume / unit of time
Rainfall depth (i)	Unit of length / unit of time
overflowing rate from upstream (O_1)	Unit of volume / unit of time
the infiltration rate of the first layer ($i_{2.1}$)	Unit of length / unit of time
Water levels in the SUDS ($S_{2.2}$)	Unit of volume / unit of time
Infiltration rate in the soil ($i_{2.2}$)	Unit of length / unit of time

groundwater levels (s_3)	Unit of length / unit of time

It should be noted that the indicators of rainfall depth (i), infiltrations through the first layer and soil, and the water levels in the soil, have units of length divided by time while the indicators of overflows and storage in the SUDS have units of volume divided by time. Using volumes as indicators of performance for infiltration, rainfall, and storage in groundwater would not provide such valuable information. This is because infiltrations and rainfall occur over a surface and are hence better understood in units of length divided by time and ground water rise are also considered as the groundwater flow activation that is calculated based on the groundwater level differences. The other indicators are understood as the volume in time, considering the water balance.

One important notice for the indicators concluded to be monitored, is the exclusion of the overflow through the drain ($DO_{2.2}$) from the list of Key Performance Indicators. This is due to the result of the Hydraulic response Graph for the SUDS in WaterStreet. In section 4.1.2 Hydraulic response of SUDS on WaterStreet it was concluded that most of the systems are not full even during extreme events of once in 100 years. So only for this study area, overflow is considered to occur on the surface and only due to the maximum infiltration through the first layer being reached.

Regarding water quality performance indicators, TSS, Total Phosphorus, pH, and ground water temperatures are suggested to be monitored in the study area based on the findings of section 4.2.6 Possible Water Quality key performance indicators. It was also concluded that lab tests are appropriate to validate suggested indicators before advising on sensors. Additionally, the limitation of time for this work did not permit further research on sensors to monitor the water quality Key Performance Indicators for WaterStreet.

4.4 Selection of sensors

Table 19 summarizes the selection of sensors with their equipment while Table 20 shows the way the indicators can be calculated from the data acquired from the sensors. The selection of sensors was constrained by the hard criteria shown in section 3.3.1 Criteria for monitoring. The limiting values of the criteria that constrain the choice of every sensor are provided in the sub-sections following. For example, the values of the rainfall range, that the sensor should be able to measure are decided and motivated in section 4.4.1 Acoustic disdrometer sensor, which regards the sensor for rainfall.

To better understand the equations explained in Table 20 and the connection of the measured data and the indicators with the water balance, Figure 36 was made.

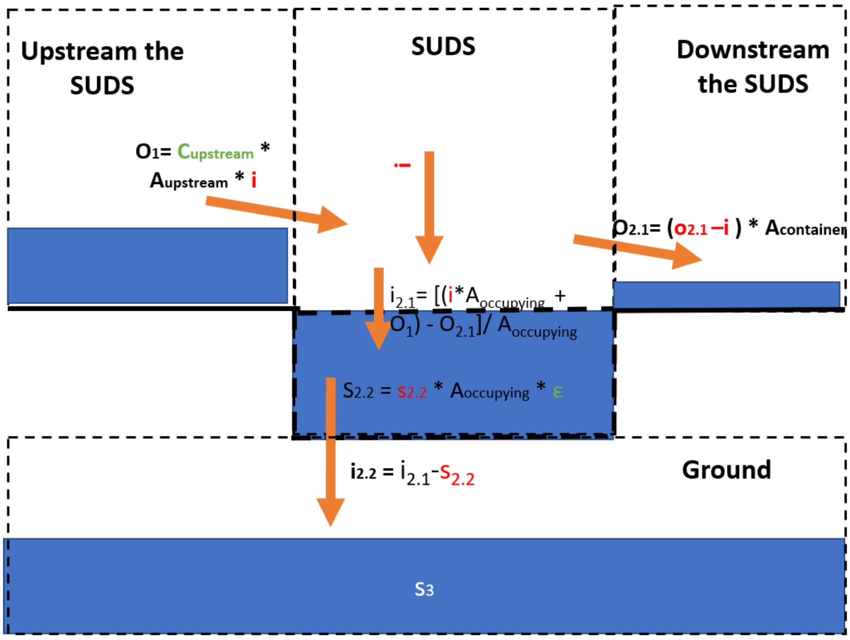


Figure 36 Water balance of the SUDS in WaterStreet with the KPIs and IPs together with the equations that provide them based on the data from the monitoring network. With red are the data that are provided by the monitoring network and with green are the assumed or have to be researched for the study area.

Table 19 Summary of selected sensors with the data they directly provide and the equipment that accompany the sensor. More on every sensor can be found in the next sub-sections.

Sensor's type	Data provided	Name in the Market	Exiting on the field	Equipment supporting the sensor
Acoustic disdrometer	i = mm of rain in one minute	Disdro (51)	YES	-
Diver in controlled volume	$o_{2.1}$ = mm of water in the container in one minute	mini – Diver DI501 (52)	NO	Container downstream the SUDS
Diver in SUDS	$s_{2.2}$ = mm of water in SUDS during one minute	mini – Diver DI501 (52)	NO	Perforated pipe
Sonar pulse sensor	s_3 = mm of ground water in one hour	Level Log (53)	YES	-

Table 20 Indicators provided by the analysis of data provided by the sensors. The parameters in red are the data provided by the sensors and in green are suggested to be assumed or be provided by field experiments on the study area. The equations to conclude the indicators from the data are included as an explanation of the link between the data and the indicators.

Indicator	data measured	Equations connecting data with indicator	link EXPLAINED	Parameters of equation
(D) Duration of overflow from either drain or surface	Time measurements of water in the container	$\Sigma(dt)_{\text{when O2.1 not zero}}$	Sum of minutes that overflow occurs in one event	-
(F) Frequency of overflow	Time measurements of water in the container	$\Sigma(O_{2.1})$/year	Sum the times per year that overflow occurs for one year	-
($O_{2.1}$) Overflowing rate	mm of water in the container in one minute	$O_{2.1} = (o_{2.1} - i) * A_{container}$	The volume of water that overflows in one minute is equal to the water level change in the container times the area of the container minus the rainfall occurring on the container area	$A_{container}$: the occupying area of the container, placed to measure the overflow downstream

(i) Rainfall depth	mm of rain in one minute	i	The rainfall depth during one minute is directly measured with the sensor	-
(O_1) Overflow rate from upstream	mm of rain in one minute	$O_1 = i{*}A_{upstream}{*}C_{upstream}$	The volume that overflows from upstream during one minute is equal to a percentage of the precipitated water. That percentage is the runoff coefficient.	$A_{upstream}$: The upstream drainage area $C_{upstream}$: The estimated runoff coefficient of the upstream area
($i_{2.1}$) Infiltration in the system through the first layer of SUDS	mm of rain in one minute, mm of water in the container in one minute	$i_{2.1}= [(i{*}A_{occupying} + O_1) - O_{2.1}]/ A_{occupying}$	The infiltrated water during one minute along the infiltration area is calculated with the balance of the first layer of SUDS	$A_{occupying}$: The occupying area of the SUDS
($S_{2.2}$) Water in the SUDS	mm of water in SUDS during one minute	$S_{2.2} = s_{2.2} * \varepsilon * A_{occupying}$	The volume of water stored in the SUDS is equal to the calculated water depth times the occupying area of the SUDS and the porosity of the SUDS	$A_{occupying}$: The occupying area of the SUDS ε : porosity of the soil mixture in the system if applicable, else eliminate that parameter
($i_{2.2}$) infiltration of water in the surrounding soil	mm of water in SUDS during one minute	$i_{2.2} = i_{2.1}-s_{2.2}$	The infiltrated water during one minute along the infiltration area of the soil is equal to the infiltrated water of the first layer minus the measured water level in the SUDS during one minute	-
(s_3) groundwater level	mm of ground water in one hour	s_3	The groundwater depth during one hour is directly measured with the sensor at the location of the observation well	-

As seen in Table 19, a Sonar pulse water level sensor (Level Log) collects groundwater levels (s_3). Already two of those sensors are placed in the study area. The acoustic disdrometer (Disdro) sensor collects the rainfall depth (i) information representing the entire study area. Based on estimates or experimental research for the runoff coefficient of the drainage area, the overflowing water from upstream (O_1) can be estimated as a percentage of the precipitated water. Next, and based on the water balance of the first layer of the SUDS the water entering the SUDS ($i_{2.1}$) can be estimated. Measurement of the overflowing water downstream ($O_{2.1}$) of the SUDS can help with the previous estimation after subtracting the rainfall that falls on the container. It is suggested to measure the rate of water rise ($o_{2.1}$) in a container downstream of the SUDS for that flux. The container is designed to capture the maximum water of once in 100 years. This addition can also help isolate the downstream SUDS from the upstream which is an important consideration based on the findings of this thesis (section 4.1.3 System's interaction with surroundings). The water that enters the SUDS is then partially stored in it and partially infiltrates the soil under and around the SUDS. For the water level stored in the SUDS ($s_{2.2}$), a diver in a perforated pipe is suggested while the water entering the SUDS during one minute minus the water level observed in the SUDS, provides the infiltration in the soil ($i_{2.2}$). Lastly, to calculate the duration and frequency of the overflowing water downstream the time information of the diver in the controlled volume could be analyzed.

All 9 indicators needed are monitored directly or indirectly with the help of the sensors suggested as can be seen in Table 20. Only rainfall is measured directly because the variability in rainfall in the small study area is not significant to motivate more than one sensor. For the other 8 indicators, the calculation of the flux or storage in the water balance included the assumption of parameters. The assumptions and the use of water balance in the calculations introduce errors that need to be addressed. These errors are also considered limitations for the monitoring network suggested in this thesis.

One example is the indicator of the overflow from the upstream drainage area (O_1) which is assumed to be a percentage of the rainfall that falls on that area. This assumption of that percentage called runoff coefficient as well as the assumption that the upstream area does not change provide errors in the calculation of runoff. Both parameters can change if more losses are expected or if subsidence happens, respectively. In addition, the small variability in rainfall introduces also errors. These assumptions should always be considered when interpreting the results and this is the reason why systematic experiments should be performed to define the variability of the parameters. Experimenting with the losses of the non-permeable terrain in different seasons and antecedent conditions and validating the upstream drainage areas are two ways to reduce the errors introduced by the above assumptions. Directly monitoring overflow flux on the terrain was not easy due to the small volumes of water that overflows. Also, constraining the water in a container was not possible because that water is expected to infiltrate through the first layer of the SUDS. This would mean that the monitoring should be on the terrain. The function of the terrain to also be a path did not easy implementation of a sensor on the terrain in addition to the small, expected volumes of water. This motivates the calculation of overflow (O_1) with the use of assumptions.

For the calculation of the water that enters the SUDS ($i_{2.1}$) the water balance is used. This means that the water that is not measured to overflow downstream ($O_{2.1}$) from the incoming, should enter the SUDS. Two main assumptions are hidden in the previous sentence. The first is that no losses are considered and the second is that the errors that are introduced in the calculation of the overflow and incoming to the SUDS water are accumulated in the value of the $i_{2.1.}$ Since due to the functions of the area there could not be a sensor on the terrain to measure that during a rainfall it is suggested to regularly experiment to define the variability of the infiltration on the terrain and the losses. Full-scale infiltration experiments (38) in different seasons and antecedent conditions are appropriate for that. If the variability is established, then the errors originating from the upstream incoming water calculations could be estimated.

Another assumption in the calculation of the water volume stored in the SUDS ($S_{2.2}$) is the assumption of the porosity in the system. This is included only in the systems that have a soil mixture that reduces the available area for water storage. FLOWSAND, URBAN RAINSHELL, and ZOAK BESTRATING are the systems that include that and for them, an assumption was made that only 30% of the available area can be provided for water storage. This overall assumption could be false if compaction of the soil occurs due to a heavy vehicle passing by. Or the initial value of the porosity can be different than assumed here, for example, URBANRAINSHELL has no soil but crashed shell material and could conclude to different porosity. The assumption that the rest of the systems provide all the available areas for water storage can also be false. For example, DRAINLINE & BUFFERTROTTOIR store the water in a trottoir system that reduces the available volume for water. Experiments should be done to measure the percentage of total storage that can be used for water. The experiments should be performed in a lab with a prototype system to eliminate the infiltration to the soil that would otherwise lead to an overestimation of the storage.

The limitations introduced by the choice of the sensors should be understood and where possible mitigated to reduce the errors in the estimation of the indicators that are of value in this thesis. It is also important to say that eliminating the errors is not possible due to the errors in the validation and calibration sensors and experiments, so it is more important to have knowledge on the variability of the indicators due to errors than to try to eliminate them.

4.4.1 Acoustic disdrometer sensor

Rainfall depth was defined in this work as the water per surface area in mm, which falls in the time frame of 1 min. The required periodicity of the sensor is linked to the time scale of the rainfall flux explained in section 3.3.1 Criteria for monitoring.

Picture 1 Disdro sensor. Acoustic disdrometer measuring rainfall.

To evaluate the possible sensors, the rainfall of once in 100 years was used as an extreme. The rainfall depth was calculated based on the research of Overeem (37) for the one-minute rainfall duration. It is found that 13.50 mm of rainfall is expected to fall once in 100 years with a duration of one minute. For the minimum rainfall, the value of 1 mm/min was used as a minimum limit. This value is considered in the light precipitation category (54) and a needed precision of 0.1 mm is required.

An acoustic disdrometer is one of the ways to collect rainfall (**i**) data. One type of disdrometer called Disdro (Picture 1) is already installed in the study area and complies with the needed quality of data as can be seen in Table 21. The choice to use that sensor reduces the overall cost of the monitoring network. An acoustic disdrometer uses drops sound to measure the volume of the droplet that falls on the sensor. A tipping bucket is already placed in the study area and can be used to validate and calibrate the Disdro sensor. The research of Islam et al. (55) presents the expected correlations between tipping bucket measurement and a Joss-Waldvogel disdrometer measurements and concludes that the hourly rainfall accumulation obtained with a disdrometer, one tipping bucket, and two rapid response counting gauges are well correlated. This means that the tipping bucket could be a way to validate and calibrate the Disdrto sensor.

The sensor selected and presented in Table 21 is the Disdro sensor (51) that is installed already on site.

Table 21 Comparison between the characteristics of the Disdro sensor that is chosen and the required values for every hard criterion.

Criterium	Limitation of criteria	Acoustic Disdrometer (56), (57)	Sensor Reference
Periodicity of measurement	1 min	1 min	(51)
Range	1-13.50 mm/min or maximum rainfall of 40.50 mm/hour for the same return period	One drop of 0.3mm diameter /min - 200mm/hour	(56) for min boundarie (58) for max boundarie
Precision	0.1 mm	0.1 – 0.45mm	(55)
Accuracy		5% of drop diameter	(56)
Environmental aspects and limitations		Wind (vibration), calibration errors	(55)

Distance between sensor and system		50m maximum	(55)
Available space		Around 0.1 m2 (On the office roof of The Green Village)	(59)
Cost		n/a (the investment is already done)	
Power availability		Available on the roof	
Data collection and display		The Green village data platform	Joep van der Weijden (personal communication, July 21th, 2021)

Considering the study area and the spatial variability of rainfall intensity, it would be redundant to use more than one point observation. This is because the variation in rainfall intensity in the small distances of this study area will not be that high to justify more than one rainfall observation. This is supported by the variogram created from the study of Schuurmans et al. (60) resulting from rainfall data from all over the Netherlands. Based on the variograms for all possible extend of rainfalls it can be concluded that for the maximum expected distance of 50m in the study area the variation in rainfall within that space is not expected to be high.

4.4.2 Diver in a controlled volume

To monitor the water that overflows from the system to the terrain downstream ($O_{2.1}$) and the water stored in it ($S_{2.2}$), the flow measurement principles listed in the report, Urban Stormwater BMP Performance monitoring, published by EPA (8), were researched. The significance of this report is that it focuses the research on monitoring SUDS which is also the main objective of this thesis. Based on that report the most appropriate methods to measure flow for SUDS were, Stage – based with the use of a weir or flume, velocity-based, volume-based, and stage-based with the use of empirical equations. Among them, the most appropriate for this study area was the volume-based (8) because it traps the overflowing water and also ensures hydraulic isolation from the top. The volume-based methodology was used in an experimental set-up in the research of Nielsen et al. (61). In this research, they used a runoff container that collected the overflowing water from a 1m x 1m vegetated plot in a controlled volume and measure the flow rate by measuring the change in water level ($o_{2.1}$) in the container. The same principle was suggested to be used in the study area.

For the water that overflows on the surface downstream of the SUDS, a controlled volume should be placed that will collect all the overflowing water and the rain falling on the container. A top view of this can be seen in Figure 37. This methodology will also help isolate the systems from the top because the water that does not infiltrate the system will be collected and will not affect a downstream system. The collected water could be directed next to the storm sewer.

For the water level measurement in the SUDS ($s_{2.2}$) and the infiltration to the soil ($i_{2.2}$), the same principle was suggested because the SUDS is a "leaky" container, and therefore by measuring the water level in it and the difference in water level, the storage in the SUDS and infiltration could be estimated.

Two different monitoring setups were considered. The first will provide the overflows from the surface ($O_{2.1}$) and the second the storage ($S_{2.2}$) and infiltration in the soil ($i_{2.2}$). The first setup consists of a controlled volume for which a volume estimation will follow, a water level sensor, and a device to empty the volume automatically. The second setup consists of a perforated pipe in the SUDS and a water level sensor. These components will be discussed next.

Water level sensor - Diver

The chosen diver should be able to deliver water levels with a periodicity of one minute which is also the time scale of the overflow and storage in the SUDS indicators (see section 3.3.1 Criteria for monitoring). It should also be able to measure the maximum and minimum water levels expected in the SUDS and the controlled volume ($o_{2.1}$). Based on the design of the SUDS the maximum water level that the diver might encounter is around 1.50m so this is the maximum range for the water level expected. The minimum water level can be expected at zero although all sensors have higher limitations for the minimum measurement. This means that the minimum possible water level depth that can be measured with the selected sensor should be considered the limit. The precision is selected to be 0.05 cm. This is the smallest water level change that needs to be detected.

The Diver chosen to collect the water levels is a mini–Diver DI501 from van Essen. Divers from this company were used in the research of J. Gravenberch (62). He experimented in the same study area by doing, among others, a full-scale infiltration test using the suggested sensor. The same type of divers from a different company was used in the dissertation report of Boogaard (63). Both pieces of research used the same principle to measure water level change to indicate the infiltration in the SUDS and hence motivate the choice to suggest it in this thesis. The characteristics of the chosen sensor can be found in Table 22.

Table 22 Comparison between the characteristics of the Diver sensor that is chosen and the required values for every hard criterion.

Criterium	Limitation of criteria	Diver sensor (van Essen)	Reference
Periodicity of measurement	1 min	From 0.5 sec	(52)
Range	0-1.5 m	3mm-10 m	(52)
Precision	0.05 cm	0.058 cm (The smallest increment in pressure that the Diver can measure)	(52)
Accuracy		+-0.5 cm	(52)
Environmental aspects and limitations		Maximum data that can be stored in the logger.	(52)
Distance between sensor and system		In the system	(52)

Available space		22 mm diameter x 90 mm length	(52)
Cost		Around 600 euro	(64)
Power availability		Batteries	(52)
Data collection and display		Add to The Green village data platform	Joep van der Weijden (personal communication, July 21th, 2021)

<u>Control volume container</u>

Two different types of controlled volume containers were considered for the two setups. The first will be for the overflowing water downstream on the surface or type 1, the second is considered to be the SUDS itself, or type 2. The design of the volume type 1 and dimensioning can be found next and the research on the maximum and minimum conditions that the sensor will encounter in the container. While for container type 2 and considering that the systems are already dimensioned, there is only needed to research the maximum and minimum water levels in the SUDS.

To estimate the maximum volume required for the type 1 container, first, it was assumed that all the upstream drainage area has no losses. This means that the maximum runoff coefficient of the upstream drainage area is 1. Then for the occupying area, it was assumed that 30% of the incoming water is infiltrating the system and the other 70% overflows downstream. This estimation was done based on the maximum runoff coefficient used for permeable pavements SUDS which is often assumed 0.7. Only for the system WATERTABLE [2] a runoff coefficient of 0.1 (10% will overflow downstream) was assumed because this system lets the water enter through a drain that is more efficient than a permeable material.

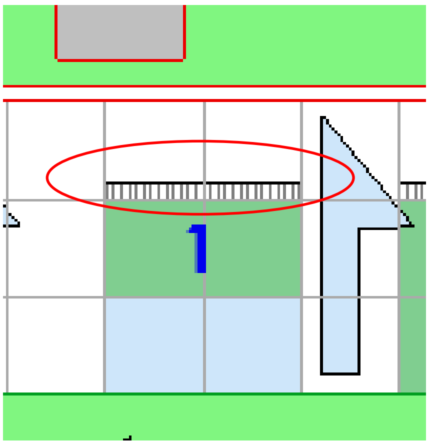


Figure 37 Overview of the Controlled volume container type 1 for the measurement of the overflow (O2.1). The container can be seen downstream the system and is circled with red. With grey vertical lines the entrance to the container for the overflow is indicated.

Additionally, to be able to capture the water level change at least 3 measurements should be taken in the condition of maximum incoming water. Knowing that the sensor is considering taking one measurement per minute, a volume of 3 minutes should be provided which will be the design volume of the container. It was also assumed that the maximum rainfall that the system could encounter is a one-minute rainfall occurring once per 100 years and was calculated based on the research of Overeem (37). That intensity is around 13.50 mm/minute. Based on the above the needed volume was calculated with the next equation:

$$V_{type1} = [A_{upstream} * (C_{upstream}) + A_{occupying} * (C_{occupying})] * i_{(T=100\text{ years, Duration of rainfall} = 1\text{ minute})} * 3\text{ minutes}$$

An estimation of the dimensions for the controlled volume type1 was provided based on the dimensions of the SUDS. To capture all the water flowing downstream of the SUDS the dimension perpendicular to the surface flow should be the same for both the controlled volume and the SUDS (see Figure 37). The dimension parallel to the overflow flux was suggested to be 0.30 m for all the SUDS for consistency in the design of the containers. The depth of the container was then adjusted to provide the needed volume to be stored for the maximum rainfall condition for 3 minutes.

A diver will be installed in the container with the known volume. The precision of the diver is one of the limiting factors for the design of the controlled volume. To estimate the minimum rainfall depth on the terrain that the diver in the container can measure, the next equation was used:

i_{min}(mm/min) = Minimum volume of water that the diver can measure in the container / [upstream and occupying areas, times the minimum runoff coefficient, for three minutes]

= (length of container * width of container * Precision of the diver)/ [($A_{upstream}$ *$C_{upstream}$ + $A_{occupying}$* $C_{occupying}$ + length of container * width of container) * 3 minutes]

For the minimum water levels, the minimum runoff coefficients of the upstream drainage and occupying area were considered to be 0.7 and 0.1 respectively. This is supported by the fact that the minimum water level in the container is expressed when the minimum water volume comes from upstream and the minimum volume overflows downstream. The results of the above research can be found in Table 23.

Table 23 Needed dimensions of the Controlled volume container type 1 along with the minimum precipitated rainfall depth that can be measured given the limitations of the proposed diver.

#	Name of system	Dimensions of system (length x width) (m)	$A_{Occupying}$ (m2)	Depth (m)	$A_{upstream}$ (m2)	V_{type1} (m^3)	Dimensions of container (length x width x depth) (m)	i_{min}(mm/min)
1	FLOWSAND	4x2	8	0.32	8	0.55	4x0.3x0.45	**0.030**
2	WATERTABLE	4x4	16	1.40	252	0.82	4x0.3x0.68	**0.001**
3	DRAINMIX	3x6	24	0.50	?			
4& 5	DRAINLINE & BUFFERTROTTOIR	8x2	16	0.23	16	1.10	8x0.3x0.46	**0.030**
6	BUFFERBLOCK	6x6	36	0.70	0	1.02	6x0.3x0.57	**0.064**
7 & 8	URBANRAINSHELL & DSI	12x2	24	0.85	64	3.27	12x0.3x0.91	**0.013**
9	RAINROAD	4x2	8	1.18	8	0.55	4x0.3x0.45	**0.030**
10	ZOAK BESTRATING	4x2	8	Not found	8	0.55	4x0.3x0.45	**0.030**

Based on the findings of Table 23 and considering the limitations of the disdrometer measuring rainfall not smaller than 0.3 mm (56), the limitation lies on the rainfall sensor first and then the diver.

For the controlled volume type 2, or the SUDS, the maximum water level was already mentioned at 1.40m and can be measured with the diver suggested. Regarding the minimum rainfall depth that the diver in the SUDS can measure the next equation was used following the same prosses as for the volume type 1:

i_{min}(mm/min) = Minimum volume of water that the diver can measure in the SUDS / [upstream and occupying area times the minimum runoff coefficient for the upstream and maximum for the occupying area for three minutes]

$= (A_{occupying} * \text{Precision of the diver} * \varepsilon) / [(A_{upstream} * C_{upstream} + A_{occupying} * C_{occupying}) * 3 \text{ minutes}]$

For the minimum water levels in the SUDS, the minimum runoff coefficient of the upstream drainage was considered to be 0.7, and the maximum for the occupying area was 0.7. This is supported by the fact that the minimum water level is expressed when the minimum water volume comes from upstream and the maximum volume overflows downstream. The parameter ε was assumed to equal 0.3 for the systems that include a soil mixture in the SUDS (FLOWSAND, URBAN RAINSHELL, and ZOAK BESTRATING) and 1 for the other systems because all the area is provided for storage. The results of the above research can be found in Table 24.

Table 24 Minimum precipitated rainfall depth that can be measured in the SUDS given the limitations of the proposed diver.

#	Name of system	Dimensions of system (length x width) (m)	$A_{Occupying}$ (m2)	Depth (m)	$A_{upstream}$ (m2)	i_{min}(mm/min)
1	FLOWSAND	4x2	8	0.32	8	**0.04**
2	WATERTABLE	4x4	16	1.40	252	**0.016**
3	DRAINMIX	3x6	24	0.50	?	
4& 5	DRAINLINE & BUFFERTROTTOIR	8x2	16	0.23	16	**0.13**
6	BUFFERBLOCK	6x6	36	0.70	0	**0.27**
7 & 8	URBANRAINSHELL & DSI	12x2	24	0.85	64	**0.075**
9	RAINROAD	4x2	8	1.18	8	**0.14**
10	ZOAK BESTRATING	4x2	8	Not found	8	**0.04**

Based on the findings of Table 24 and considering the limitations of the disdrometer measuring rainfall not smaller than 0.3 mm (56), the limitation lies on the rainfall sensor first and then the diver.

V pump to empty the controlled volume type 1

In the research of Nielsen et al. (61) the device that emptied the container was a submerged V pump. Considering that for this study area, 7 controlled volumes are considered, and one pump should be installed in every controlled volume. The exact capacity of the pump is affected by the volume of water that has to be drained away within one minute and will be activated when the water level reaches the maximum depth of container type 1. More research on the exact pump requirements will not be provided in this thesis due to time limitations and the need for validation of the upstream drainage area that affects the needed volume to be drained.

Observation pipe in the system for controlled volume type 2

A simple perforated pipe with a diver logger in it can be placed in the system to let the water enter without debris or sand entering the pipe. Both the water stored in the SUDS ($S_{2.2}$) and the infiltrated water in the soil ($i_{2.2}$) can be derived from the change in water level in the perforated pipe ($s_{2.2}$).

4.4.3 Sonar pulse sensor

The sensor chosen should provide the water levels in the aquifer (s_3). Since the ground water levels are expected to increase on a bigger temporal scale (see section 3.3.1 Criteria for monitoring) hourly measures of the water levels are required. To estimate the maximum and minimum expected water levels in the observation wells it was assumed that the water level can shift between the ground level and the water level maintained in the canal surrounding the study area. Based on section 2.3 Boundaries of thesis, that is expected to be from zero to 2.10 m. Lastly, a precision of 5 mm is needed for the sensor. That is the smallest water level change that needs to be detected.

The groundwater table **(S_3)** is already measured hourly in the study area in two locations. The sensor used already is a sonar pulse sensor that sends a pulse in an observation well and measures the time it takes for the pulse to return. The sensor, Level Log complies with the needed quality for this thesis. Knowing the water table, the exact groundwater level under the systems should be derived. The Dupuit equation with the assumption of an unconfined aquifer in one-dimensional flow and two constrained boundaries can be used for the exact water level under the systems (h(x)) (16 p. 53) based on the equations below:

$$h(x) = -[(i/2T) * (x^2 - L*x)] + [(\mathbf{h_1} - \mathbf{h_0}) * x/L] + \mathbf{h_0}$$

$$S_3 = dh(x)_{\textbf{under the system}} * Po_G$$

X: distance of the center of the system from the upstream observation well
h0 = groundwater level at the upstream observation well
h1 = groundwater level at the downstream observation well
i: precipitation
T= k*H
k= hydraulic conductivity of soil
H= saturated thickness of aquifer= average distance between the bottom of canal and average measured groundwater level= 2.40 + 0.91= 3.31 m
L= distance between the two observation wells
PoG: average porosity in % of the soil under and around the system

The characteristics of the Level Log sensor are shown below,

Table 25 Comparison between the characteristics of the LevelLog sensor that is chosen and the required values for every hard criterion.

Criterium	Limitation of criteria	Level Log sensor	Reference
Periodicity of measurement	1 h	From 0.5 sec	(53)
Range	0-2.1 m	0-20 m	(53)
Precision	5 mm	1 mm	(53)
Accuracy		+-0.5 cm	(53)
Environmental aspects and limitations		Maximum data that can be stored in the logger.	(53)
Distance between sensor and system		Maximum distance between sensors and systems = 50 m	Map of the study area

Available space		25-65 mm diameter for a pipe	(53)
Cost		Not found	
Power availability		Batteries	(53)
Data collection and display		Microsoft Power BI	(53)

4.5 Monitoring network for water quantity indicators of performance

4.5.1 Recommended experiments before implementing the sensors on WaterStreet

Validation of upstream drainage area

As concluded in section 4.1.3 System's interaction with surroundings, the use of design reports of WaterStreet's terrain to calculate the upstream drainage area of a system may lead to miscalculating the incoming volume of water in the system. It is proposed to do a topography survey to validate the upstream drainage area of the systems and validate the hydraulic interaction from above. Additionally, the surroundings of the study area terrain should also be validated because the results, shown in section 2.4 Terrain, are considered based on data collected from AHN (14). Due to subsidence, it might be the case that the upstream drainage area to the system is very differently realized than what is resulted in this research. Validation of the upstream drainage area should be done regularly as the volume of the incoming water is a significant flux of the water balance and is very much affected by the upstream drainage area.

Runoff coefficient of the upstream drainage area

To estimate the overflowing water from the upstream drainage area (O_1) assumptions for the runoff coefficient were made. This can lead to overestimation of the runoff volume leading to a high cost of monitoring network choices. One example is the dimensioning of the controlled volumes to measure the overflow downstream of the SUDS. Experimentation on the runoff coefficient of the upstream drainage area could help lead to a better estimate. Similar experimentations are found in the research of Nielsen et al. (61) and can be used as a guideline for the experiments proposed in this section.

The experiment could use the rational method. The runoff coefficient ($C_{upstream}$) of the upstream drainage area ($A_{upstream}$) is assumed to be the percentage of incoming water from rainfall that ends up upstream of the SUDS (O_1). Rainfall simulators are available in WaterStreet, so rainfall intensities (i) of once a year, once in 10 years, and once in 100 years can be simulated and the runoff coefficient can be calculated by the next equation.

$$C_{upstream} = O_1 / [\, i * A_{upstream}]$$

With a better estimate of the overflowing from the upstream drainage area (O_1) and monitoring the overflowing downstream of the SUDS ($O_{2.1}$), an estimation of the losses on the SUDS and infiltration in the SUDS, can be provided based on the water balance of the first layer.

Define the Infiltration variability of the systems

Regarding the placement of the diver in the bottom of the SUDS to measure the infiltration to the soil ($i_{2.2}$), experiments should be performed to indicate the variability of infiltration on the surface of the SUDS bottom. Based on the monitoring suggestions provided in section 4.4.2 Diver in a controlled volume and the calculation for the Hydraulic response graph shown in section 3.1.2 Hydraulic response graph (HRG), it was assumed that the infiltration to the soil is the same along the SUDS bottom and walls. That assumption might be false due to differences in clogging of the infiltration surfaces of the SUDS. To include the effects of clogging only 25% of the infiltration surface was assumed to let water flow through as a safety factor. This assumption could lead to overestimation of infiltration in the cases of much clogging or underestimation in cases of clean infiltration surfaces. Therefore, this assumption should be validated along with the variability of the infiltration on the surfaces.

4.5.2 Network of sensors in WaterStreet

Table 26 summarizes the sensor per SUDS based on their design. Additionally, the sensors regarding rainfall and groundwater levels correspond to the study area. Due to the small variability expected within this area, one sensor for rainfall can provide the needed information representing the entire study area. Regarding the groundwater levels, already two sensors are monitoring and can help visualize the groundwater table in the path section of the study area but two more should be added to represent the square area and visualize the water table in three dimensions under the total study area. The placement of the sensors is visualized on the top view of the study area in Figure 38 and in a cross-section in Figure 39.

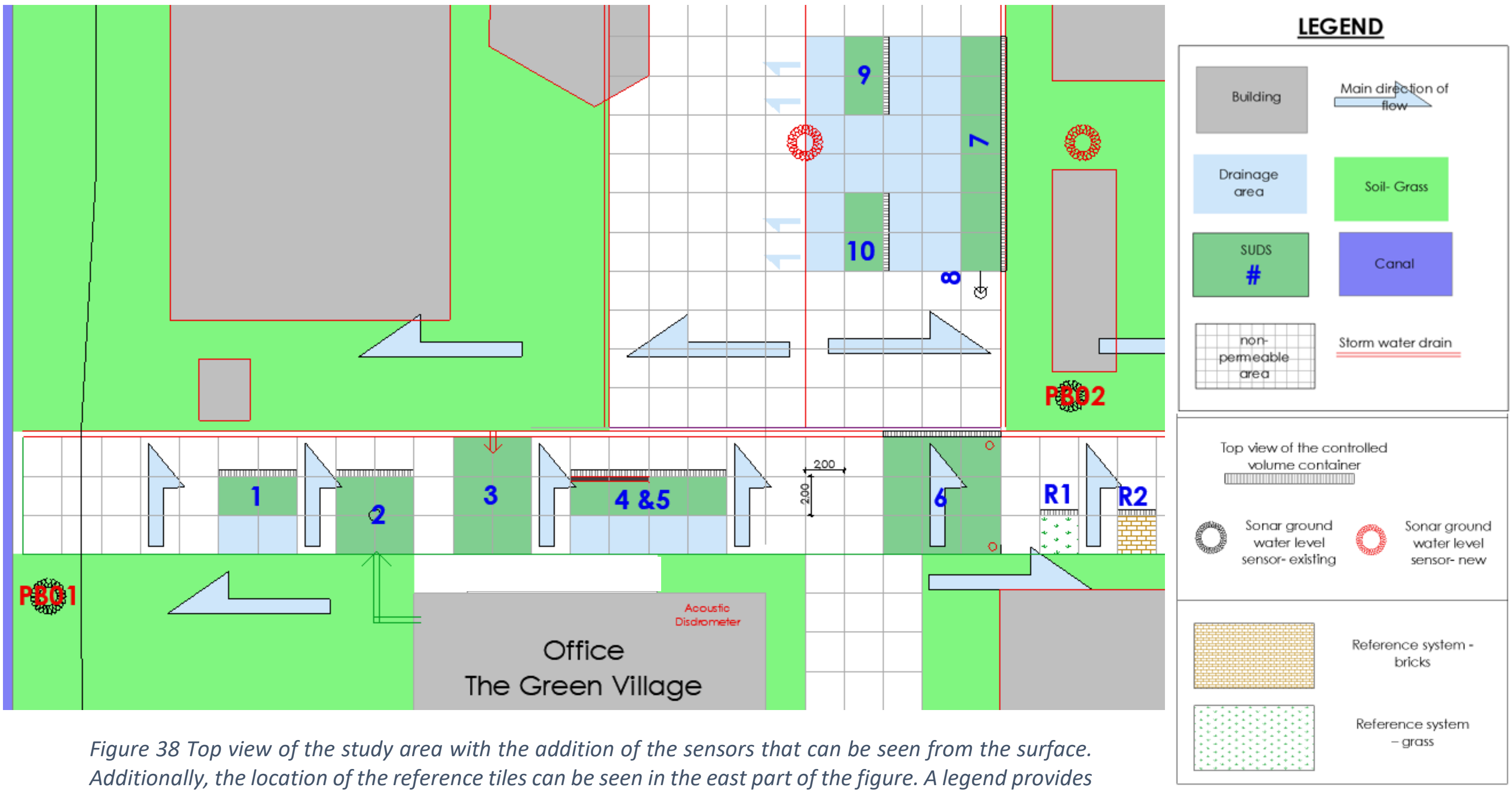


Figure 38 Top view of the study area with the addition of the sensors that can be seen from the surface. Additionally, the location of the reference tiles can be seen in the east part of the figure. A legend provides information on how the different components are represented in the figure.

Table 26 Concluded sensors for every system based on the design and the characteristics of the study area.

Sensor	Data obtained	[1] *FLOWSAND*	[2] WATERTABLE	[3] DRAINMIX	[4&5] DRAINLINE & BUFFERTROTTOIR	[6] BUFFERBLOCK	[7&8] URBANRAINSHELL & DSI	[9] RAINROAD	[10] ZOAK BESTRATING	STUDY AREA (WaterStreet)
ACOUSTIC DISDROMETER	i									√(1)
DIVER IN CONTAINER	$o_{2.1}$	√	√		√	√	√	√	√	
DIVER IN OBSERVATION PIPE	S_2	√	√	√	√	√	√	√	√	
	$i_{2.2}$	√	√	√	√	√		√	√	
SONAR PULSE SENSOR	S_3									√(4)

To visualize the placement of the sensor in and around the SUDS Figure 39 was schematized.

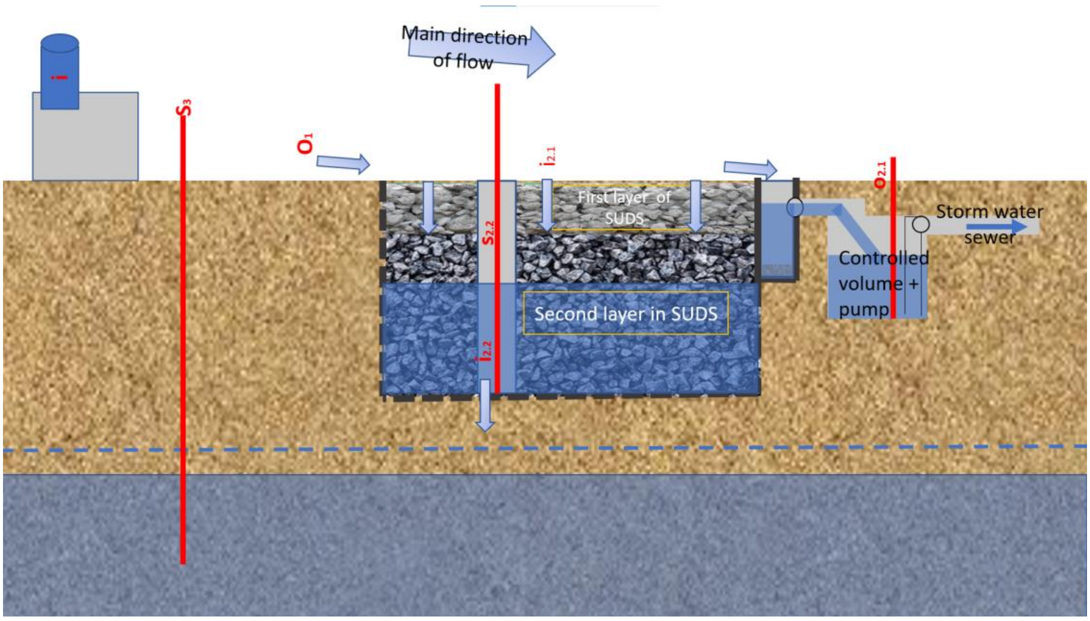


Figure 39 Indicators with red. The red vertical lines indicate a water level sensor. A disdrometer is placed on the roof of the office to measure rainfall depths (i). Groundwater level sensors called LevelLog will measure the groundwater level in the soil (S_3). A diver in a controlled volume will measure the overflowing water downstream of the SUDS ($o_{2.1}$). A pump will be placed in the controlled volume to empty it and direct the water to the storm sewer. Lastly, a perforated pipe with a diver in it is suggested to measure the water level in the SUDS ($s_{2.2}$) and the infiltration rate in the soil ($i_{2.2}$).

To reveal the added value of SUDS on the reduction of flooding, two reference plots are suggested. The first one includes a soil terrain Figure 40 and the second is a simple brick terrain Figure 41 mainly found in the Dutch pavements. Due to the chosen grid of the study area which is 2 m by 2 m the reference systems should also have the same dimensions. The location of the references should be such that no upstream area is considered so that the catchment would be easily realized and calculated. The location of the reference plots can be seen in Figure 38. The comparison of the overflow downstream ($O_{2.1}$) between the two reference systems can motivate the further implementation of infiltration systems. The types, of brick and soil terrain, are supported after discussion with the Circular economy manager of The Green Village, Willy Spanjer (personal communication, Friday 18 February 2022).

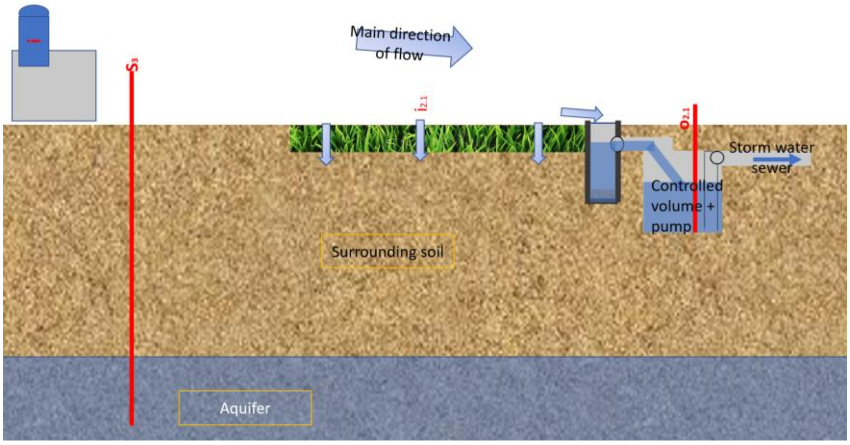


Figure 40 Reference plot of the simple soil with grass. This reference will help indicate the value of a SUDS implementation in comparison to an unpaved terrain.

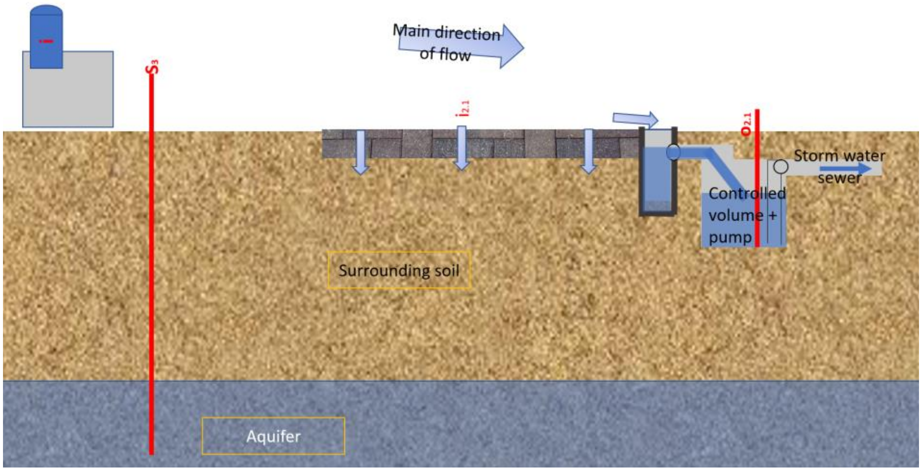


Figure 41 Reference plot of the simple brick terrain. This reference will help indicate the value of a SUDS implementation in comparison to a simple brick terrain used in the Netherlands.

5. Discussion- Limitations

Limitations are introduced in this study. Limitations on the concluded KPIs, the characteristics of the study area, and the selection of sensors to monitor the indicators are introduced. These limitations were already addressed in this report and summarized here intending to provide meaningful discussions and possible ways to resolve them.

KPIs

The focus of this research was on the water quality and quantity performance of SUDS. Functions of SUDS like biodiversity and amenity are also important to consider. Different indicators for these functions of SUDS should be considered because the measure of biodiversity is the variation in animals and plants found on and in the SUDS and a measure of amenity is represented by the positive feeling that the existence of a SUDS creates to the residents around the SUDS. Although they are measured in different units a relationship between the water quality and quantity indicators and the biodiversity and amenity indicators can be observed. For example, if one system does not infiltrate the water at the needed rate ($i_{2.2}$ small) then the residents could feel disappointed, reducing the amenity. There is also the chance that a system performs well in water stress but is not visible to the residents, meaning that the amenity is not increasing or decreasing by the SUDS. There is a correlation between the indicators of most functions but still, they are measured in different units. Interesting research on the use of eDNA sampling for biomonitoring river networks is e.g., done by Luca Carraro et al. (65). Based on the eDNA condition they asses the biodiversity condition of the stream. Samples can also be taken from the stored water in SUDS to assess the measure of biodiversity. This methodology could be more useful for SUDS, like Bioretention basins than permeable pavements. Additionally, questionnaires to residents could provide the perception of SUDS in urban areas as a measure of performance for amenity. Research done in England by Williams et al. in 2019 showed that generally, residents liked the wildlife and green space introduced with SUDS (66). A survey was performed in this study asking the residents to score the benefit of the SUDS, considering 10 functions of SUDS, like flooding, wildlife, health, and others.

Regarding the SUDS functions to water quantity, the reduction of the heat island effect in urban areas was not included in this thesis. This decision was taken because only half of the systems in WaterStreet, FLOWSAND, URBANRAINSHELL, ZOAK BESTRATING, and RAINROAD, considered this function in their design while management of rainwater is the objective of all systems on WaterStreet. Analysis of the energy balance that is connected to the water balance through the flux of evaporation, could be valuable to indicate the effect of SUDS on surface temperature. Interesting research using thermal cameras to provide the difference in surface temperatures was found by Morrison et al. (67). Implementing the same methodology on SUDS could provide an indicator of cooling.

Regarding the actors that were included in the actor's map, one limitation was the inclusion of 3 levels of actors. This means that only the actors that could relate to the problem owner (WaterStreet) within 2 steps were included. Although all closely relevant actors were included, more external ones, like the EU for example, were not. Additionally, the actors' map was validated in 6 interviews with participants of mainly academic backgrounds. Including more actor levels and validating them with a more diverse group of participants could reveal more important actors and more interdependencies between them. The EU is one important actor that could contribute more value to the actors' map.

This is because they have the power to introduce regulations to the EU members for water quality standards and management of water quantity. They also have the interest to have more SUDS implemented to reduce flooding and water quality deterioration for example. EU regulations are included in the law of the members creating a strong interdependency between the EU and the SUDS developers because they have to consider the regulations in the design. The list of actors was researched to conclude the most powerful and interested to implement SUDS. Their additions to the list of indicators were considered in this thesis for the choice of KPIs. Having more actors to compare their power and interest could affect the order of actors for their power and interest.

Also, about the power interest grid, only 17 participants out of the 68 responded to the online questionnaire to score the power and interest of the actors. Additionally, not all the actors' groups from the actor's map, could be represented in the list of participants. More participants from diverse backgrounds could provide, the most powerful and interested stakeholders with more certainty. The participants did not represent the next group of actors, ministries of infrastructure, ministries of economic affairs, and waterboards. The addition of more participants from the groups of municipalities and waterboards could be valuable considering that they are active in implementing SUDS in the Netherlands. Only two responses from municipalities and none from waterboards are included in the power interest grid of this thesis.

Based on the power interest grid the most powerful and interested stakeholders were revealed. These were then considered to validate the list of KPIs from the literature. Considering more stakeholders from the actor's map to validate the KPIs could provide more KPIs but this choice was taken to reduce the duration of this thesis. From the stakeholders that did not provide insight, interesting could be the view of waterboards because they play a significant role in the water management of urban areas in the Netherlands. Residents, ministries, and STOWA representatives could also provide additional important indicators.

Regarding the list of KPIs from the literature, the focus of the reviewed reports was on the Dutch or European environment, but other countries have also been very active in implementing and assessing the performance of SUDS. United States has created monitoring guidance for SUDS (8) for example, while Australia is also very active to implement SUDS (3). A more universal view of literature regarding the performance indicators could provide more indicators to the list and define the correlation between used indicators and climate characteristics. For example, lowlands consider groundwater rise a significant indicator while in more arid climates this indicator could not be so significant. A universal way to indicate the performance of SUDS should consider the effect of climate on the significance of the indicators provided in this thesis.

Study area analysis

One limitation that this thesis faced, regarding the study area, was the fact that the systems are dynamic. This means that developers could change the design of SUDS, and remove, or add more systems. This dynamic character results in fluxes or storages included or excluded from the water balance of the SUDS. One example of that was RAINROAD system that during this thesis changed the design. More accurately they reduced the surface that lets water enter the soil to store more water in the SUDS and increase evaporation. Additionally, the system BUFFERBLOCK was removed from the study area sometime between May 2021 and February 2022. Moreover, other systems have been added to the terrain of the Green Village. The decision to consider only systems and the design from the start of this thesis, around April 2021, was taken to reduce the complexity of the study due to the need for remote working. Future research should consider regular visits to the study area to validate the condition of the systems. Additionally, new systems should consider the issue of hydraulic isolation in the location they are considered to be placed. This means that the placement of the new SUDS should not affect or be affected by other systems.

Sensors and monitoring network

Not all the decided Key performance indicators for water quantity were realized with the suggested sensors. Starting with the overflow from the SUDS through a drain ($DO_{2.2}$) to the storm sewer, this was excluded because based on the results of this thesis the SUDS implemented in WaterStreet are not expected to be full even with the incoming water of a once in 100 years occurs. In different setups, this flux might be important to monitor not only for the performance of SUDS but also for the stress to the storm water sewer introduced due to SUDS. The significance of this flux in other set-ups is the reason why it is included in the Key Performance Indicators list.

The proposed monitoring network consists of sensors that acquire data from which the indicators are either directly provided or calculated with assumptions for the runoff coefficient or the use of the water balance. One example is the calculation of the water that overflows from the upstream drainage area (O_1) to the SUDS for which the runoff coefficient was assumed. The amount of water that enters the system ($I_{2.1}$), on the other hand, is calculated based on the water balance. This means that what is not measured in the controlled volume, that captures the overflowing downstream water ($O_{2.1}$), from the incoming water ($P+O_1$) should enter the SUDS and eventually infiltrate the soil. The assumptions of the runoff coefficients carry an uncertainty that should be considered in the interpretation of the results. This uncertainty was introduced due to the assumption that losses on the terrain are steady although that is not the case because they are affected by other factors, like antecedent conditions. Using the water balance to calculate the water that enters the SUDS, for example, should consider the accumulated error of the sensors and methods used to provide the parameters of the water balance. Regular validation of the sensors and considering the errors in the interpretation of the results is essential to provide valuable conclusions for the performance of SUDS. One example of a sensor that could validate the rainfall data provided by the disdrometer is the tipping bucket that is already installed in the study area.

Another limitation of this thesis was the focus of the monitoring network to provide the key performance indicators and indicators of performance. This excluded some indicators that could provide a closed water balance. Indicators of soil moisture storage, evaporation, and transpiration were the three components not included in this research. Analysis of how to monitor all the fluxes and storages of the water balance could help calibrate and validate hydraulic models to simulate the response of SUDS. In that respect, the addition of sensors for soil moisture, evaporation, and transpiration could provide all the necessary indicators for a closed water balance.

Regarding the selection of sensors, one limitation was that only the hard criteria were used to direct the selection. This choice was made to limit the time frame of this thesis. Selection based on more criteria could lead to different sensors. Cost and accuracy are the most important criteria not taken into account, that could contribute to higher data quality and better motivation for the overall implementation of the network. A cost analysis of the proposed monitoring network for WaterStreet could be a useful future study following this thesis.

The choice of sensors was based on literature findings reporting the use of the same or similar sensors. Validating the feasibility of the chosen sensors was not possible due to remote working. This motivated the future need to validate the feasibility of the chosen sensors by implementing them. Additionally, all the sensors can provide errors, either random or systematic. Knowing the boundaries of the sensors can help understand unexpected data and exclude them from the data set used to provide the indicators. The limitations of the chosen sensors should be validated and considered for the use of the data. WaterStreet is a living lab that could benefit from that feasibility research because it could lead to a more advanced monitoring network.

A maintenance scheme of the monitoring network is not included in this research because it is beyond the objective of this thesis. Maintenance of the sensors is essential to the interpretation and usefulness of the data. For example, after analyzing the rainfall data from the tipping bucket it turned out that the data could not be used because the bucket was full of leaves. Scheduled maintenance of the devices could help reduce errors and increase the usefulness of the data sets from the monitoring network.

The quantity of the sensors that form the suggested monitoring network was based on spatial limitations of the study area, like the dimensions of the plots and the study area. This means that using the same monitoring network in different study areas should be done with caution. As done in this research the temporal and spatial scales of the water balance components should be reviewed first. An analysis of the spatial boundaries of the proposed monitoring network could help identify the limitations of the network suggested.

6. Recommendations for future implementation of SUDS

Based on the findings of this thesis several recommendations for the study area of WaterStreet were highlighted. Considering these recommendations could decrease the complexity of the water balance and increase the quality of the data provided by the monitoring network.

An important recommendation was the research of hydraulic isolation for the existing systems and consideration for future implementations. To ensure the isolation from the bottom, it was suggested to put drainage pipes under the study area to achieve a drainage depth of at least 0.5 m under the bottom of the deepest system. Additional groundwater observation wells were recommended to visualize the groundwater table in 3D view. For the isolation from the top, the drainage area of a system should be ensured. This can be achieved either by placing the systems in a way that no system is downstream or by trapping the overflowing water in a container and directing it to the storm sewer. The last suggestion was considered in this work to also provide a measurement point for the overflow, making it essential for the monitoring network of SUDS.

More information on the initial characteristics of the system when they are implemented should be provided. Experimenting with the initial infiltration in the soil under a system or the initial infiltration of the first layer of SUDS are two examples of experiments. Moreover, before implementing them the design rainfall should be calculated based on the upstream drainage area of the system. The provided storage for the SUDS already designed and implemented in WaterStreet was found much bigger than the needed for rainfall with a return period of once in 100 years. The criterium of the design rainfall of once in 100 years is set in the CIRIA report “The SUDS Manual” (2015) (5). It is suggested for future implementations provide a more representative balance between the incoming water and the provided volume of storage. This could be done by increasing the upstream drainage area, designing the SUDS smaller, or doing both.

Possible water quality indicators were based on findings in Dutch reports of STOWA that in turn considered the EU water framework directive. So, first, the existence of pollutants should be validated as well as their ability to be absorbed and adsorbed on Total Suspended Solids. WaterStreet is a unique study area because it resembles the activities of a village but at the same time, it is a living lab that is more carefully managed than in strictly residential or urban areas, meaning that some pollutants might not enter the area. Additionally, the effect of pH and water temperature on the reduction and remobilization mechanism of pollutants is suggested for further lab experimentation. This will allow for motivated suggestions for the monitoring network for water quality.

Lastly, it was suggested for the monitoring network to add two reference plots, one with vegetated soil and one with regular brick terrain. This could enhance the motivation for more SUDS in residential areas due to the reduction of overflow downstream. While the type of terrain and the available storage plays a significant role in the regulation of urban overflow, the type of subsoil can also play a significant role. For future considerations of living labs like WaterStreet, it could provide valuable results to consider a section with subsoil with good infiltration properties like sandy soil and a section with clay soil. Especially in the Netherlands and other lowlands, clay formations can be often found.

The recommendations in the previous section were more dedicated to the study area of WaterStreet. Other actors that implement SUDS could also benefit from some of the recommendations. The consideration of the hydraulic isolation, the existing pollutants, the experimentation of the initial conditions, and the provision of overflow to a drain to help monitor the performance easier are recommendations that could be useful for implementations of SUDS from other stakeholders, like municipalities.

7. Conclusion

Key performance indicators (KPIs) are a valuable tool to assess the performance of Sustainable Urban Drainage Systems (SUDS). They permit the comparison between different systems, especially newly designed ones, like the ones implemented in the study area of WaterStreet. Although it is a useful tool, no comprehensive set of KPIs was agreed upon between key stakeholders in the Netherlands, like municipalities and SUDS developers, or in literature. Important indicators are provided in literature like the infiltration of the permeable material or the available storage in the system, but they are in the form of advice and no obligation, leading to different stakeholders prioritizing indicators in a different order or even considering additional. The focus of stakeholders and literature was on the indicators connected to the overflowing condition and the stress that leads to it but did not reflect the cause of overflow as much. A distinction between the key performance indicators (KPIs) and indicators of performance (IP) was introduced in this work with the help of the water balance of SUDS in WaterStreet, to reflect that observation. Key Performance Indicators (KPIs) are, the overflowing volume of water downstream ($O_{2.1}$) or through an overflow drain to the storm sewer ($DO_{2.2}$), the duration of overflow (D), the frequency of overflow, and the volume of water that enters the system, reflected in the indicators rainfall (i) and incoming water from upstream drainage area (O_1). Indicators of performance (IP) are the infiltration to the system ($i_{2.1}$) and the subsoil under the system ($i_{2.2}$), the available storage in the system ($s_{2.2}$), and the soil (S_3).

An important observation reflected in the interviews with stakeholders was that the KPIs discussed did not reflect water quality. In the literature, possible water quality Performance Indicators for SUDS were indicated. These were Total Suspended Solids (TSS), Total Phosphorus, pH, and ground water temperatures. The reduction in the concentration of TSS as a proxy for the reduction of pollutants is used in Germany as an "authoritative evaluation" parameter because it absorbs heavy metals and car pollutants. Additionally, they consider including the reduction in Total Phosphorus (12). No specific guidelines for removal efficiencies are considered in the Netherlands (12) although key pollutants are considered to be copper, zinc, and total phosphorus (12). In the Netherlands much research was done on the harmful pollutants that can attach to rainwater but understanding the mechanisms of reduction of those pollutants as they pass through a SUDS or soil, to end up in a stream is complicated. PH and temperature changes can affect the mechanisms or even remobilize the pollutants stored in SUDS. Considering proxies, like TSS reduction, for SUDS indicators of water quality should be done with caution because a reduction in TSS does not always mean an equal reduction in pollutants resulting in over or underestimating the performance of SUDS. Knowledge of what pollutants can end up in the study area, the prevalent reduction or remobilization mechanism, and already existing pollutants stored in the soil or existing geogenic pollutants are suggested for further research before indicating a list of Key Performance Indicators for SUDS. Concluding on the KPIs for water quality is essential before suggesting sensors to monitor them.

To visualize the performance of SUDS and show the connection between KPIs and IPs, a hydraulic response graph (HRG) was developed. The HRG distributes the incoming volume of water, based on the Depth Duration Frequency curves (DDF) with a certain return period, in the soil, storage, and overflow, considering the design of SUDS and the infiltration capacity of the surrounding soil. Plotting the HRG for the SUDS in WaterStreet concluded that all 5 studied out of 8 total SUDS are overmentioned. This means that they provide more storage than needed for a rainfall occurring once in 100 years. Also, for 3 out of 4 systems researched that also include infiltration through the first layer of the SUDS, the limiting factor that led to overflow was the infiltration through the first layer of the SUDS, meaning that although they would not be full, overflow would occur due to that. Living labs, like WaterStreet, are an intermediate step between lab and real implementation. The challenge is to design them and place them to fit the living lab and also respond proportionally to reality when rainfall occurs. That was not the result for WaterStreet based on the analyses with the HRG. Designing SUDS for implementation in living labs should consider those aspects to get more valuable results from their response to rainfall.

The concept of hydraulic isolation was introduced in this thesis. Especially in a living lab like WaterStreet where many SUDS are implemented next to each other and can easier affect each other's performance. Stakeholders that implement SUDS should not forget the issue of hydraulic isolation when designing and implementing them. Isolation from the top or bottom of the systems is important when interpreting the performance of SUDS. Isolation from the top means that in the upstream drainage area of one SUDS there is no other SUDS located. Isolation from the bottom means that SUDS are not under the groundwater table at any time. If that occurs, then the groundwater flows from one system to the next. Based on the terrain slopes of WaterStreet and the observation of groundwater tables within two years, only half of the systems were found to be isolated from both the top and bottom. Constraining the water that overflows downstream of the SUDS in a container and ensuring a drainage depth of at least 0.5 m under the bottom of the deepest system are important to provide the condition of hydraulic isolation. In lowlands like the Netherlands, high groundwater tables can often be observed, and the slopes are not that steep to guarantee the drainage area of a SUDS. Small subsidence of the terrain can alter the drainage area much.

WaterStreet is a living lab that demonstrates the use of new SUDS and conducts field experiments to promote their implementation on a bigger scale. Suggesting a monitoring network to provide both the KPIs and IP can increase the value of WaterStreet by measuring the performance of the implemented SUDS. Infiltration tests can be performed, and a weather station and groundwater observation sensors already provide some KPIs and IP like rainfall (i) and storage in the soil (s_3), but a full understanding of the response could not be realized only with them. The use of divers to measure, the water level stored in the system ($s_{2.2}$), the water infiltrated in the soil ($i_{2.2}$), and the water level in a controlled volume to measure the water overflowing ($o_{2.1}$), were the additional sensors proposed for the monitoring network. An acoustic disdrometer to measure rainfall (i) is already placed in the study area and a suggestion for more groundwater sensors to capture the 3D view of the groundwater table was given. The sensors for groundwater and rainfall represent the entire study area based on the variation of the parameters within that area. Although the monitoring suggested includes both KPIs and IP, the cost of all the sensors combined can constrict the implementation of all the sensors in other areas. To only measure the KPIs for example a diver in a controlled volume and rainfall sensors are only needed along with research on the runoff coefficient of the drainage area upstream of the SUDS. To further reduce the cost of monitoring, rainfall information can be derived from regression of neighboring weather stations, if the distance between the weather station and the system is not significant to provide a high variability of the estimated rainfall. For easier monitoring of the overflowing water, which was found to be the most challenging, a container capturing the flux was considered that would also lead the overflow to the combined sewer system. In this way overflow would not be visible to residents and monitoring is also possible although it is important to research the overflowing frequency and amount because the direction of that water to the storm sewer should not lead to an increase in Combined Sewer Overflow events.

References

1. EEA. *Urban adaptation in Europe: how cities and towns respond to climate change.* Luxembourg : Publications Office of the European Union, 2020.

2. *Performance and implementation of low impact development – A review.* Eckart, Kyle, McPhee, Zach and Bolisetti, Tirupati. s.l. : Elsevier B.V., 2017, Science of the Total Environment, Vols. 607-608, pp. 413-432.

3. *Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States.* Roy, A.H., et al. 2, 2008, Environ. Manag., Vol. 42, pp. 344-359.

4. Village, The Green. About us. *The Green Village.* [Online] The Green Village. https://thegreenvillage.org/en/.

5. CIRIA. *The SUDS Manual.* s.l. : CIRIA, 2015.

6. *Integrating Local Scale Drainage Measures in Meso Scale Catchment Modelling.* Hellmers, Sandra and Fröhle, Peter. 71, s.l. : Water 2017, 2017, water, Vol. 7, pp. 1-26.

7. CIRIA. *Guidance on the construction of SUDS.* s.l. : CIRIA, 2017. 978-0-86017-783-8.

8. Geosyntec Consultants and Wright Water Engineers, Inc. *Urban Stormwater BMP Performance Monitoring.* 2009.

9. Services, Roads and Maritime. *Water sensitive urban design guideline. Applying water sensitive urban design principles to New South Wales transport projects.* Sydney : NSW Goverment, 2017. 978-1-925421-88-0.

10. STOWA. *VERKENNING VAN DE KENNIS VAN ONTWERP, AANLEG EN BEHEER VAN ZUIVERENDE REGENWATERSYSTEMEN ZUIVERENDE VOORZIENINGEN REGENWATER.* s.l. : STOWA, 2007. 978.90.5773.369.7.

11. EPA. *Storm Water Management Model User's Manual Version 5.1.* s.l. : Office of Research and Development, 2015.

12. *General Technical Approvals for Decentralised Sustainable Urban Drainage Systems (SUDS)—The Current Situation in Germany.* Dierkes, Carsten, Lucke, Terry and Helmreich, Brigitte. 2015, Sustainability, Vol. 7, pp. 3031-3051.

13. Waterstraat, website. Projects/ Waterstraat. *The Green Village.* [Online] [Cited: 14 01 2021.] https://www.thegreenvillage.org/projects/waterstraat.

14. viewer of AHN. *ahn.nl.* [Online] https://www.ahn.nl/ahn-viewer.

15. Wensink, N. . *VERKENNEND MILIEUKUNDIG BODEMONDERZOEK AAN DE VAN DEN BROEKWEG (TERREIN GREEN VILLAGE) TE DELFT .* s.l. : VanderHelm Milieubeheer B.V. , 2017.

16. Verruijt, A. *Theory of Groundwater Flow.* s.l. : MACMILLAN, 1970.

17. The Green Village, Web site. About the Green Village. *The Green Village.* [Online] [Cited: 14 01 2021.] https://www.thegreenvillage.org/about-us.

18. Leskens, Anne and Lekkerkerk, Jonathan . *RAAK MKB PROJECT DE INFILTRERENDE STAD" WERKPAKKET 1: SYSTEEMANALYSE.* 2020.

19. van de Ven, Frans H.M. *Water Management in Urban Areas.* Delft : Faculty of Civil Engineering and Geosciences, 2016.

20. RIONED. riool.net/kennisbank. *riool.net.* [Online] https://www.riool.net/kennisbank.

21. —. missie en strategie. *riool.net.* [Online] [Cited: 13 09 2021.] https://www.riool.net/over-rioned/missie-en-strategie.

22. STOWA, about. over-stowa. *STOWA.nl.* [Online] [Cited: 13 09 2021.] https://www.stowa.nl/over-stowa.

23. CIRIA.ORG/CIRIA/ABOUT. *CIRIA.ORG.* [Online] [Cited: 13 12 2021.] https://www.ciria.org/CIRIA/About/About_CIRIA/About/About_CIRIA.aspx?hkey=ee27f3c1-3a9b-49ec-a99c-58621b3d7319.

24. Ballard, Woods, et al. *The SuDS Manual.* London : CIRIA, 2015. 978-0-86017-760-9.

25. Liefting, H.J. , Boogaard, F.C. and Langeveld, J.G. *Kwaliteit afstromend hemelwater in Nederland Database kwaliteit afstromend hemelwater.* s.l. : Stichting RIONED en STOWA, 2020. 978.90.5773.884.5.

26. *Effect of pH, Temperature, Dissolved Oxygen, and Flow Rate of Overlying Water on Heavy Metals Release from Storm Sewer Sediments.* Li, Haiyan , et al. s.l. : Hindawi Publishing Corporation, 2013, Journal of Chemistry, Vol. Article ID 434012, p. 11.

27. *Heavy Metal Removal and Remobilization under De-icing Salt Applications using Lab-scale Column Experiments.* Huber, M, et al. Lyon : s.n., 2021. 9th International Conference on planning and technologies for sustainable management of Water in the City.

28. Galfi, Helen. *Suspended solids and indicator bacteria in stormwater runoff: Sources of bias in field measurements.* s.l. : Division of Architecture and Water Department of Civil, Environmental and Natural Resources Engineering, 2014. ISBN 978-91-7439-979-0 (pdf.

29. *Using total suspended solids (TSS) and turbidity as proxies for evaluation of metal transport in river water.* Nasrabadi, T. , et al. s.l. : Elsevier, 2016, Applied Geochemistry, Vol. 68, pp. 1-9.

30. *Distribution of extractable heavy metals in different soil fractions.* Orrono, Daniela I. and Lavado, Raul S. 3, 2009, Chemical Speciation and Bioavailability, Vol. 21.

31. *Characterization of the Particle Size Fraction associated with Heavy Metals in Suspended Sediments of the Yellow River.* Yao, Qingzhen, et al. 6, 2015, Int J Environ Res Public Health., Vol. 12, pp. 6725–6744.

32. *Analyzing Particle-Associated Pollutant Transport to Identify In-Stream Sediment Processes during a High Flow Event.* Glaser, Clarissa , et al. 2020, Water , Vol. 12.

33. ***Oil and SUDS: managing a priority urban pollutant.*** **Napier, Fiona , et al. Thailand : s.n., 2008. 12th International Conference on Integrated Diffuse Pollution Management (IWA DIPCON 2008). pp. 25-29.**

34. Enserink, B., et al. Actor analysis. ***Policy Analysis of Multi-Actor Systems.*** **The Hague : Lemma, pp. 79-108.**

35. Climate cafe. ***groenblauwecafe.*** **[Online] https://climatecafe.nl/groenblauwcafe/.**

36. LABS, GRAFANA. ABOUT. ***grafana.*** **[Online] https://grafana.com/grafana/.**

37. ***Extreme rainfall analysis and estimation of depth-duration-frequency curves using weather radar.*** **Overeem, A., Buishand, T. A. and Holleman, I. . 2009, WATER RESOURCES RESEARCH, Vol. 45.**

38. ***Evaluating the Infiltration Performance of Eight Dutch Permeable Pavements Using a New Full-Scale Infiltration Testing Method.*** **Boogaard, Floris, et al. s.l. : water, 2014, Vol. 6, pp. 2070-2083.**

39. Wilson, Steve. ***Using SuDS close to buildings.*** **s.l. : CIRIA, 2012.**

40. ***A review on implementing infiltration-based green infrastructure in shallow groundwater environments: Challenges, approaches, and progress.*** **Zhang, Kun and May Chui, Ting Fong. 2019, Journal of Hydrology, p. 124089.**

41. USGS. usgs.gov. ***artificial-groundwater-recharge.*** **[Online] https://www.usgs.gov/mission-areas/water-resources/science/artificial-groundwater-recharge.**

42. RIONED. Waterdoorlatende en waterpasserende verharding . ***RIONED.*** **[Online] https://www.riool.net/waterdoorlatende-en-waterpasserende-verharding.**

43. Amsterdam, Rainproof. rainproof. ***hemelwaterverordening.*** **[Online] 10 May 2021. https://www.rainproof.nl/hemelwaterverordening.**

44. cop. ***Handreiking waterinfiltrerende verhardingen.*** **s.l. : cop, 2020.**

45. Infrastructuur en Milieu. wetten.overheid. ***wetten.overheid.*** **[Online] 03 11 2021. https://wetten.overheid.nl/BWBR0003245/2021-11-03#Hoofdstuk10b.**

46. CAMPBELL, BRIAN . ***WHAT IS TOTAL SUSPENDED SOLIDS (TSS)?*** **2021.**

47. ***USE OF A FIELD-BASED WATER ELUTRIATION SYSTEM FOR MONITORING THE IN SITU PARTICLE SIZE CHARACTERISTICS OF FLUVIAL SUSPENDED SEDIMENT.*** **WALLING, D.E. and WOODWARD, J.C. 9, GREAT BRITAIN : s.n., 1993, War. Res., Vol. 27, pp. 1413-1421. 0043-1354/93 .**

48. ***Changes in soil pH and mobility of heavy metals in contaminated soils.*** **Kicińska, A., Pomykała, R. and Izquierdo-Diaz, M. 1, 2022, European Journal of Soil Science, Vol. 73.**

49. Huizinga-Heringa, J.C. and Hirsch Ballin, E.M.H. ***Water Act.*** **s.l. : Ministry of Transport, Public Works and Water Management, 2010.**

50. Rainproof, Amsterdam. rainproof . ***hemelwaterverordening.*** **[Online] https://www.rainproof.nl/hemelwaterverordening.**

51. Distro. *TU Delft.* [Online] https://www.tudelft.nl/myanmar/innovations/disdro.

52. van Essen instruments . *HANDLEIDING divers.* s.l. : van Essen, 2016.

53. Log, Level. Specification. *Level Log Product.* [Online] Level Log. https://www.levellog.nl/product/specificaties/.

54. van de Beek, Remco. *Rainfall variability in the Netherlands from radars, rain gauges, and disdrometers.* Wageningen University. 2013. 978-94-6173-643-7.

55. *A Joss – Waldvogel disdrometer derived rainfall estimation study by collocated tipping bucket and rapid response rain gauges.* Islam, Tanvir , et al. 2012, ATMOSPHERIC SCIENCE LETTERS, Vol. 13, pp. 139-150.

56. Bartholomew, MJ. *Impact Disdrometer Instrument Handbook.* s.l. : U.S. DEPARTMENT OF ENERGY, 2016. DOE/SC-ARM-TR-111 .

57. LUXEMBURG , W. M. J . and COENDERS, A. M. J . . *CI E4440 HYDROLOGI CAL PROCESSES AND MEASUREMENTS.* s.l. : TU DELFT, 2017.

58. *Affordable Acoustic Disdrometer: Design, Calibration, Tests.* van de Giesen, Nick , Degen, C. and Hut, Rolf. 2009. AGU Fall Meeting Abstracts.

59. *Development of Improved Acoustic Disdrometer Through Utilization of Machine Learning Algorithm.* Cruz, Febus Reidj G., et al. 2018, TENCON 2018 - 2018 IEEE Region 10 Conference, pp. 1679-1682.

60. *Automatic Prediction of High-Resolution Daily Rainfall Fields for Multiple Extents: The Potential of Operational Radar.* SCHUURMANS, J. M. , et al. Utrecht, Netherlands : s.n., 2007, JOURNAL OF HYDROMETEOROLOGY , Vol. 8, pp. 1204-1224.

61. *Automated rainfall simulator for variable rainfall on urban green areas.* Nielsen, Kristoffer T. , et al. s.l. : wileyonlinelibrary, 2019, Hydrological Processes, Vol. 33, pp. 3364-3377.

62. Gravenberch, Jip. *Vegetated Permeable Pavement Systems: Evaluation of the hydrologic behaviour to improve climate-adaptive design.* Delft : TU Delft repository, 2022.

63. BOOGAARD , Floris Cornelis. *Stormwater characteristics and new testing methods for certain sustainable urban drainage systems in The Netherlands .* s.l. : Technische Universiteit Delft, 2015. 978-94-6259-745-7.

64. FONDRIEST. *ENVIRONMENTAL PRODUCTS.* [Online] [Cited: 17 01 2022.] https://www.fondriest.com/van-essen-td-diver-water-level-loggers.htm.

65. *How to design optimal eDNA sampling strategies for biomonitoring in river networks.* Carraro, Luca, Stauffer, Julian B and Altermatt, Florian. 2020, Wiley, pp. 157-172.

66. *Residents' perceptions of sustainable drainage systems as highly functional blue green infrastructure, Landscape and Urban Planning,.* Williams, J.B., et al. s.l. : sciencedirect, 2019, science, Vol. 190. ISSN 0169-2046.

67. ***Urban surface temperature observations from ground-based thermography: intra- and inter-facet variability.*** **Morrison, William, Kotthaus, Simone and Grimmond, Sue. 2021, Urban climate, Vol. 35, p. 100748.**

68. Netherlands, Government of the. government,nl . ***water-management/water-management-in-the-netherlands.*** **[Online] https://www.government.nl/topics/water-management/water-management-in-the-netherlands.**

69. —. https://www.government.nl/. ***ministries/ministry-of-infrastructure-and-water-management/organisation.*** **[Online] https://www.government.nl/ministries/ministry-of-infrastructure-and-water-management/organisation.**

70. Havekes, Herman, et al. ***Dutch Water Authorities.*** **Den Haag : Opmeer BV, 2017.**

71. ***Community-based initiatives in the Dutch water domain: the challenge of double helix alignment.*** **Duijn, Michael, et al. 2019, International Journal of Water Resources Development.**

72. Moene, Arnold F. and van Dam, Jos C. ***Transport in the atmosphere-vegetation-soil continuum.*** **s.l. : Cambridge University Press, 2014. 978-0-521-19568-3 .**

73. ***Ponding time and infiltration capacity variation during steady rainfall.*** **M.H. Diskin, N. Nazimov. March 1995, Journal of Hydrology, Vol. 178, pp. 369-380.**

74. ***Hot Water Treatments To Inactivate Escherichia coli O157:H7 and Salmonella in Mung Bean Seeds.*** **M. L. BARI, Y. INATSU, S. ISOBE, AND S. KAWAMOTO. 2008, Journal of Food Protection, pp. Pages 830–834.**

75. ***Demonstration sites to speed up innovations in delta technology.*** **Kreijns, Marjan, Gerardts, Ruben and Rutten, Martine. s.l. : Elsevier, 2018, Journal of Cleaner Production, Vol. 171, pp. S144-S146.**

76. ***Estimating evaporation with thermal UAVdata and two-source energy balance models.*** **Hoffmann, H., et al. s.l. : Copernicus Publications, 2016, Hydrology Earth System Sciences, Vol. 20, pp. 697–713.**

77. ***Modelling Decentralised Systems for Urban Drainage and Flood Mitigation.*** **Hellmers, S., et al. s.l. : Hamburg - Lehfeldt & Kopmann (eds), 2014, ICHE 2014, pp. 375-382. ISBN 978-3-939230-32-8.**

78. ***Urban heat islands and cooler infrastructure – Measuring near- surface temperatures with hand-held infrared cameras.*** **Chui, Andrew C., et al. s.l. : Elsevier, 2018, Urban Climate , Vol. 24, pp. 51-62.**

79. ***Detailed Geophysical Mapping and Hydrogeological Characterisation of the Subsurface for Optimal Placement of Infiltration-Based Sustainable Urban Drainage Systems.*** **Andersen, Theis Raaschou . 446, 2020, geosciences, Vol. 10.**

80. bmpdatabase/monitoring. [Online] [Cited: 22 10 2021.] https://bmpdatabase.org/monitoring.

81. GEMEENTE, REDACTIE. Gemeenten zoeken alternatieven voor hemelwaterafvoer. ***Gemeente.nu.*** **2017.**

82. WIKIPEDIA. WIKIPEDIA. *Faculteitsgebouw_Bouwkunde_(TU_Delft).* [Online] https://nl.wikipedia.org/wiki/Faculteitsgebouw_Bouwkunde_(TU_Delft).

83. *Fire-Induced Changes in Soil and Implications on Soil Sorption Capacity and Remediation Methods.* Ngole-Jeme, Veronica . 2019, Appl. Sci, Vol. 9, p. 3447.

84. DINOloket. dinoloket. *ondergrondgegevens.* [Online] [Cited: 10 11 2021.] https://www.dinoloket.nl/ondergrondgegevens.

85. Hutter, Jaap-Willem. *Toetsingstabel Besluit Bodemkwaliteit .* Analysis report.

86. *DIRECTIVE 2006/118/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the protection of groundwater against pollution and deterioration.* DIRECTIVE 2006/118/EC . 2006, Official Journal of the European Union, pp. 19-31.

87. Journal, Official. *DIRECTIVE 2000/60/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 October 2000 establishing a framework for Community action in the field of water policy.* Official Journal of EU . 2000. pp. 1-93, EU DIRECTIVE.

88. CIRIA. Filtration overview. *susdrain.* [Online] CIRIA. https://www.susdrain.org/delivering-suds/using-suds/suds-components/filtration/filtration.html.

89. —. Component: Filter trench. *susdrain.* [Online] https://www.susdrain.org/delivering-suds/using-suds/suds-components/filtration/filter-trench.html.

90. *Two-source energy balance model estimates of evapotranspiration using component and composite surface temperatures.* Colaizzi , Paul D., et al. 2012, Advances in Water Resources, Vol. 50, pp. 134-151.

91. Google maps. [Online] [Cited: 23 07 2021.] https://www.google.com/maps/d/viewer?mid=121t7Wgv0wTC7m4PZeDwk5I6jx8aaBZGP&ll=51.998281051954784%2C4.373268905025038&z=16.

92. BOOGAARD , Floris Cornelis. *Stormwater characteristics and new testing methods for certain sustainable urban drainage systems in The Netherlands.* s.l. : Technische Universiteit Delft, 2015. 978-94-6259-745-7.

93. OPTRIS. thermal-imager-optris-pi-400i-pi-450i. *optris.global.* [Online] OPTRIS. https://www.optris.global/thermal-imager-optris-pi-400i-pi-450i.

94. *Evaluation of surface ponding and runoff generation in a seasonally frozen drained agricultural field.* Saadat, Samaneh , et al. s.l. : Elsevier, 2020, Journal of Hydrology , Vol. 588, pp. 1-11.

95. *micrObs – A customizable time-lapse camera for ecological studies.* Winterl, Alexander , et al. e00134, 2020, HardwareX , Vol. 8.

96. *Propagation of soil moisture sensing uncertainty into estimation of total soil water, evapotranspiration and irrigation decision-making.* Sharma, Kiran , Irmak, Suat and Kukal, Meetpal S. s.l. : Agricultural Water Management, 2021, Vol. 243.

97. campbell. cs655. *campbellsci.com.* [Online] https://www.campbellsci.com/cs655.

98. ***Performance of Hydromedia Pervious Concrete Pavement in Ontario Subjected to Urban Traffic Loads.*** **Crookes, A., et al. 2015.**

99. openrivercam. openrivercam. [Online] [Cited: 21 03 2022.] https://openrivercam.readthedocs.io/en/latest/.

Abbreviations list

SUDS	Sustainable Urban Drainage Systems
KPIs	Key Performance Indicators
IP	Indicators of Performance
$\mathbf{A_{upstream}}$	Area that is upstream the SUDS and drains towards it
$\mathbf{C_{upstream}}$	Runoff coefficient of the upstream to the SUDS area that incorporates all losses before the water overflows to the SUDS
$\mathbf{A_{container}}$	Area that the container to measure overflow occupies
$\mathbf{A_{occupying}}$	Area that the SUDS occupies
$\mathbf{C_{occupying}}$	Runoff coefficient of the SUDS area that incorporates all losses before on the SUDS, like evaporation, transpiration and interception
$\mathbf{A_{walls}}$	Infiltration surface towards the soil that is the bottom and vertical walls of the SUDS
i	Rainfall depth that falls during a time step
P	Rainfall volume that falls during a time step on a certain area
$\mathbf{O_1}$	Volume from overflowing water from the upstream drainage area
$\mathbf{i_{2.1}}$	Water depth that enters the SUDS during a time step
$\mathbf{I_{2.1}}$	Water volume that enters the SUDS during a time step
$\mathbf{s_{2.2}}$	Water level observed in the SUDS
$\mathbf{S_{2.2}}$	Volume of water stored in the SUDS
$\boldsymbol{\varepsilon}$	Average porosity of the soil that is in the SUDS
$\mathbf{i_{2.2}}$	Water depth that enters the soil during a time step
$\mathbf{I_{2.2}}$	Water volume that enters the soil during a time step
$\mathbf{o_{2.1}}$	Water depth that is observed in the container during a time step
$\mathbf{O_{2.1}}$	Water volume overflowing to the container during a time step
$\mathbf{S_3}$	Ground water levels representing the storage in the soil
$\mathbf{S_{2.1}}$	Volume of intercepted water on the SUDS
$\mathbf{M_2}$	Volume of water in the form of moisture in the SUDS
$\mathbf{E_2}$	Volume of evaporated water the leaves the SUDS
$\mathbf{T_2}$	Volume of transpired water the leaves the SUDS
$\mathbf{DO_{2.2}}$	Volume of water that exits the SUDS through a drain towards the storm sewer
$\mathbf{M_3}$	Volume of water in the form of moisture in the soil under the SUDS
G	Groundwater flow

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Appendix A- Systems design and water balance

The systems that will be presented are numbered and shown in the study area (Figure 42) and the same code number is used in this thesis.

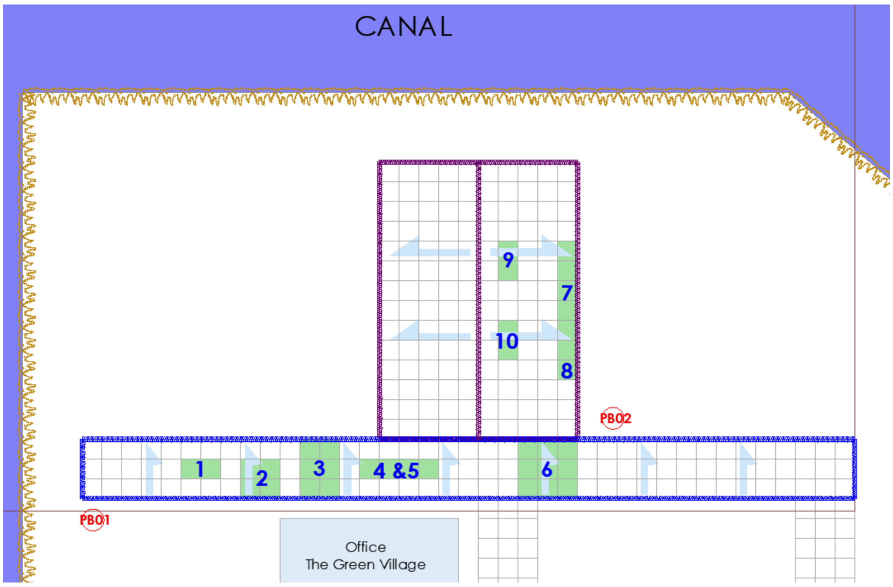


Figure 42 Location of the systems in the study area

1. *FLOWSAND*

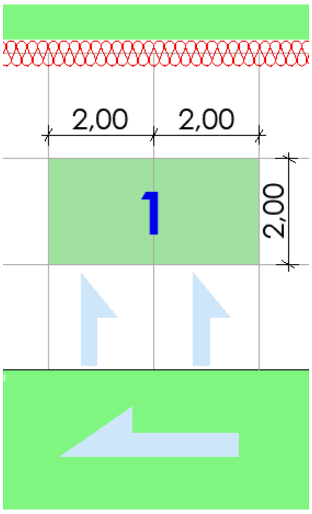


Figure 43 Top view FLOWSAND in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated and the drainage area help calculate the connected area to the system.

FLOWSAND is a system developed by Aquaflow BW, it is located in the area with number 1 and it occupies 2 tiles of 2x2 dimension on the WaterStreet study area (Figure 43). Due to the terrain slope of the section where the system is located two more impervious tiles are overflowing towards that system making the active area affecting FLOWSAND equal to 4 x (2x2) or 16 m2. The active area is the sum of the drainage area and the occupying area of a system.

On the vertical axis, the depth of the system measured by the ground level is at its maximum of 0.32 m. The permeable tiles let water infiltrate into the system or pond on the tile and then infiltrate. Then in the first soil layer, some amount of water is stored to evaporate from there and the rest is infiltrating further into the system where some are stored in a gravel layer and infiltrates into the surrounding sandy soil. These processes are schematized in Figure 43.

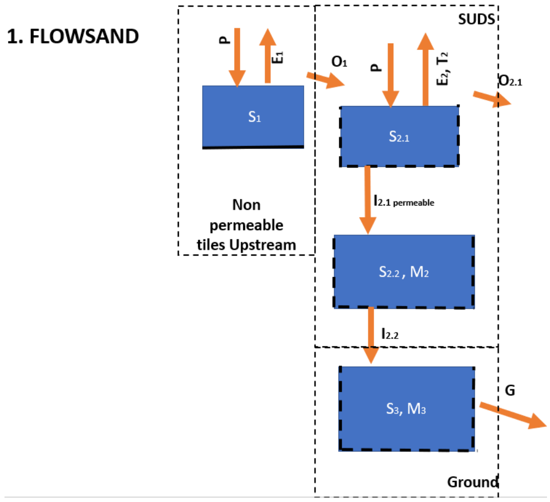


Figure 44 Water balance of FLOWSAND system

2. WATERTABLE

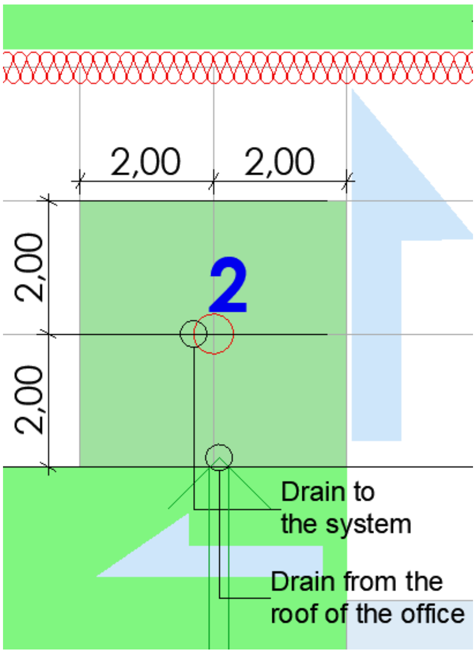


Figure 45 Water flowing to WATERTABLEin dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system.

WATERTABLE is a system developed by TREWATIN BV and is located in the area with the number 2. It neighbors with FLOWSAND on the left and DRAINMIX on the right with a 2 m distance between them as shown in Figure 42, WATERTABLE occupies 4 tiles of 2x2 m dimension and there are no other tiles overflowing to that system. Moreover, some water that is stored in the system originates from the roof of the Green Village office building. The water is collected on the roof and with a pipe it is transported directly into the system. Knowing that the building of the office is 14m x 18m or 252 m2 the drainage area to that system is 252 m2 and 16 m2 from the tiles that the system occupies. The active area is equal to 268 m2 altogether Figure 45 shows the dimensions of the system along with the drain from the roof of the office. Additionally, one drain is located in the center of the system to let water enter it.

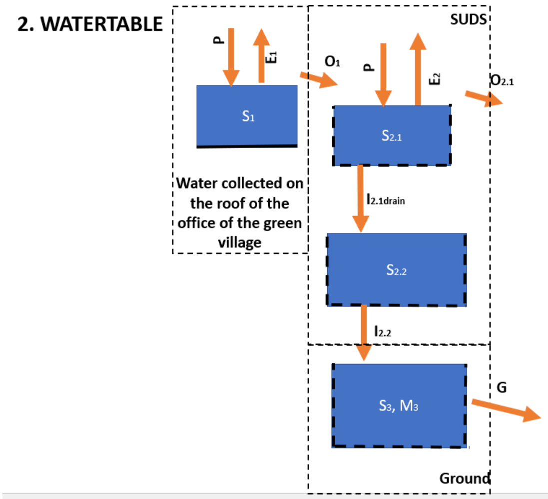


Figure 46 Water balance of WATERTABLE

On the vertical axis, the system of WATERTABLE has a total depth of 1.40 m and consists of a table-like system with the top of the table being the tile to walk on. The water that precipitates on the tiles and the roof of the office flows through a drain to the open space under the table-like structure and in the case of WaterStreet. Then the water is stored under the table and slowly infiltrates the surrounding sandy soil. The water balance of that system is also schematized in Figure 46.

3. <u>DRAINMIX</u>

DRAINMIX is a system developed by DRAINMIX BV and is located in the area with the number 3. It neighbors with WATERTABLEo n the left and DAINLINE & BUFFERTROTTOIR on the right with a 2 m distance between them as shown in Figure 42. DRAINMIX occupies 6 tiles of 2x2 m dimension and there are no other tiles overflowing that system. Moreover, some water that is stored in the system originates from the storm sewer located parallel to the path as shown in Figure 47. The active area for the system of DRAINMIX is not easily calculated since the amount of water that overflows from the storm sewer differs per event. Moreover, a system outside the scope of this thesis is also managing the storm water of the area after it is collected by the sewer making the calculations of the active area even more complex.

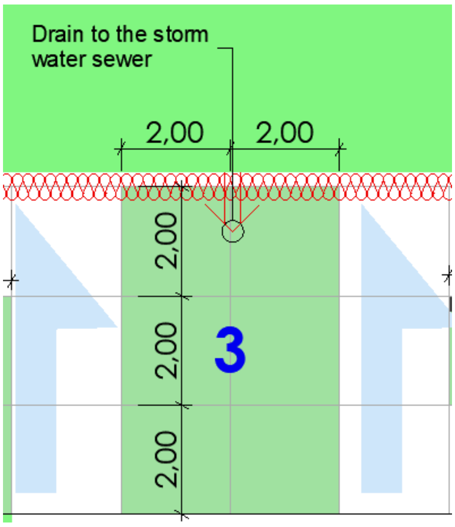


Figure 47 Water flows for DRAINMIX . in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system

On the vertical axis, the system has a depth of 0.5 m and consists of one upper layer of bricks that are not permeable while the water can infiltrate from the soil material between the bricks. In the case of WaterStreet water can also originate from the storm sewer as analyzed above. Then it is stored in the DRAINMIX material and later it infiltrates the surrounding sandy soil. The processes are schematized in Figure 48.

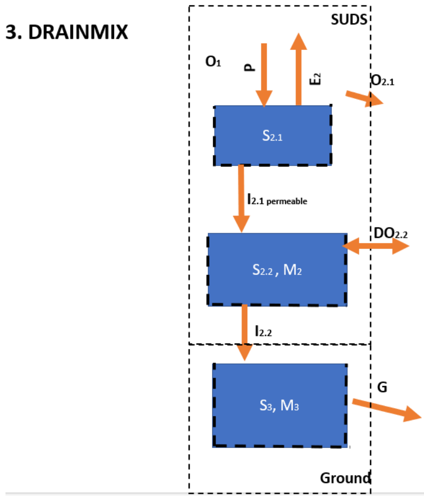


Figure 48 Water balance of DRAINMIX

4. <u>& 5. DRAINLINE & 5. BUFFERTROTTOIR</u>

DRAINLINE is a permeable brick, developed by DRAINLINE while BUFFERTROTTOIR developed by Waste Works and is a system that consists of crates that makes room for the water to be stored in it. It is in the area with the numbers 4&5. They are put in combination on the WaterStreet terrain. This means that DRAINLINE is the permeable tile that lets the water infiltrate the system and BUFFERTROTTOIR creates the room for water storage under the tile. The combined system, neighbors with DRAINMIX on the left and BUFFERBLOCKs on the right with 2 m and 8m distance between them respectively, as shown in Figure 42 DRAINLINE & BUFFERTROTTOIR system occupies 4 tiles of 2x2 m dimension. DRAINLINE permeable brick occupies around 1m2 from the total 16 m2 of the combined system as shown in black color in Figure 49, 4 more tiles are overflowing into that system making the active area equal to 8 x (2m x 2m) or 32 m2.

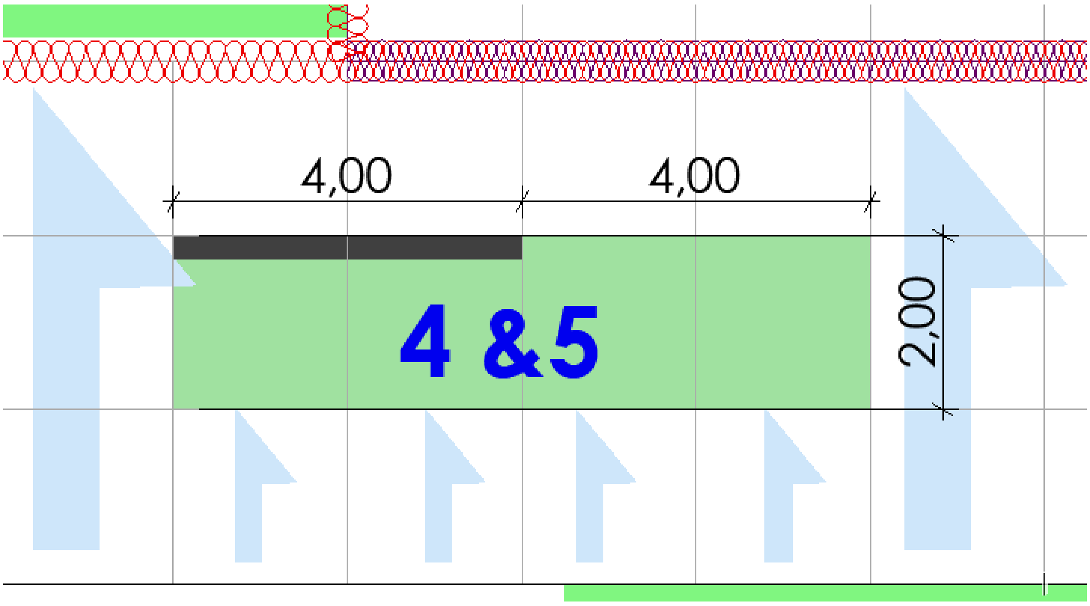


Figure 49 Water flows for DRAINLINE & Buffetrottoir system in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system

On the vertical axis the system had a total depth of 0.23 m and as explained above water can pond on the street then it infiltrates the system through the DRAINLINE permeable brick. Then it gets stored in the crate area to be infiltrated into the surrounding sandy soil. The fluxes and storages involved in that system can be schematized in the following Figure 50.

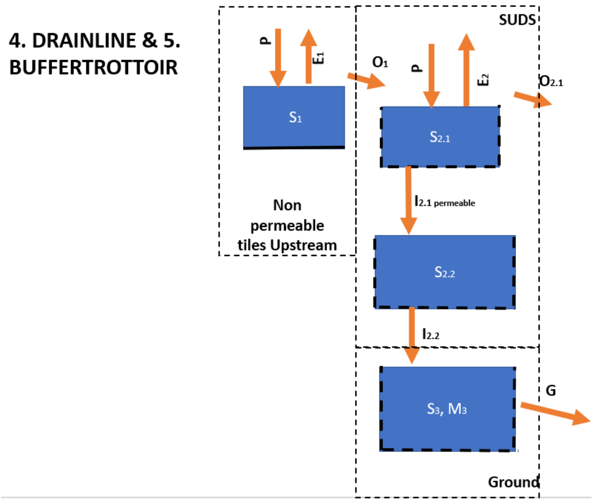


Figure 50 Water balance DRAINMIX & BUFFERTROTTOIR

6. BUFFERBLOCK

BUFFERBLOCK is a system developed by BUFFERBLOCK BV and is located in the area with the number 6. It neighbors only from the right with the system DRAINLINE &

BUFFERTROTTOIR with a distance of 8 m (Figure 42) and occupies 6 tiles of 2 m x 2m dimension, making the total active area of the system equal to 36 m2 (Figure 51).

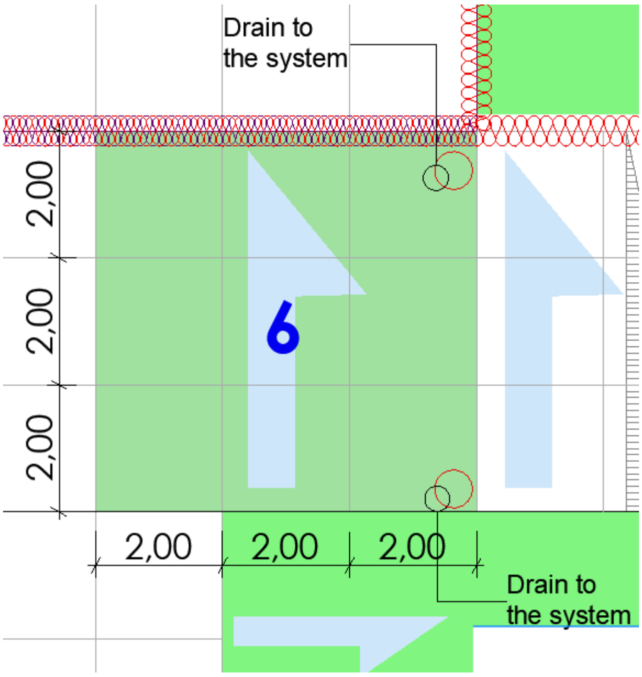


Figure 51 Water flows for BUFFERBLOCK system in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system.

On the vertical axis, the depth of the system is 0.70 m and the water flows through the two drains shown with red circles on the figure and is stored on the BUFFERBLOCKs under the tile system. The blocks are designed in such a way to be able to withstand the load of cars and create space for water to be stored. After the water is stored, it can infiltrate slowly into the surrounding sandy soil. The processes involved in this system are schematized in Figure 52.

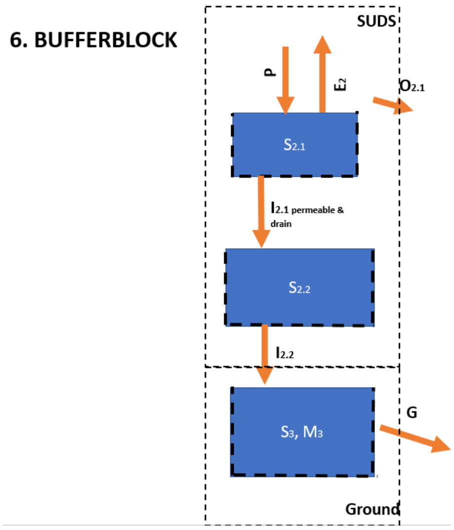


Figure 52 Water balance of BUFFERBLOCK

7. *& 8. URBANRAINSHELL and DSI*

URBANRAINSHELL and DSI are two systems that work in combination in the WaterStreet terrain. They are developed by EWB and HENK VAN TONGEREN WATER & TECHNIEK respectively. URBANRAINSHELL is a permeable shell material that lets water infiltrate faster into the soil and at the same time it is designed to reduce pollutants. The DSI system is a deep drain that directs the water in the deep aquafer without having the water flow through the surrounding unsaturated sandy soil. It is located in the other section of the study area coded with purple color and it neighbors upstream with ZOAK BESTRATING system and RAINROAD system with a distance of 4 m from both (Figure 42). It occupies an area of 7 tiles of 2 m x 2m dimension or 28 m2 area (Figure 53). Moreover, 14 more impermeable tiles are overflowing from the upstream tile area making the total active area for that system equal to 84 m2. Last what is not infiltrated from the systems ZOAK BESTRATING and RAINROAD are also collected in the system of URBANRAINSHELL & DSI.

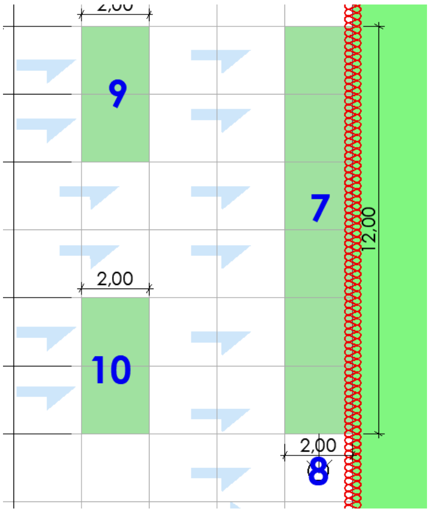


Figure 53 Water flows for URBANRAINSHELL & DSI system in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system.

In the vertical axis, it consists of the URBANRAINSHELL material that has a depth of 0.85 m and collects the water that is then directed to the DSI system that drains the stored water to the deep aquifer. The two systems are working in combination and are considered as one system for this research while the processes are schematized in Figure 54.

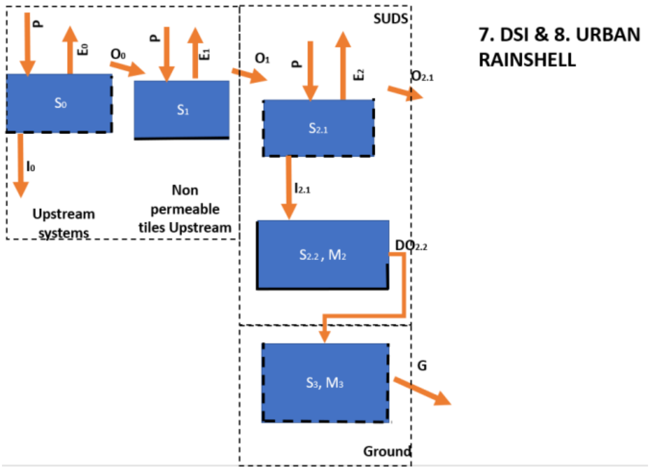


Figure 54 Water balance URBANRAINSHELL & DSI

9. RAINROAD

RAINROAD is a system developed by MOVARES and it consists of two storage layers, in the upper layer the water is stored and evaporated while in the second section the water is stored to infiltrate the surrounding sandy soil. It neighbors downstream with the URBANRAINSHELL & DIS at a distance of 4 m and the ZOAK BESTRATING tile system again at 4 m (Figure 42). The occupying area of the system is 2 tiles of 2 m x2 m or in total 8 m2 area while 2 more impervious tiles are overflowing to that system making the total active area for the system equal to 16m2 (Figure 55). Based on the slope of the terrain at that location, the system of RAINROAD is not affected by overflowing water from any other area on the terrain.

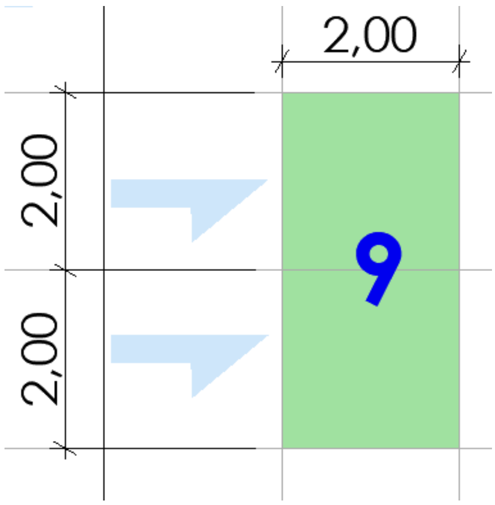


Figure 55 Water flows for RAINROAD system in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system.

In the vertical axis, the depth of the system is 1.18m and the water that precipitates is infiltrated through and between permeable bricks in the first bucket where it is stored util a certain level, this stored water is available for evaporation to create a cooling effect. If the water level exceeds a level, it is further infiltrated in a second section where it can later infiltrate the surrounding sandy soil. The fluxes and storage activated in this system are also presented in the scheme below (Figure 56).

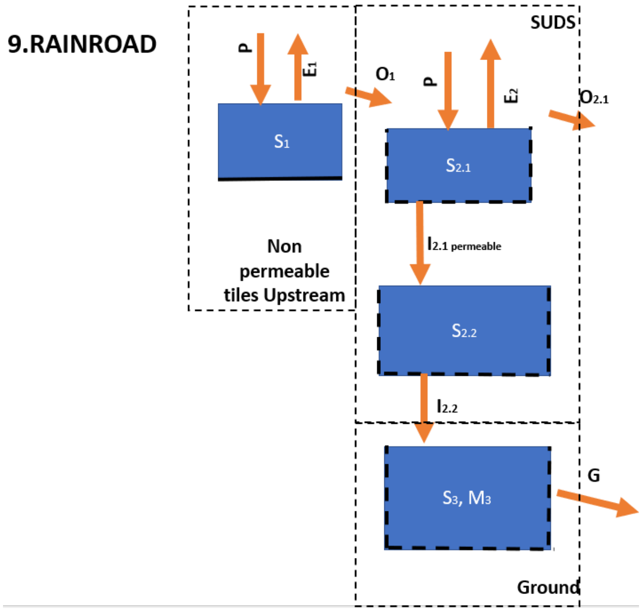


Figure 56 Water balance of RAINROAD

10. ZOAK BESTRATING

ZOAK BESTRATING system is developed by TILESYSTEMS and it consists of ZOAK BESTRATING permeable bricks from ceramics and several layers of soil in a different order within the ZOAK BESTRATING area. This means that that system consists of many different systems put next to each other that interact hydraulicly. No more information was available on the difference between the materials used in that system. It is neighbors with RAINROAD and URBANRAINSHELL & DSI downstream and with distances of 4 m between them as shown in Figure 42. The occupying area of the system is 2 tiles of 2 m x2 m or in total 8 m2 area while 2 more impervious tiles are overflowing to that system making the total active area for the system equal to 16m2 (Figure 57). Based on the slope of the terrain at that location, the system of ZOAK BESTRATING is not affected by overflowing water from any other area on the terrain.

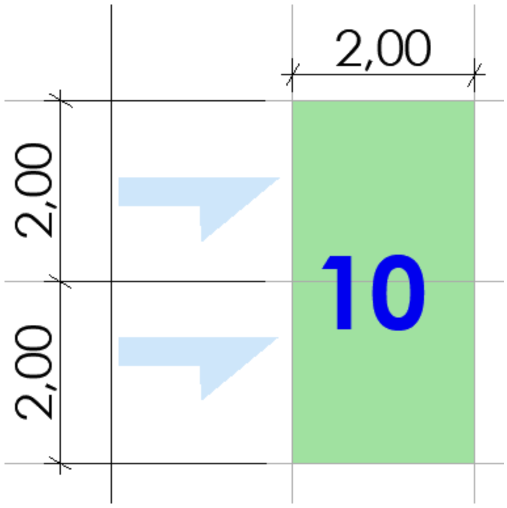


Figure 57 Water flows for ZOAK BESTRATING system in dark green. The main direction of the flow is indicated with the blue arrows, the green section is the soil terrain, and the white tiles indicate the non-permeable tiles around the system. The red curly line indicates the storm water drain. The dimensions of the system indicated the drainage area to help calculate the connected area to the system

In the vertical axis, the system consists of the upper permeable tiles and where the water infiltrates and is then stored in the soil mixture under it until it can infiltrate further into the surrounding sandy soil. The processes are schematized below in Figure 58.

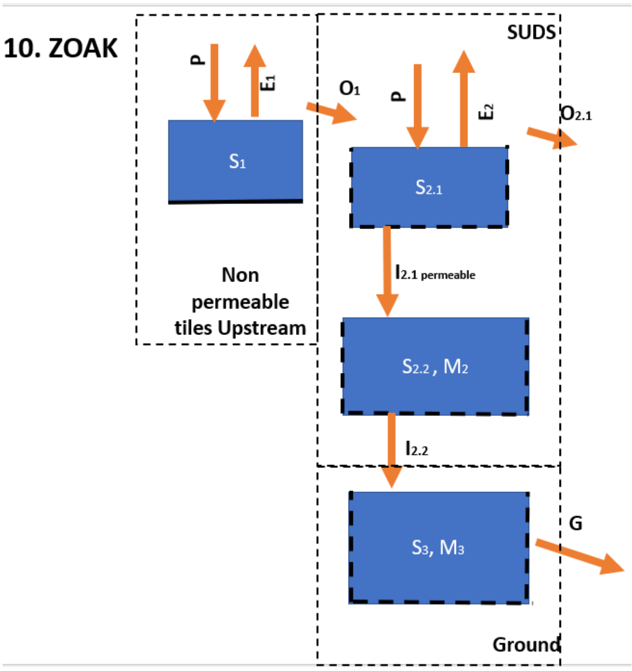


Figure 58 Water balance of ZOAK BESTRATING

Appendix B- Actors

An extensive description, values, perception, and added value to the problem of the actors can be seen in Table 27. The information shown in the table below is gathered from the meetings with Climate Cafe and Charlie Jurjus and Brahmanand Goerdat. Moreover, the management of water in the Netherlands was drawn from governmental sites (68), (69) or reports (70) and journal reports (71).

Table 27 Actor's description, Values, perception, and ways to affect the problem of defining KPIs for SUDS.

Actor	Authority over	Description	Value of Actor	Perception of Actor	Resources (what does this actor give to the problem)
Field living labs (WaterStreet)	SUDS was implemented in the living lab.	Physical SUDS research areas that are exposed to real stresses.	Sustainability Climate adaptation Meeting point	Collaborate on a sustainable future	Site for a test →increase knowledge on SUDS
Water Boards	Draw up management plans regarding the water quality of the waters within their district. In addition, the district water boards are responsible for the regional flood defense systems, that protect the country against, e.g., water from the canals.	regional or national organizations that manage the water functions	Managing the sources of water in a region	Climate adaptation and resilience	Define limitations on the SUDS based on the water management of the region
Universities	Design and research new SUDS	Knowledge centers and promotion of new ideas	Learning	Increase understanding of the technology and innovate	Students and expert knowledge
Entrepreneurs – Developers	Design and research new SUDS	Person or company that builds and creates new SUDS to get funding and implement on a bigger scale	Innovate/ funding / implement	Innovation that performs and gets accepted for implementation on a bigger scale	Prototypes to get tested
Municipalities	Groundwater in urban areas drainage of wastewater and excess rainwater through the sewer systems is the responsibility of the municipalities.	Governmental units that have goals to implement SUDS to comply with sustainability and climate change regulations	Create the web of the city	Permit implementations that guarantee performance	Urban implementation of SUDS
STOWA- RIONED	Data gathering	Organizations that collect and distribute knowledge on SUDS	Create a network of knowledge	Share performance information for study and comparison	Information and establishing guidelines
Ministry of Economic Affairs and Climate Policy	Funding new implementations.	department of the government that ensures funding of SUDS	Business and nature-friendly/fund /invest in innovation and sustainability	Fund innovations	Financial regulations/ support business/ establish financial policies for innovations
Ministry of Infrastructure and Water Management	The Directorate-General for Water and Soil Affairs is responsible for policy development in the fields of water policy and flood risk management, climate adaptation, water projects in specific areas, water, and soil issues. Rijkswaterstaat ensures that policy is implemented.	department of the government that is responsible for the waterways in a region	ensure that the top political and civil service layers, as well as the employees, can perform their work	responsible for the main waterway network, the main water systems, and the environment in which they are embedded	Promote innovation and provide data, regulations, and inspection
Residents	Small-scale SUDS, like water barrels.	Inhabitants of an area that are daily in contact with a SUDS that might be implemented in their neighborhood	Increase their quality of life	They want systems that can provide a reduction of risks	Vote the ministries, municipalities, and Waterboards

Resident initiative for Climate adaption (Holtenbroek, Markdal) (71)	Different per goal of the initiative, but mainly regional water.	Independent organization of residents that are interested in climate change adaptation and try to implement small scale SUDS	Sustainable rainwater management	Introduce initiatives from residents	Driver for more sustainable solutions

After evaluating the actors' map a questionnaire was sent to 68 candidates from which 17 replied, to define the power and the interest of the actors. Additionally, one open question was posed in the questionnaire about, suggestions of other stakeholders. The responses to that question are shown in Table 28. The responses concluded more actors as well as important conditions for successful interaction between them. First, the collaboration between the actors is very important. Another interesting mention was the inclusion and cooperation of sub-departments within the municipalities and the organizations. The inclusion of the building firms and real estate in the actor's map was also an interesting suggestion. Another interesting suggestion was to enhance the education on urban water management, of citizens and municipality employees not directly related to water management. These actors are not active in implementing SUDS themselves but their view on the importance of the solutions can have a big impact on future implementation of SUDS.

Table 28 Additions of interviewees on the actor's map shown above.

Name of the participants	Profession	Suggestions for missing powerful stakeholders	Suggestions for missing interested stakeholders
Lennart Droppert	student	No answer	No answer
Volkert Lubbers	developer	The Stakeholders have to combine the power and collaborate	No missing stakeholders
Ad de Groot	developer	Engineering companies, landscape Architects, Architects, project developers	Engineering companies, landscape Architects, Architects, project developers
Jip Gravenberch	student	No answer	No answer
Floris Boogaard	academic	all triple helix partners are present, but it's important to involve different departments from 1 organisation (eg from urban planners to maintenance of municipality)	all triple helix partners are present, but it's important to involve different departments from 1 organisation (eg from urban planners to maintenance of municipality)
Aroen Mughal	developer	No answer	No answer
Brahm Goerdat	student	No answer	No answer
Antal Zuurman	consultant	housing associations, they have a lot of property including green around their buildings	Housing associations. If you want to implment SUDS they own a lot of buildings en parts of the semi - publicly accessible green space.
Frits Ogg	Municipality-educated citizen	1. (elementary) schools. Water education (as part of sustainable UN goals) should be adressed already at a young age (and their parents during the time their children are at a school). A school has also a big schoolyard to be drained. Waterboards can play a role in this education.	A part of the ministry of public health; the RIVM could also play a role in attracting residents with a measurement program. See:

		2. industry (other than SUDS developers), because they have big roof surfaces and parking lots and could use the rain water in their offices (toilets) and industrial processes. VNO-NCW, their organisation could play a role in this. And a special role for companies working in the field of ground road and hydraulic engineering (in Dutch: grond- weg- en waterbouw GWW). It is a very conservative party, but if they can earn money with it 3. Media, in the broadest sense of the word. Especially newspapers. Articles should be ready to publish directly after a downpour. Special articles should be ready for glossy's to reach the public that only act as a consumer in our society.	https://www.samenmetenaanluchtkwaliteit.nl/international
Wies van Lieshout	developer	contractors, (landscape) architects: they are the ones designing space and executing the / proposing the materials building projects. They are therefore also having a big influence on how urban areas are shaped.	same as above: architects and building contractors
Marco Hoogvliet	consultant	(Real estate) developers; contractors. They are the ones that make choices about use of building materials and technologies	again, developers and contractors
Sydney Stax	municipality	It's not a missing stakeholder, but inside governmental organisations there are specific disciplines or branches that have different implementation power for this type of object (e.g. street management, green management and water management)	No answer
Martine Rutten	academic	No answer	No answer
Emilie Buist	WaterStreet	No answer	No answer
Sander Apeldoorn	developer	No missing stakeholders	No missing stakeholders
Tijs van Ruth	developer	No answer	No answer
Ger Pannekoek	developer	Engineering firms (influence municipalities in design, tendering, implementation), construction firms (can bring in innovations in tenders)	No answer

The actors map was be provided based on the interdependencies first. Then the first view of the actor's map was made, that is then updated with responses from the questionnaires participants.

Appendix C- Questionnaire's participants and preview

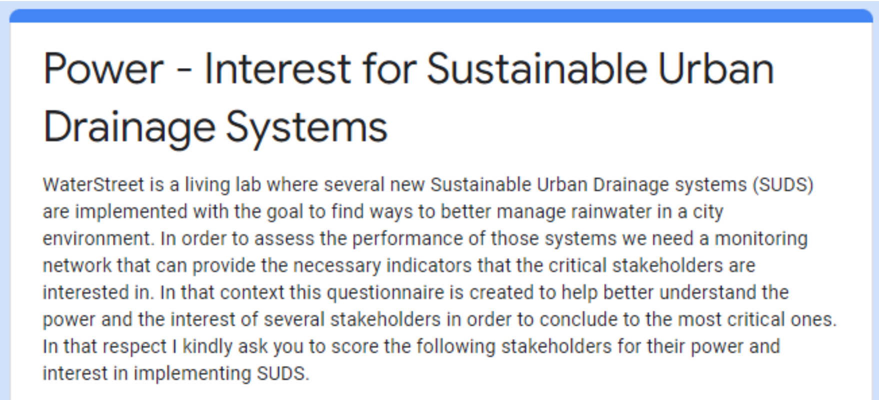
In the next table, the participants can be seen with the additional information on their profession and the value they bring to the questionnaire's conclusion.

Table 29 Participants responded to the questionnaire about the power and interest of the actors

Participant	**Profession**	**Importance of participant**

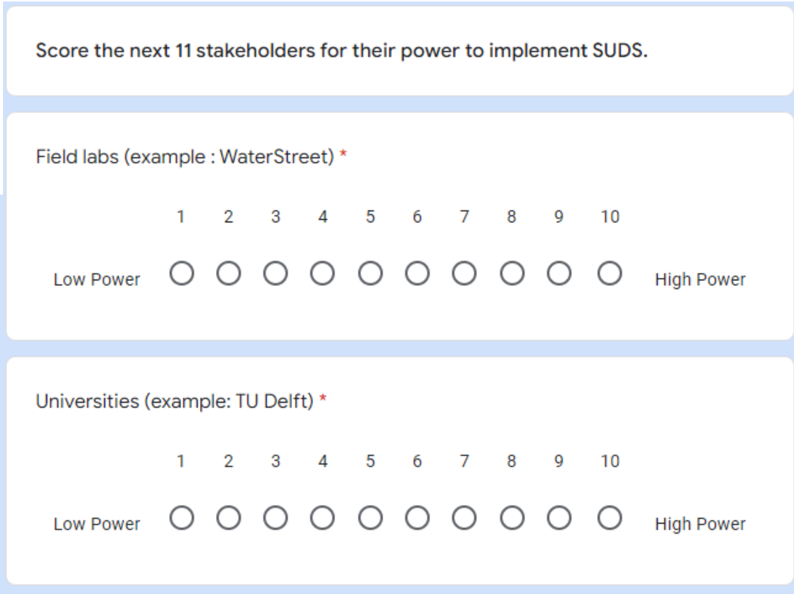
Lennart Droppert	Water management student	Lennart did his internship in the municipality of Rotterdam working alongside water managers.
Volkert Lubbers	Geohydrologist at Fugro (developer)	One of the developers of WaterStreet.
Ad de Groot	business unit manager, Aquaflow bv (developer)	One of the developers of WaterStreet.
Jip Gravenberch	Water management student	Jip is doing his thesis on the performance of vegetated SUDS and has done experiments on the WaterStreet.
Floris Boogaard	Academic	Floris Boogaard is involved in testing the performance of SUDS.
Aroen Mughal	Technical director of BUFFERBLOCK (developer)	One of the developers of WaterStreet.
Brahm Goerdat	Water management student	
Antal Zuurman	Senior consultant urban water & climate adaptation at Roelofs	One of the developers of WaterStreet.
Frits Ogg	educated citizen	Working for the municipality of Nijmegen and interested in implementing SUDS.
Wies van Lieshout	Founder of Waterweg (developer)	One of the developers of WaterStreet.
Marco Hoogvliet	urban water consultant in Deltares	Project leader in Deltares specializing in constructing integral solutions which add to the sustainability and resilience of the urban area and utilize the potential of the water and subsurface system.
Sidney Stax	Water and Environmental City Management, Nijmegen	Working for the municipality in environmental solutions.
Martine Rutten	Academic	Associate professor Water management TUDelft and RUAS, Co-director Delta Futures lab.
Emilie Buist	Project manager Water innovations of The Green Village	Running of the living lab WaterStreet.
Sander Apeldoorn	Commercial Technical Advisor at AquaBASE (developer)	One of the developers of WaterStreet.
Tijs van Ruth	Innovator and motivator in participation projects on water problems and solutions, Founder WaterLeider (developer)	One of the developers of WaterStreet.
Ger Pannekoek	Co-founder bij EWB Circular Rain (developer)	One of the developers of WaterStreet.

The questionnaire first stated a small introduction to inform the interviewee about the context of this work and the reason for this questionnaire. Additionally, the personal information of the participant was asked and then they were asked to score a list of stakeholders about their power or interest. The list of stakeholders can be seen here, and a preview of the question asked.


Power - Interest for Sustainable Urban Drainage Systems

WaterStreet is a living lab where several new Sustainable Urban Drainage systems (SUDS) are implemented with the goal to find ways to better manage rainwater in a city environment. In order to assess the performance of those systems we need a monitoring network that can provide the necessary indicators that the critical stakeholders are interested in. In that context this questionnaire is created to help better understand the power and the interest of several stakeholders in order to conclude to the most critical ones. In that respect I kindly ask you to score the following stakeholders for their power and interest in implementing SUDS.

Figure 59 Preview of the introduction to the questionnaire.


Score the next 11 stakeholders for their power to implement SUDS.

Field labs (example : WaterStreet) *

1 2 3 4 5 6 7 8 9 10

Low Power ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ High Power

Universities (example: TU Delft) *

1 2 3 4 5 6 7 8 9 10

Low Power ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ High Power

Figure 60 Preview of the formulation of the questionnaire.

The same question was posed to every one of the stakeholders and for both the power and interest they have in implementing SUDS.

Appendix D- Box plots of the results of the questionnaire

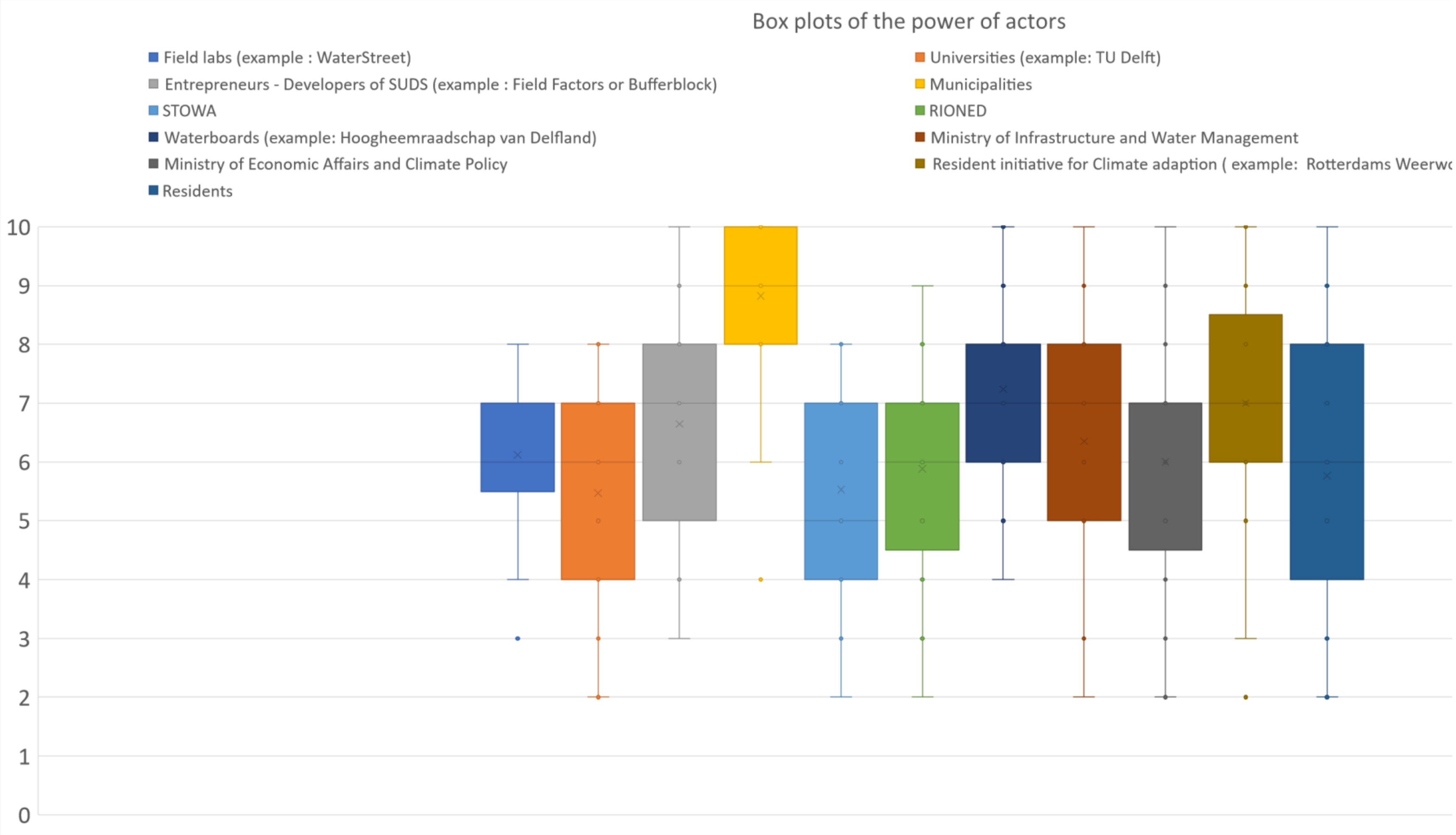


Figure 61 Box-plots of scores for the Power of actors indicating the relevant agreement of the candidates for one actor.

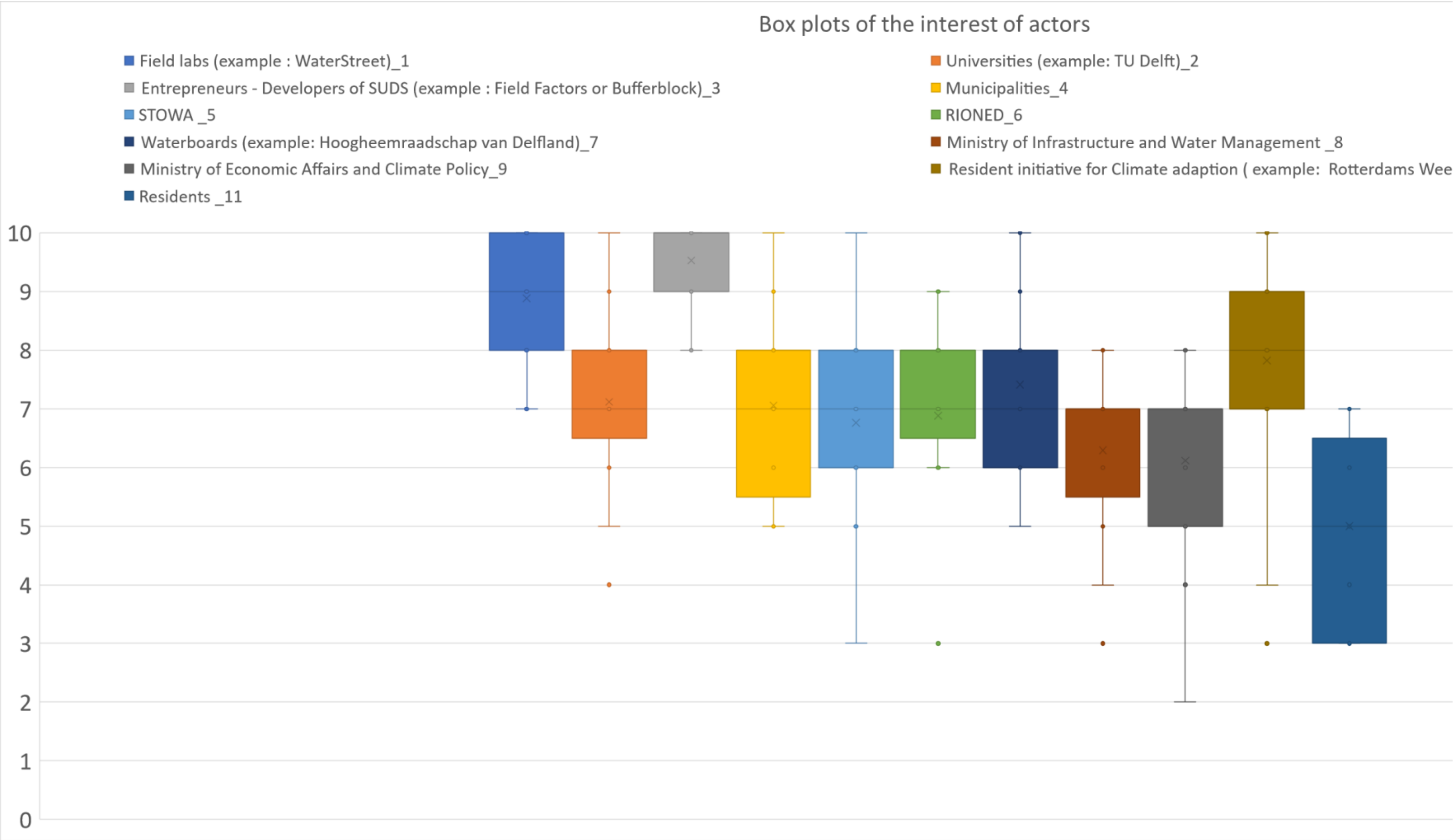


Figure 62 Box-plots of scores for the Interest of actors indicating the relevant agreement of the candidates for one actor.

Appendix E – Interview results of key stakeholders

Table 30 Responses from interviews with key stakeholders concluded from stakeholder analysis about important indicators to monitor for SUDS performance.

Interviewee	Category of interviewee	Indicators mentioned
Charlie Jurjus	Internship at the Municipality of Amsterdam	1. available storage in the system 2. emptying time 3. the volume of water directed to the public wastewater sewerage system
Emilie Buist	Representative of the developers on WaterStreet	1. the infiltration capacity of the permeable tile 2. the infiltration capacity of the surrounding soil 3. emptying time of the system 4. available storage in the system
Brahmanand Goerdat	Student in collaboration with municipalities	1. rainfall return period 2. available storage in the system 3. the volume of water directed to the public wastewater sewerage system
Sydney Stax	Working in the municipality of Nijmegen	1. emptying time 2. the time that water can stay ponded on streets 3. the infiltration capacity of the permeable tile 4. available storage in the system 5. soil types (hydraulic conductivity)

Appendix F – Groundwater simulation

The location of the center of the SUDS is given first. The assumption of point recharge is made for these calculations. The same recharge is also assumed to be 0.01m3/day. This is a simple assumption that permits the graphical representation. In reality, the recharge of every SUDS will differ, but the possible will be the same. The system [7&8] URBAN RAINSHELL & DSI was not included because it directed the infiltrated water to the deep aquifer and therefore does not act as a recharge well like the other systems. In Table 31 the location of the SUDS in reference to the coordinate system shown in Figure 63 can be seen.

Table 31 Location SUDS for the Groundwater simulation.

Name of SUDS	x_i(m)	y_i(m)
[1] FLOWSAND	-42	0
[2] WATERTABLE	-36	0
[3] DRAINMIX	-30	0
[4&5] DRAINLINE & BUFFETROTTOIR	-22	0
[6] BUFFERBLOCK	-7	0
[9] RAINROAD	-11	21
[10] ZOAK BESTRATING	-11	13

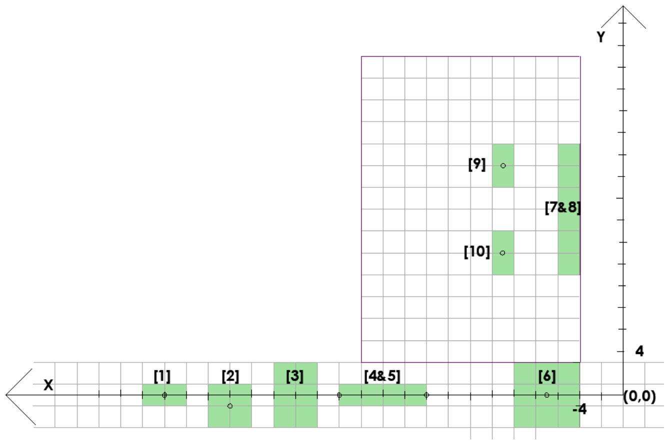


Figure 63 Coordinate system for the Groundwater simulation.

To plot the streamlines and then the contours the next equation was used and run with Python programming.

For the streamlines:

$$Q(x,y) = \Sigma\{Q_i/(2*\pi) * (x-x_i)/[\sqrt{(x-x_i)^2 + (y-y_i)^2})]^2\}$$

Q is the groundwater discharge in every location (x,y) from which the streamlines are plotted.

For the contour lines:

$$\Phi=\Sigma\{Q_i/(2*\pi) * \log_{10}(\sqrt{(x-x_i)^2 + (y-y_i)^2})\}$$