Investigating the potential of real-time control (RTC) and blue-green infrastructure integration in Rotterdam's Spangen neighborhood

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I learned many new applied skills, new ways of thinking, and specific knowledge about RTC and BGI that I had never heard of before. I was able to apply my skillset and previous knowledge to uniquely tackle this thesis project and convey fresh, new knowledge in the pages that follow.

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I am proud to have drafted this thesis as a MADE student, as it is a product concluding the fascinating journey of studying what can be best summarized as urban engineering, here in the Netherlands, a civil engineer's playground. Through the diverse methodology employed in this thesis, you will be able to understand our MADE interdisciplinary way of working and thinking, and what I have learned over the past two and a half years as a MADE student.

Dear reader, please enjoy this thesis.

All the best, thank you.

Winter
2025

Investigating the potential of real-time control (RTC) and blue-green infrastructure integration in Rotterdam's Spangen neighborhood

Developing a comprehensive district-wide hydrological representation and strategy to integrate real-time control (RTC) and blue-green infrastructure (BGI) to mitigate flooding, decrease sewer demand, and enhance climate resilience in the Spangen neighborhood of Rotterdam.

By

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Abstract

The Spangen neighborhood in Rotterdam West, the Netherlands, is highly vulnerable to pluvial flooding due to its low elevation, numerous impervious surfaces, and proximity to the Delfshavense Schie canal and a surrounding feeder canal. These factors contribute to high local surface runoff and strain on the local combined sewer system (CSS), leading to combined sewer overflows (CSOs) and local street fooding ("water op straat"). This study investigates the potential of integrating blue-green infrastructure (BGI) together with real-time control (RTC) to mitigate flood risk by reducing both the volume and frequency of CSOs and swale overflow events. A hydrological model, built utilizing 20 years of meteorological data with a 10-minute resolution from November 01, 2004 to October 01, 2024, simulated the hydrological effects of three progressively integrated bioswale configurations, a baseline scenario, and further modeled the effectiveness of RTC as valves outfitted at the base of the swale overflow structure in preemptively releasing forecasted runoff over a 12-hour lead time. Results demonstrated that while the baseline scenario revealed 582.5 mm of CSO overflow over 188 events during the study period, when implemented, bioswales alone reduced net flow to the receiving water body by up to 95%, and RTC-enabled bioswales, in the most intensive configuration, could fully, pre-emptively remove stored swale volume to completely eliminate uncontrolled overflow. The 25% interception fraction performed best for Configuration 1, and 50% fraction performed best for Configurations 2 and 3, which all minimized the net flow out to the receiving water body, most efficiently integrating the existing CSS and proposed bioswales. Beyond mitigating flood risks, BGI offer co-benefits such as enhanced ecological connectivity, improved water quality, and urban livability, serving as a tool to provide Gemeente Rotterdam with a new possibility to achieve other sustainability goals, such as increasing green space access. This research demonstrates that the integration of RTC with BGI can serve as a scalable model for climate-resilient urban water management in Rotterdam, and worldwide.

Key findings

- 20 years of rainfall data with a 10-minute resolution collected at Rotterdam The Hague AP weather station **(November 1, 2004 to October 1, 2024)**, was obtained from KNMI Open Data: **18,594 mm** total precipitation.
- **Baseline scenario** (Scenario 1): With 60 ha of land area (currently at 30.2 ha [50.2%] permeable, 29.9 ha [49.8%] impermeable), Spangen experienced **188 CSO events** with a volume of **582.5 mm** of CSO overflow over the study period.
- **Scenario 2, Config_1** (+56 swales, +1.6% permeable area): The recommended 25% interception fraction led to the lowest "net flow out" of **240.7 mm**, however, the 100% interception fraction, while reducing CSOs to **0 events (0 mm)**, caused **1,642.7 mm** of uncontrolled overflow over 1,158 events.
- **Scenario 2, Config_2** (+131 swales, +3.2% permeable area): The recommended 50% interception fraction led to the lowest "net flow out" of **67.8 mm**.
- **Scenario 2, Config_3** (+144 swales, +4.4% permeable area): The recommended 50% interception fraction led to the lowest "net flow out" of **31.3 mm**, and for **Scenario 3**, RTC successfully pre-emptively removed all uncontrolled overflow volume from the 50% fraction.
- **Road to adoption:** The three configurations represent suggested phases of local bioswale adoption, with progressively more bioswales added to every configuration, suggesting implementation phases over time.
- **Urban co-benefits:** BGI integration provides significant local co-benefits, such as urban beautification, ecological connectivity, noise reduction, water quality improvements, and limiting urban heat stress.
- Public urban green spaces in Spangen are currently poorly maintained and not thoughtfully implemented, reducing their potential to intercept surface runoff and contribute to local climate resiliency.
- Residents of the Spangen neighborhood are currently not keen on community engagement, for example by maintaining public BGI through collective efforts.

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List of Abbreviations

BGI – Blue-green infrastructure
[*interchangeable:*
BMP – Best management practice]
CSO – Combined sewer overflow
DWF – Dry weather flow
EEA - European Environment Agency
EN - English
IMP – Impervious [area]
IUWM - Integrated Urban Water Management
IWMM – Integrated Water Management
KNMI – (***NL:*** *Koninklijk Nederlands Meteorologisch Instituut,* ***EN:*** *Royal Netherlands Meteorological Institute*)
MPC – Model predictive control
NbS – Nature based solutions
NL – The Netherlands [*as language*: Dutch]
P - Precipitation
PAT - Pump as turbine
PDF – Probability density function
PER – Pervious [area]
PLC - Programmable logic controller
PRV - Pressure reducing valve
RTC – Real time control
RTU – Remote terminal unit
SCADA - Supervisory control and data acquisition system
SW – Stormwater
UDS – Urban drainage system
US EPA – United States Environmental Protection Agency
WDN – Water distribution network
WTP – Water treatment plant
WW – Wastewater
WWTP – Wastewater treatment plant

1 – Introduction

The Spangen neighborhood of Delfshaven, Rotterdam West, in Rotterdam, the Netherlands, is particularly vulnerable to pluvial flood risk from three main causes:

① geographical location, surrounded by the Delfshavense Schie
② flat, and low elevation up to 11m below sea level
③ numerous impermeable surfaces & lack of urban greenery.

This research investigates the potential of implementing blue-green infrastructure (BGI) with real-time control (RTC) on a neighborhood-level scale, to intercept surface runoff and control the outflow of the intercepted volume to the nearby surface water, analyzing how water level variability and combined sewer overflow (CSO) volumes and frequency respond. In theory, local flooding risk can potentially be reduced by decreasing combined sewer system (CSS) demand and controlling bioswale outflows to the local receiving water body. Bioswales also can improve local livability by introducing more green spaces, which have many co-benefits including providing habitat space, and increasing local aesthetic appeal.

1.1 CSOs in Spangen

In a traditional CSS, stormwater and sewage are channeled into the same pipes, which can lead to filling sewer pipes to, and even past, their capacity during events of heavy rainfall. Once the CSS reaches capacity, the CSO associated with the particular sewer system is then activated, discharging the extra, untreated sewage effluent into nearby rivers and waterways, threatening local public health and flooding by directly raising the water level of these receiving bodies of water with the sewage. CSO use, of course, also has poor environmental effects on the receiving water body that are out of the scope of this thesis, including water pollution, eutrophication, and displacement of local plant and animal species.

Rotterdam, a forward-thinking city known for developing innovative urban water management strategies, currently faces consequential impacts with its CSO systems in Spangen, a neighborhood in Rotterdam West as seen in Figure 1. Located along the Delfshavense Schie, Spangen currently releases CSO volumes into this canal during periods of CSS capacity exceedance, spiking local water levels quickly by releasing untreated sewage into the surrounding canals, and threatening both flooding as well as local public health. Therefore, hosting around 10,000 residents (Gemeente Rotterdam), it is extremely important for Spangen to manage, and ideally, eliminate CSO volumes and canal water levels to reduce the likelihood of urban flooding, and improve public health by limiting sewage discharge into the surrounding water bodies.

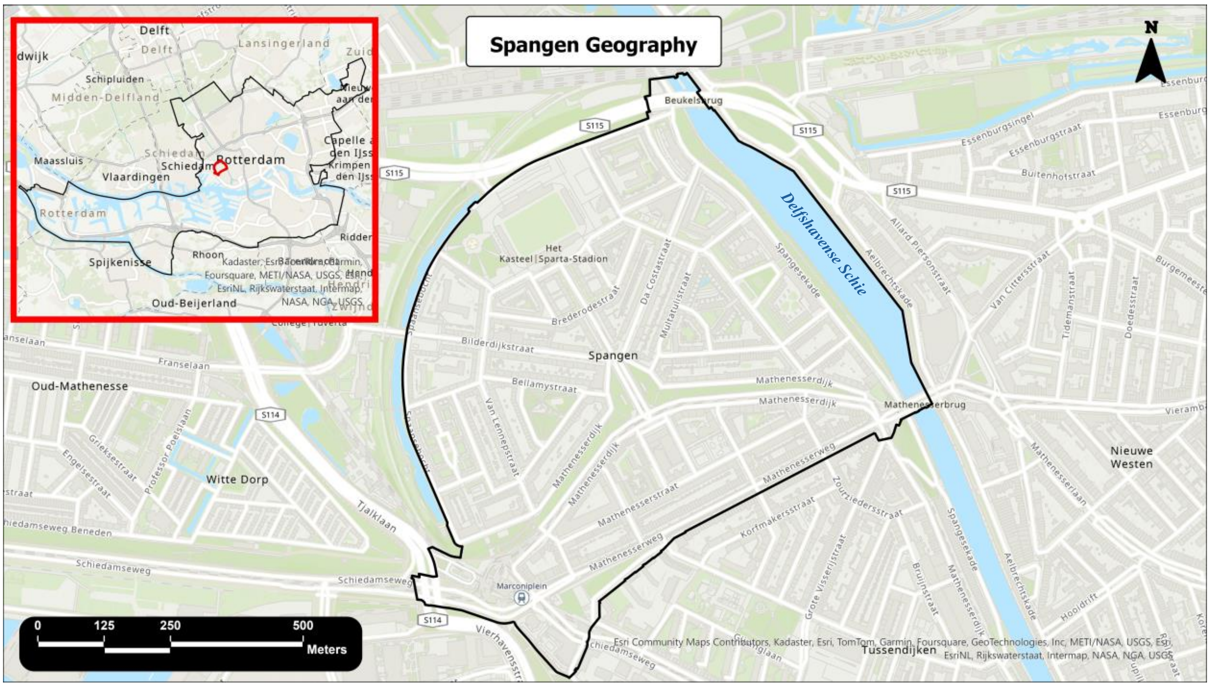

Figure 1 - The location of the Spangen neighborhood (outlined, black), with respect to the rest of Rotterdam (outlined, red). The Delfshavense Schie, the receiving body of the CSOs of Spangen, runs along, and mostly surrounding Spangen save for the South side.

Figure 2 (below), accessed from Gemeente Rotterdam's Gisweb2.2, depicts a map of CSO overflow points (*NL: overstorten punten*) in the neighborhood, with OVS 42341 and OVS 65724 directly overflowing into a surrounding canal of Spangen, connected to the Delfshavense Schie. These two overflow structures in particular are weirs directly discharging CSO overflow into an exposed water body meters away from local residences and recreational facilities, such as the nearby Sparta Park and Kasteeltuin Spangen. Ultimately, this discharge ends up in the Delfshavense Schie and nearby Maas River, further threatening water level rise and public health.

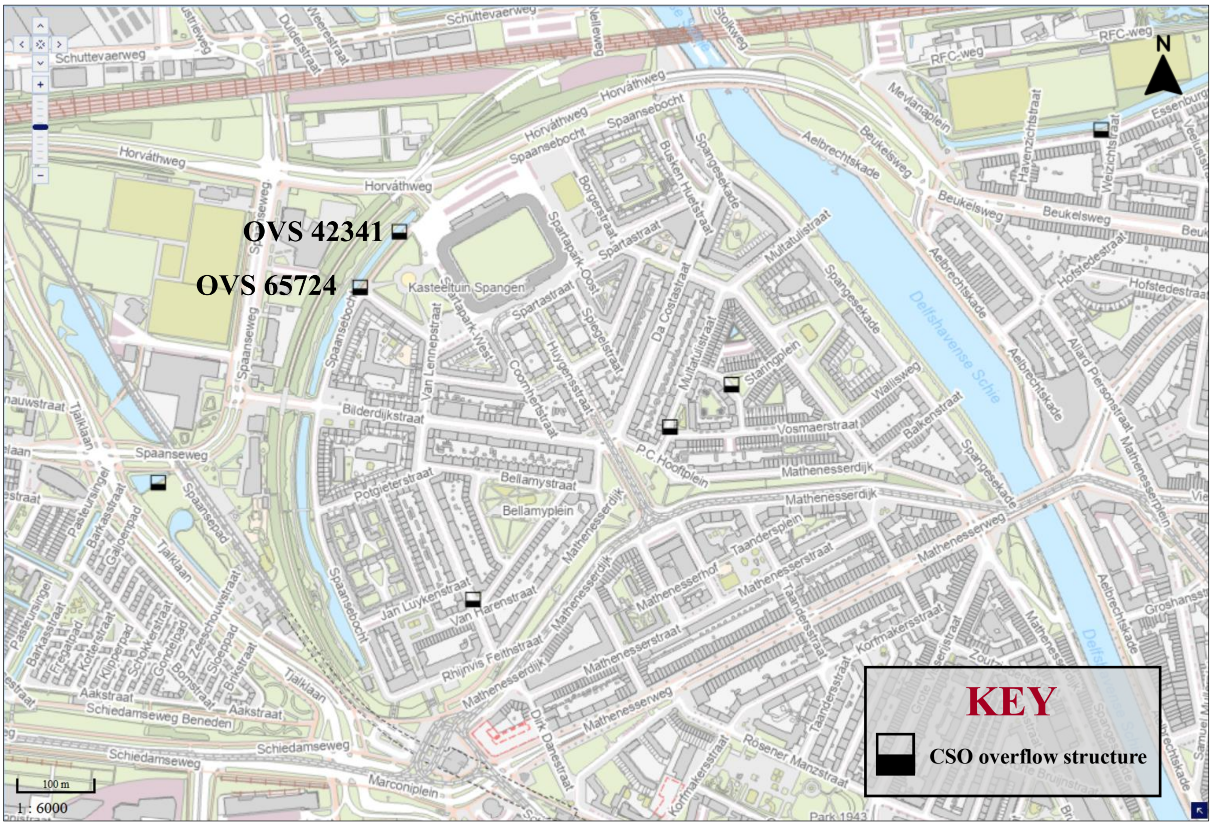

Figure 2 *- An aerial overview of CSO overflow points in, and around, Spangen, with OVS 42341 and OVS 65724 labeled.*

Such close proximity to the public of CSO overflows, like OVSs 42341 and 65724, calls for stringent CSO management protocols and modeling to understand its behavior. This thesis will examine regulating water levels caused by CSO outflows by introducing swales as BGI throughout Spangen to intercept surface runoff, directly decreasing CSS input, and in turn, minimizing CSO overflow events and volumes. The swales will be modeled to empty their stored volumes in two scenarios – (1) in an uncontrolled manner, where all of the cumulative volume from every swale will rush to the canal in swale overflow instances, and (2) in a controlled manner aided by RTC, where the equivalent projected overflow volume will be pre-emptied from the swale over a lead time from their current stored volume to accommodate for the incoming runoff. In a future shaped by climate change, increased urban growth, and aging infrastructure, managing CSOs and water levels of receiving water bodies like the Delfshavense Schie is critical to maintaining urban livability and protecting public health and urban waterways.

1.2 BGI as water management infrastructure

Various BGI have emerged in recent years as methods to combat the problem of anthropogenic and climate change-induced increased demand on CSSs. Defined as "an interconnected network of natural and designed landscape components including...open spaces" built to handle an influx of stormwater runoff, many water management experts and stakeholders including engineers, scientists, residents, and scholars suggest that this type of urban planning method, of building to accommodate water on-site, provides multiple benefits such as: (1) water storage [for irrigation and non-potable use], (2) flood control, (3) wetland areas for wildlife habitat or water purification, and many others, such as reduced heat stress (Ghofrani et al., 2017). Instead of the "old-school" method of building infrastructure to immediately convey all stormwater to the local wastewater treatment plant (WWTP), this new school of thought of in-situ stormwater management aims to build urban green infrastructure such as parks or bioswales to retain runoff and spread releases over time, either into the subsurface or another catchment, ultimately decreasing peak flows into the local CSS (Fletcher et al., 2014; Liao et al., 2017). In this way of building, stormwater immediately is not rushed off-site, but rather treated on-site, delaying peak flows to a central place of collection, such as a WWTP, instead distributing the flows over a longer period of time to better distribute demand.

1.3 Real-time control (RTC) in water management infrastructure

Standard BGI do not have the real-time capability to adapt to changing conditions. They are not "smart". BGI are pieces of infrastructure that have been built to act as local sinks to intercept runoff from reaching the local CSS and ultimately, the WWTP. BGIs traditionally have a set capacity for handling inflow, and nothing more can be done by and to themselves to adapt to changing inflows. For example, a swale can only infiltrate and store a certain amount of stormwater, and release through an overflow once a certain depth of water has been exceeded. RTC adds a dynamic, urban digitalization ability to any applicable system, with the idea of RTC being to leverage technology to fully utilize the available infrastructure. In the case of BGI, the addition of RTC to BGI could unlock a new potential for data-driven decision making, enabling the proposed BGI to become more powerful of a water management tool by giving it an ability to dynamically adapt to changing and forecasted environmental conditions and integrate into a "smart city" network, giving more insights and optimization into the urban environment.

The RTC objective of this research is to investigate the potential of implementing RTC in the form of a valve attached to the base of the drainage pipe running from the swale outlet to the catchment water body nearby. This can be numerically modeled by drafting a set of rules to pre-empty a projected overflow volume from the existing stored volume of the swale over a lead time, better distributing the would-be uncontrolled overflow volume over a longer period of time to control peak outflow. This gives the municipality, and water board more control over flows to the receiving water body, better managing flood risk and reducing public health risk. Small-scale BGI, proposed in three different configurations, will be modeled as a collective, investigating how RTC can control them on a larger, neighborhood-level scale.

1.4 Relevant metropolitan challenge

The innovation of integrating BGI with RTC technology offers a transformative approach to strengthen local climate resilience in Spangen, in response to the increasing severity of rainfall events driven by climate change. This research delves into the potential of combining these systems to allow BGI to dynamically adjust to varying rainfall conditions by using RTC. This study explores how Spangen can mitigate the risk of flooding and improve public health by proposing BGIs to reduce CSOs. The findings will not only address immediate, local water management challenges but will also provide a scalable solution that can be applied to urban areas worldwide. Ultimately, this research supports the broader metropolitan challenge of creating climate-resilient cities, proposing a model for integrating advanced stormwater management technologies to safeguard neighborhoods against future climate risks. Therefore, this research is linked to the metropolitan challenge of "climate resilient cities" (AMS Institute) as this paper will investigate how Spangen can become more climate resilient as a neighborhood.

2 - Literature Review and Interview

Water is the single most important resource on Earth to manage for decades to come, especially in response to climate change. More frequent and higher-intensity rainfall events are projected to overwhelm existing water management infrastructure, leading to: localized and regional flooding, damage to property and civil infrastructure, and significantly amplified public health risks (Lawrence et al., 2020). Managing existing water resources to ensure their sustainability and reduce the danger they can have on people and the built environment therefore becomes extremely important. Ideas such as peak flow attenuation are essential in mitigating these risks by slowing down and controlling the flow of stormwater during heavy rainfall events and adapting to future climate conditions. By releasing stormwater and overflows at a controlled rate, infrastructure such as BGI reduce the burden on existing drainage systems. In this thesis, BGI are proposed to decrease peak flows of stormwater into the CSS, reduce CSO occurrences in terms of volume and frequency, and reduce likelihood of urban flooding.

2.1 RTC systems

RTC systems for water management infrastructure, including for urban drainage systems (UDS), wastewater treatment plants (WWTPs), water distribution networks (WDNs), and water storage units, have emerged as an interesting and viable option to manage climate change-induced increased demand on these infrastructures. RTC systems use control loops to regulate process variables in the water network, simultaneously using data inputs to the system as measured by sensors to adjust actuators "to achieve minimum deviations of the controlled process variable from its desired value" (Schütze et al., 2004). As a conceptual example, if a series of tanks have different water levels and the goal is to have an even distribution (to reach a common set point), an RTC system will read the water levels using sensors, relay the disturbance measurement to the controller, who will execute commands to physically move the actuator to even the water levels. Figure 1 (p.336) from Schütze (Fig. 3 in this paper, modified) schematically demonstrates the RTC process.

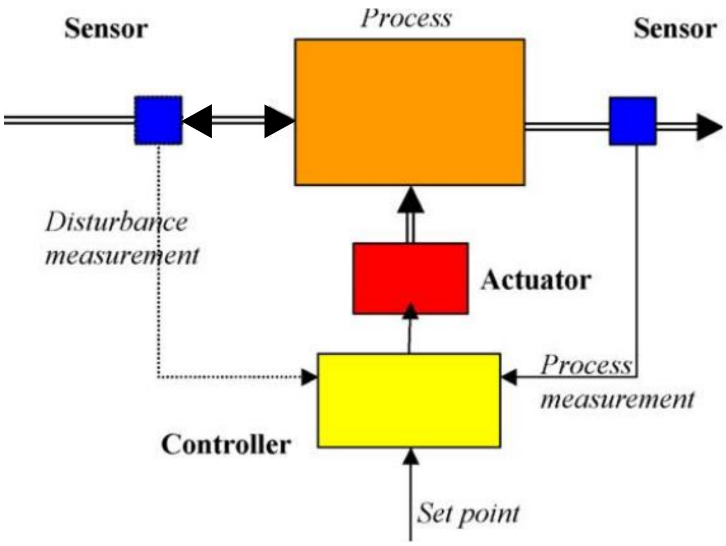

Figure 3 - *From Schütze et al (2004, p.336), a schematic of an RTC system process feedback loop. Sensors, programmed to monitor a certain objective such as flow rate (process measurement), can detect changes in this variable away from the set point, relay this change to a controller, which executes logic to activate an actuator to regulate any disturbances and revert to the pre-disturbance (set point) condition.*

RTC applications to stormwater infrastructure are novel, as current stormwater management practices such as CSSs are still largely dominant due to cheaper implementation costs, yet "poorly equipped to adapt to consequences of continuously changing climate and land use" (Sharior et al., 2019). RTC is therefore oftentimes seen as an emerging technology retrofitted to existing water infrastructures, especially CSSs, to "enhance water quality treatment and quantity management" in response to climate change (Schmitt et al., 2020).

2.1.1 Governing processes of an RTC system

RTC systems can be governed by three types of operations (Schwanenberg et al., 2015):

1) feedback control (closed loop)
2) feed-forward control (open loop)
3) [model] predictive control (MPC).

Feedback control loops are closed-loop control systems that consider the *real time* deviation (error) of a control variable from a pre-specified set point, and keeps the error at a minimum possible value (Pereira, 2018). This type of loop responds to changes after a set point has been deviated from, as illustrated in Figure 4.

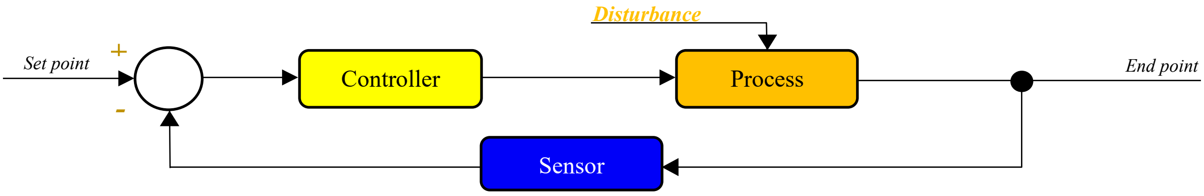

Figure 4 - *A schematic representation of a feedback loop. (Own). Wherein a disturbance is planted into the system, is recognized by the sensor, and acted on by the controller to regulate the system back to its original set point (end point).*

Feed-forward control loops are open-loop control systems that compensate system dynamics without needing information about the system states as the tracking error, and instead use forecasts to control the system (Hernández and Sierra, 2023, p.91). This type of loop, illustrated in Figure 5, pre-adjusts the set point in advance of a disturbance and models the performance of the system based on this forecasted deviation from the set point.

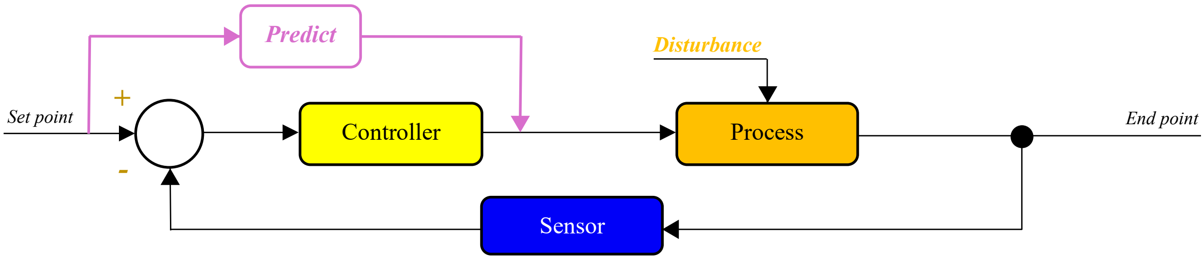

Figure 5 - *A schematic representation of a feed-forward loop. (Own). Wherein before a disturbance is planted and recognized in the system, the set point has already been predicted, modeled, and adjusted to match the disturbance, and the system has been pre-adjusted by the controller.*

Model predictive control is widely used in CSSs around the world, and is "is an adaptive control strategy in which the optimal control is recalculated recursively as new information about the state of the sewer system and new rainfall forecasts become available" (Lund et al., 2018, p.281). As real-time information such as peak inflow becomes available through sensors in the CSS, a model can be developed over time to model the response of the CSS (or any other water management infrastructure) to the influx of water. Over time, the model can be tuned and later used as the predominant method to control the desired variable and predict the response of the water infrastructure to any forecasted disturbances.

Ideally, an RTC system should integrate all three types of controls (feedback, feed-forward, and MPC) to enable the most efficient handling of water. Efficiency in maintaining set points is maximized by constantly optimizing based on analyzing existing states in the system (feedback), predicting changes and calculating responses based on forecasts (feed-forward), and utilizing past data instances to model the best response to future disturbances (MPC). There currently exists minimal literature on how to apply RTC to BGI to improve the efficiency of the BGI.

2.1.2 Devices in RTC infrastructure

Numerous devices including sensors, actuators, and controllers are present throughout an RTC system to ensure smooth functioning. Creaco et al. (2019) lists numerous devices used in WDNs, written as follow, which are equivalent devices also used in RTC wastewater and stormwater systems.

Sensors

- water level gauges: floating hydrometers, bubblers, pressure inductive gauges and sonic gauges
- pressure sensors: piezoresistive, capacitive, electromagnetic, piezoelectric and optical gauges,

- flow meters: optical flow sensors, electromagnetic, or ultrasound flow meters.
    - Pressure-based meters: Venturi-meter and Pitot-tube
- electromagnetic and ultrasound flow meters
- traditional mechanical meters (e.g., Woltman and current meter) for volumetric measurements

Actuators

- pumps: (axial or screw) with 1) constant or 2) variable speed
- control valves with mechanical actuator: plunger, globe, piston and butterfly valves
- valves with spring-controlled actuator: pressure reducing valves (PRVs)
- turbines/pumps as turbines (PATs), to enable conversion of surplus of total head into electrical energy

Controllers

- Programmable Logic Controllers (PLCs), Remote Terminal Units (RTUs), SCADA systems

This outline of devices has been included in this literature review to give a holistic understanding of what devices physically make RTC systems. Valves are of interest to this research, as later described.

2.1.3 RTC in the Netherlands

RTC as a concept and technology is presently used in water management efforts across the Netherlands, especially in polders. RTC is also used in urban settings, albeit on a smaller scale, and oftentimes only in CSSs.

Polders

The Netherlands, bounded by the North Sea to the North and West, and traversed by major rivers including the Rhine (East to West), Waal, and the Maas, has waged a "war on water" for centuries (Steen & Pellenbarg, 2004), preventing the North Sea from engulfing land, and taking back land from the sea, such as with the Flevopolder. With 26% of the Netherlands below sea level (Schiermeier, 2010), managing water becomes a matter of life or death. In the Netherlands, RTC is actively used to manage water levels of polders, which constitute about 60% of the country (Deltares). One may see weirs such as in Figures 6 and 7 (below) around the Netherlands, methods used to manage water levels especially during periods of heavy rainfall and droughts. These weirs are an example of how Dutch water authorities use automation and real-time data to monitor and control polder water levels. Automation is used to adjust the angle of the weir opening based on predetermined logic of desirable water heights.

Figure 6 - *An automated adjustable tilt weir with an RTC box (top right), which monitors the water level at the weir by automatically processing incoming data and adjusting the weir as needed to maintain a set point of a certain water level height. Picture from GWW-Bouw.*

Figure 7 - *An adjustable tilt weir (Dutch: "kantelstuw") in a channel along the Kamperhoeve street in Hattem, NL, located here. Image referenced from local newspaper Nieuwsblaad Schaapskooi.*

Sensors at the weir and around various points throughout a polder (such as in canals) monitor water levels and engage in a feedback loop with weirs, to control local and regional water levels for the entire polder. As can be seen by Figures 8 and 9, weirs (blue triangles) are placed throughout a polder system, and all the canals are connected to each other. The weirs are programmed with a certain set point (**NL:** Beheermarges, **EN:** Management margins), and can regulate water levels to keep this acceptable range between sections and for the entire polder by rotating to adjust the angle of the opening, letting varying volumes of water pass (Waterschap Zuiderzeeland). In the figures below, certain overshoot and undershooting can also be seen, where once faced, weirs and sensors will communicate with each other to discuss how to address these to regulate water levels back to the acceptable range.

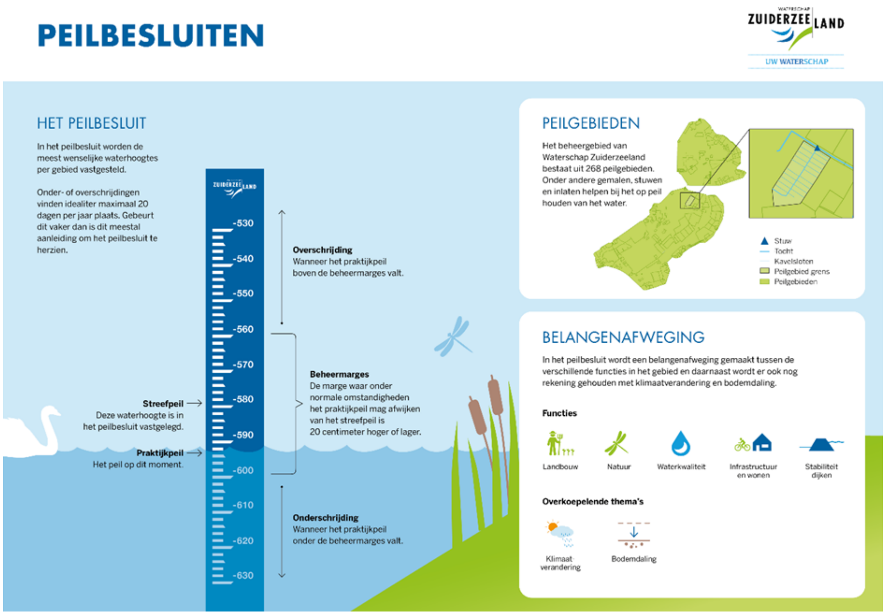

Figure 8 - [NL] *An infographic explaining the water level management policy of Zuiderzeeland Water Authority, highlighting target levels, deviations, and considerations for agriculture, nature, infrastructure, and climate impacts.*

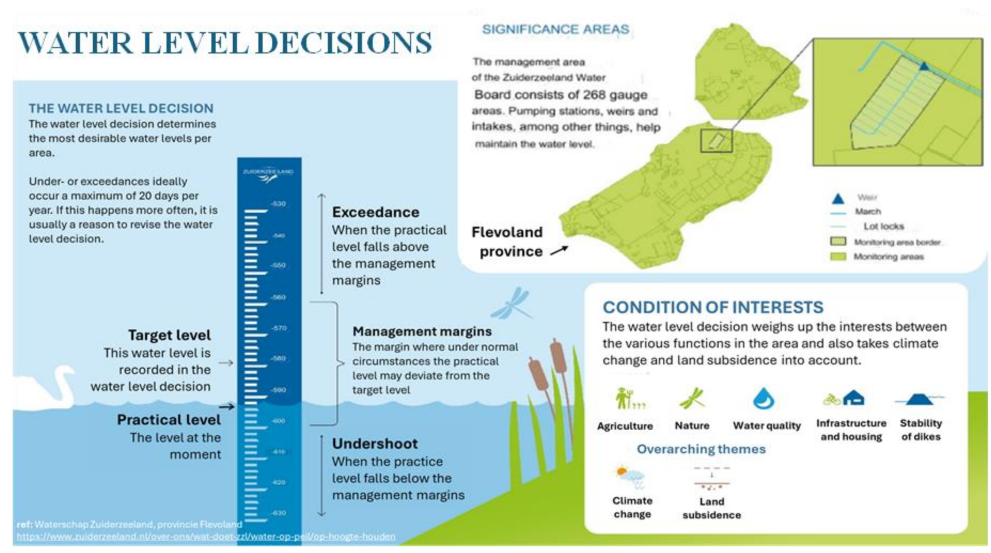

Figure 9 - *Figure 8, translated to English.*

Urban

RTC systems likewise exist in urban spaces of the Netherlands, albeit very few. A well-researched RTC system exists in the Eindhoven, NL catchment, which is used to control regional WWTP input and CSS & CSO flows in the system, as illustrated in Figures 3.2 & 3.3 from [van der Werf, 2023](#) (pp.39,40). In this RTC system, a comprehensive monitoring system was set up in order to gain a better understanding of the system, and certain rules and setpoints were proposed for two control stations, and showed a high potential for the reduction of both dips in the dissolved oxygen (DO) and peaks in ammonium (NH_4^+) in receiving water bodies (van der Werf, 2023; [Langeveld et al., 2013](#)).

Likewise, an RTC system exists to control regional WWTP input and CSS flows in Rotterdam, as illustrated by Figure 3.6 in van der Werf, 2023 (p.45). Using RTC to control WW outflow is especially important in Rotterdam, as the city is transversed by urban canals (***NL:*** *"singels"*) through densely populated areas. CSO overflows must be minimized, and ideally avoided completely to be released into singels due to the proximity of contaminated water outflow to sizeable urban populations, as well as negative environmental impacts to the local ecosystems.

2.2 Current state of BGI

BGI is an important means of dealing with flooding and extreme weather, since it consists of a network of interconnected water reservoirs, wetlands, and their associated (natural) open spaces ([Ghofrani et al., 2017](#)). This means that the capacity of the local area (with BGI integrated) can retain much more stormwater than if the same area was impermeable, built over by paved surfaces. This is because stormwater can flow into the ground through the soil of the BGI, decreasing volumetric outflow to the local sewer system, and reducing peak flow and load onto the WWTP ([Berland et al., 2017](#)). The European Environment Agency's (EEA) *Nature-based solutions in*

Europe report, under the overarching European Union's Flood Directive (EUFD), highlights numerous "Nature-based solutions for urban water management" (EEA, 2021, p.66), namely:

- Bioswales
- Retention and detention basins (or bioretention cells/filters),
- (Constructed) wetlands
- Rain gardens
- Permeable pavements
    - *...linked to underground storage tanks and infiltration basins*
- Riparian vegetation strips and green roofs
- Removing excess asphalt and concrete in private and public urban spaces
- Retention ponds, rain gardens
- Vertical greening

The EEA report splits nature-based solutions (NbS) in urban areas into two types: 1) large-scale, and 2) small-scale. Since large-scale NbS focuses on topics such as reforesting and agriculture, this research only examines small-scale NbS. Finally, the United States Environmental Protection Agency (US EPA) has a catalogue of stormwater best management practices (BMPs [*interchangeable: "*BGI"]) which, while not in Europe, further highlight the state of existing BGI technology very well (US EPA, 2023).

BMP	Pollutant Removal							Flow Attenuation	
	Trash	Solids	P	N	BOD	Metals	Bact	Peak	Volume
Percolation trenches/pits	■	■	■	□	■	○	■	□-■	□-■
Grassed swales	NA	□	□	□	□	¤	□	¤-□	¤
Grassed buffer zones	NA	¤	¤	¤	¤	¤	¤	¤-□	¤
Pervious pavements	■	¤	○	■	○	■	□	¤	¤-□
Infiltration basins	■	■	■	□	■	○	■	□-■	□-■
Vegetated waterways	NA	□	□	¤	□	¤	□	¤-□	¤
Inlet controls/traps	●	□	¤	¤	□	¤	¤	NA	NA
Detention basins (wet, dry)	NA	●	■	□	■	○	●	□-○	¤
Retention ponds/wetlands	NA	○	■-○	□-■	□-■	○	■-●	□-■	¤
Aeration	NA	NA	NA	NA	●	NA	NA	NA	NA
Street sweeping	○	□-■	¤	¤	¤	¤	¤	NA	NA

Key: Removal efficiency
● 80-100% ○ 60-80% ■ 40-60% □ 20-40% ¤ 0-20%
NA - not applicable

Figure 10 - *A table evaluating common BGI technologies with respect to their 1) pollutant removal, and 2) peak flow attenuation capabilities (Lawrence et al., 2010).*

This catalogue splits BGI into three types: point, linear, and area, with point BGI including technology such as bioretention basins, linear BGI including infiltration trenches, and area BGI porous pavement (over a large area). Figure 10 denotes the capabilities of many common BGI technology with respect to peak flow attenuation (of interest to this research), and pollutant removal (Lawrence et al., 2010).

2.2.1 BGI in the Netherlands

The Netherlands is a country that has been working on integrating BGI into the urban fabric of cities across the country for many decades, especially as a result of the LANDS (Land-use and climate change) project undergone by the Wageningen University and Research (WUR) and Vrije Universiteit (VU) (Ghofrani et al., 2016; Wageningen Universiteit). LANDS resulted in a land use model of the Netherlands with high-resolution 100x100 meter coverage cells, yielding for the first time at the completion of the research a lack of green in all three residential zones, and a call to municipalities to build more BGI in their respective areas.

The only available literature discussing BGI integration in the NL are city climate plans such as Enschede's Water- en Klimaatadaptatieplan and Groeneambitieplan Enschede 2050, or Amsterdam's Green Infrastructure Vision 2050. These pieces discuss the visions of cities and municipalities towards integrating BGI, but literature discussing the progress of these cities in doing so, or ranking how the Netherlands compares to other countries, is missing. BGI is very present in newer [re-]development plans, and many streets and urban areas are being retrofitted to include more BGI, such as Meerwijk, in Haarlem, NL (Gemeente Haarlem). Some key examples of BGI seen around the Netherlands can be seen in Figures 11-14 below, taken by the author of this paper during excursions around the country. Many cities are implementing BGI, especially that can be seen in new development areas.

Figure 11 - *Photo (own) of the interactive GW injection & pumping site in Spangen.*

Figure 12 - *A photo (own) of bioswales and retention basins along the Molenstraat in Enschede, NL.*

Figure 13 - *A South-facing view of the very large bioswale along the Oldenzaalsestraat in Enschede, NL. Picture referenced from the YouTube channel video of Enschede (own), by the author, A Young Engineer.*

Figure 14 - *A photo (own) of a bioswale (wadi) along the Groene Boord in Heerlen, NL.*

2.3 Local Insights from Interview

As part of understanding local residential dynamics and knowledge regarding BGI, green space usage, and flooding knowledge, a semi-structured interview was conducted on June 07, 2024, at the Westervolkshuis Community Center in Spangen with an elderly local who has lived in the neighborhood for over 40 years. The interviewee spoke little to no English, so two translators were present to facilitate communication. Appendix II shows notes taken from the interview.

One of the most striking interview results was her description of a complete lack of community involvement in maintaining the neighborhood's existing green spaces. The interviewee emphasized that residents in Spangen do not take responsibility for the upkeep of local greenery, nor do they show concern for its condition. With the interview held in the summertime, she made a point to gesture to, and describe the green areas outside the window as unkempt. According to her, this was representative of a larger local trend: no sense of shared responsibility for public spaces, and maintenance occurring only for formal public spaces such as the Sparta Park or the Bellamypark. Informal open spaces, and streetside vegetation are largely ignored. She expressed frustration that the municipality does little to intervene, resulting in many overgrown plants, invasive species, neglected patches of grass, and poorly maintained trees throughout the neighborhood. The limited municipal involvement means that the already absent community participation is compounded by a broader institutional neglect. Additionally, she noted that many streets in Spangen—most notably Spartastraat and the intersection of Da Costastraat and P.C. Hooftplein—could be made greener, as they are highly paved at the moment, consistent with the author's observations during field visits. She recommended the streets of the entire neighborhood to have more plants and trees, as most have expansive paved walkways that could be reclaimed for greenery. This was a direct input into the three different swale configurations. Overall, she explicitly stated that if bioswales or other forms of BGI were to be introduced in Spangen, their maintenance would inevitably fall on the municipality.

The interviewee also spoke about her personal experiences with flooding in Spangen. She advised that whereas the neighborhood has gone through many socio-economic changes over time, water management has always been a top priority in Spangen due to its low-lying location by the Maas River and the Delfshavense Schie. Never once in her 40 years of living in the neighborhood had there been a local flood. However, she did not explicitly rule out the possibility of runoff issues, minor ponding, or inefficient drainage, suggesting that such occurrences may either go unnoticed or be perceived as normal rather than problematic. More interviews, perhaps with local sewer managers, are recommended. More notably, she indicated that there is no real discussion of stormwater management among residents, reinforcing the broader theme of disengagement. People do not seem concerned about whether drainage systems are functioning well or whether improvements are necessary, taking hydrological systems for granted. The absence of complaints or community-driven initiatives related to water management overall demonstrates that there is no real investment from residents in shaping or maintaining their physical surroundings. However, some sentences and questions were lost in translation, with the language acting as a barrier despite the presence of two translators.

2.4 Literature Gap

The previous sections of the literature review discussed topics including RTC and BGI in various contexts and depths. Putting these together in practice has never been done on an urban scale in the Netherlands, in particular, the combination of bioswales controlled by RTC opening a valve at the base of its overflow pipe to pre-drain a calculated forecasted overflow volume over a lead time to accommodate for incoming runoff. This is a new, innovative idea of managing stormwater and outflows to the receiving water body in the urban environment.

In recent years, the combination of implementing RTC and BGI together on decreasing demand on CSSs and combined sewer overflows (CSOs) is well-studied, with results showing that CSO overflow volumes are reduced when both technologies are working together (van der Werf et al., 2023; Altobelli et al., 2020). The combination of RTC and BGI decreases CSS demand by utilizing weather forecasts to predischarge the BGI and detain the maximum available runoff during incoming peak storm events (Zhou et al., 2023). However, there is no existing research that has investigated the effects of RTC combined with BGI on CSO reduction and peak BGI outflow attenuation, especially in an urban context. In fact, one of the only studies that comes close is by Jean et al. (2022), which demonstrated the potential of RTC combined with distributed green infrastructures to reduce CSO volumes significantly. However, their study did not focus on controlling individual BGIs such as bioswales, nor examine the specific dynamics of outflow attenuation at the BGI level.

In summary, a research gap exists as described to study the application potential of implementing RTC together with BGI to control the bioswale stored volume and outflow volume and rates with respect to forecasted overflows to mitigate peak flows to the receiving water body. This research investigates the potential of implementing RTC together with BGI to measure impacts on the CSO volumes and frequency, as well as to control outflows to the local receiving water body.

3 - Research Questions

How can real-time water management control (RTC) be integrated with **blue-green** infrastructure in the Spangen neighborhood in Rotterdam, NL to mitigate flooding and build local climate resiliency by controlling outflow to the local receiving water body?

3.1 Sub-Research Questions

1. What is the current capacity of the combined sewer system (CSS) and the combined sewer overflow (CSO) for handling stormwater flows, in terms of volume and frequency, in Spangen, Rotterdam?
2. How would the local implementation of swales in Spangen, in different configurations, impact the receiving water body in terms of CSO volume and frequency, as well as uncontrolled overflow volume and frequency, based on historical precipitation data from the past 20 years?
3. Using a perfect forecast of 20 years from the Spangen area, if the combined maximum volume of all swales were to be exceeded in the near future from a large precipitation event, how can real-time control (RTC) be used to re-distribute forecasted peak swale outflows to the local receiving water body?
4. How does the integration of blue-green infrastructure (BGI) and real-time control (RTC) impact urban livability in Spangen in terms of public health, green space accessibility, and urban resilience?

4 - Theoretical Framework

The modeling process of this research is framed using the framework of linear reservoir modeling, and the background concepts of this research are analyzed under the framework of Integrated Urban Water Management (IUWM). Defined as an “urban development model based on the utilization of human, collective, and technological capital for the enhancement of urban livability and prosperity” (Angelidou, 2014), smart cities aim to leverage technology and data-driven solutions to enhance sustainability and overall livability for their residents, which is the primary goal of pairing RTC and BGI.

This research frames the effects of implementing RTC and BGI within the framework of three key concepts of smart cities, directly tied to the research questions:

a) Climate resiliency & climate-proof
b) Urban digitalization & Data-driven decision making
c) Nature-based multifunctional solutions

Points a, b, and c are all linked together insofar as RTC acts as the "keystone" towards implementing BGI in a sustainable manner, building climate resiliency for this neighborhood. RTC can also be viewed as forming a feedback loop for BGI, where RTC can constantly improve climate resiliency, decision-making, and nature-based green solutions for this neighborhood.

4.1 Integrated urban water management

Integrated urban water management is a theory defined by UNESCO as "an approach to managing the entire urban water cycle in an integrated way...by [incorporating] the various dimensions of water, including surface and groundwater resources...[and] the fact that water is a system and component which interacts with other systems" (Choi et al., 2023). IUWM largely advises switching a city to decentralized water management systems with the goal of providing "socially acceptable, economically viable and environmentally sustainable water supply, wastewater and stormwater services in urban areas by considering interdependencies between water/wastewater/stormwater, energy, urban design and the surrounding environment" (Burn et al., 2012).

This approach can be seen as favorable to cities, as in-situ water management and reuse decreases strain on central water processing systems such as WWTPs by using and treating water closer to the source. Under this theory, the various systems of urban water including water supply, drainage, and sanitation should not be viewed in isolation, but rather, in connection as part of an integrated physical system (Mitchell, 2006).

4.2 Climate-proof Rotterdam

The Spangen district has faced numerous flooding and stormwater management problems in the past, including recently, in early 2024 (De Havenloods, 2024). Numerous solutions have been proposed in this district including a freshwater bubble underground stormwater detention/groundwater replenishment system used to water the pitch of the local Sparta football stadium (metro, 2018; H2O, 2018), a rainwater basin in the local Al-Ghazali school (Rijnmond, 2018), and sponge gardens in the larger Delfshaven district (Rijnmond, 2019). Several sources point to the fact that because climate change will continue to cause extreme variability in rainfall and water availability in this district, measures to enhance local climate resiliency are crucial to maintaining the desired level of local livability (Gemeente Rotterdam, 2024; BNNVARA, 2022).

The implementation of BGI will create more green spaces, which have many benefits including coupling surface flow with subsurface water storage, activating evapotranspiration abilities of plants of the BGI, decreasing local heat stress, and above all, decreasing the demand on the local sewer system. From a climate resiliency perspective, this research will investigate and quantify these benefits to improve local livability and enhance the sustainability of the neighborhood for decades to come, enabling the urban spaces to meet the changing demands on the CSS caused by climate change. RTC will help in the implementation of BGI, as RTC technology can be retrofitted to BGI infrastructure to actively reduce flood risk by smoothing peak outflows to the local receiving water body, as well as to minimize the demand on local CSS.

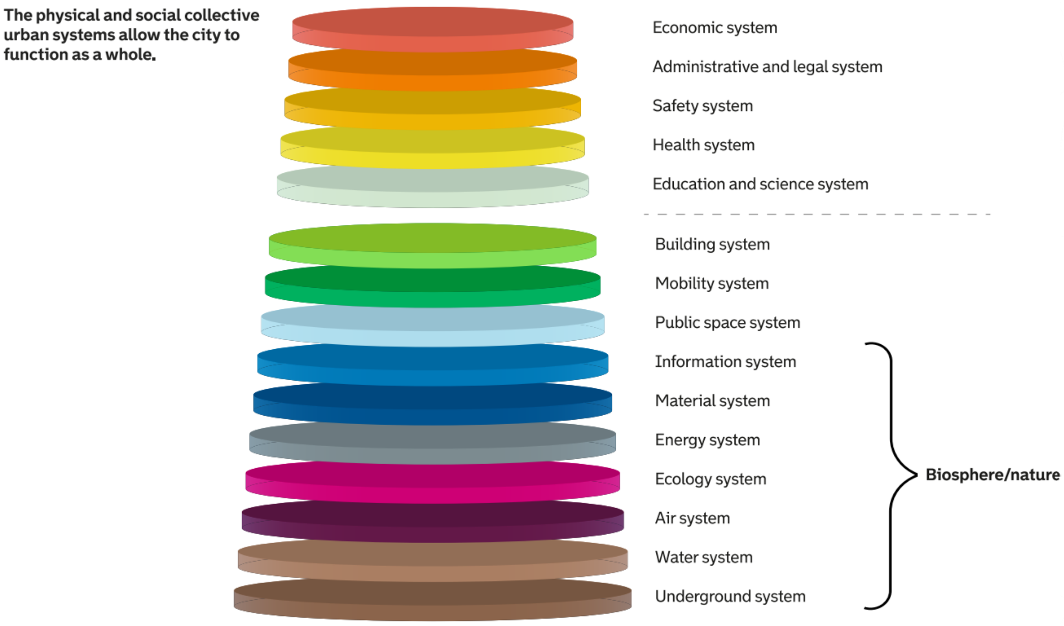

Figure 15 - *From bottom (most important) to top (least important), the aspects of Rotterdam which are necessary to ensure a sustainable and well-functioning Rotterdam by 2027 and into the future.*

Rotterdam has numerous editions of a climate adaptation plan, including Rotterdam Climate Proof 2008, Rotterdam Adaptation Strategy for Climate Change 2013 (C40 Cities), and most recently, the Resilient Rotterdam

Strategy 2022-2027 (Gemeente Rotterdam). The most recent plan, the Resilient Rotterdam Strategy 2022-2027, asserts that Rotterdam has been "making the city greener in streets and neighborhoods, [and] on squares and on roofs" with the goal of protecting residents and making sure that vulnerable homes are kept dry (Gemeente Rotterdam). This demonstrates that Rotterdam is actively making a point to greenify their city. Rotterdam has also identified that the two most important "crucial" systems to the city that need attention in recent years: the 1) Underground system, and 2) Water system, as seen in Figure 15 below [Figure 1.6b (p27) in the Resilient Rotterdam Strategy]. This further boosts the importance of this research.

4.3 Urban digitalization & Data-driven decision making

Understanding dynamic blue-green infrastructure (BGI) within the context of an urban space is central to this research. Smart cities leverage technology to improve city functions and livability, and by integrating real-time control (RTC), BGI can optimize stormwater management and mitigate flooding from a physical and digital side. RTC acts as an element of urban digitalization by using technological inputs and protocols to operate stormwater infrastructure in response to changing conditions. Additionally, RTC enables data-driven decision-making, dynamically adjusting stormwater management based on forecasted rainfall, system capacity, and overflow risks. These inputs—rainfall predictions and storage availability—are critical for RTC to function effectively, making them key pieces of information in urban water management.

However, the implementation of RTC must be accompanied by fail-safes to ensure equitable flood prevention. If the RTC system were to fail, safeguards must be in place to prevent uncontrolled overflow from disproportionately affecting certain areas. In the case of this research, the fail-safes are the swale overflow pipes to prevent collected swale runoff from overflowing back onto the street during intense rainfall events. For RTC to function effectively in Spangen, the research therefore proposes dedicated outflow pathways separate from the CSS. Without a designated conveyance system to transport swale overflow directly to the Delfshavense Schie, RTC optimization remains limited by existing sewer constraints.

4.4 RTC Performance extents

The performance of an RTC system exhibits diminishing returns. van der Werf (2023) outlines this phenomenon in their Figure 2.1 (Fig. 16 in this paper), the idea being that implementing an RTC system already drastically improves baseline performance of the [water management] system. It then becomes much more difficult to reach theoretical RTC performance and maximum potential performance, as the more resources put in to try to reach those states leads to diminishing returns. The performance curve reaches a mathematical limit.

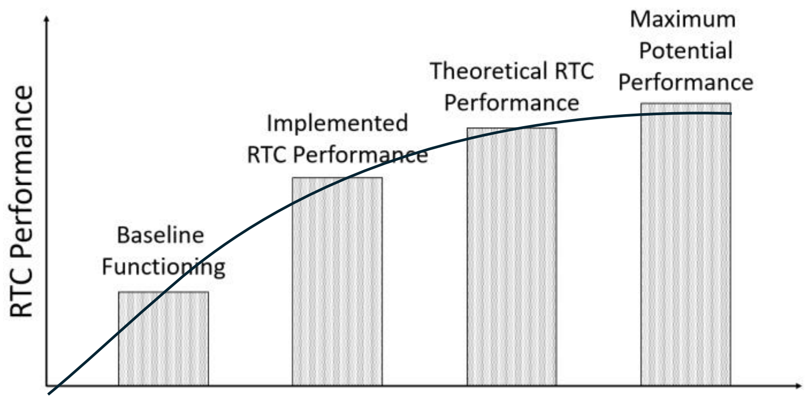

Figure 16 - *The phenomenon of diminishing returns of an RTC system.*

In this research, the first "step" will be proposed, which will show the performance of a proposed (implemented) RTC system. Already, in theory, this proposed RTC system will have a drastic improvement on the local water management scape, with the RTC objectives as discussed in section 2.

4.5 Nature-based, multifunctional solutions

This district lacks informal green spaces particularly along its streets, limiting nature-based opportunities for passive cooling, biodiversity support, and natural stormwater management. Implementing BGI in the area would enhance urban aesthetics while activating evapotranspiration, increasing shade cover, and providing critical habitat space. More importantly, BGI naturally facilitates stormwater management by coupling surface water to the subsurface via infiltration, enhancing infiltration and reducing surface runoff, reducing pressure on the CSS. Integrating RTC with BGI further strengthens these benefits by enabling real-time monitoring and adaptive water management. RTC regulates swale storage capacity in real time, preventing waterlogging, and ensuring sustained infiltration rates. As nature-based solutions, BGI elements provide cost-effective, environmentally sustainable alternatives to gray infrastructure upgrades, such as pipe resizing for stormwater conveyance. By coupling RTC with BGI, urban stormwater management can shift toward more resilient and adaptive strategies, improving both climate resilience and urban livability.

5 – Methodology

5.1 Interview

Discussed in section 2, a semi-structured interview was conducted with a local resident before the modeling process to understand the use of local spaces, historical flooding awareness, and public attitudes toward bioswale implementation in Spangen. The discussion focused on past experiences with flooding and stormwater management, including whether the neighborhood has historically struggled with excessive runoff, combined sewer overflows, or street water (“water op straat”). The interview also explored how existing green spaces function in daily life, whether they are used primarily for recreation, aesthetics, or informal drainage, and how their transformation into bioswales might impact residents. The flexible format allowed for a structured, yet open discussion, ensuring a focused discussion while leaving room for elaboration on personal perspectives.

This qualitative input complements the hydrological and spatial modeling by providing local context to the analysis, offering direct insight into how residents perceive stormwater management interventions. While modeling captures the technical performance of bioswales, the interview highlights additional considerations such as community reception, urban aesthetics, and usability, all of which influence the feasibility and long-term success of green infrastructure. The interview also reveals whether there is a general awareness of water management challenges in Spangen and if residents perceive a need for intervention. While not a statistically representative survey, this firsthand account offers valuable experiential knowledge that strengthens the study’s real-world applicability, ensuring that technical solutions align with social and urban dynamics.

5.2 Scenario building

Three implementation scenarios are proposed with respect to BGI and RTC integration.

1st scenario (Baseline) – Model the current state of the stormwater management system in Spangen, focusing on the capacity of the local CSS inflows to handle stormwater, and the corresponding CSO events in event count and overall volume.

2nd scenario (Bioswales with passive overflow release) –
Assess CSO volume, CSO event count, and uncontrolled overflow from bioswales by integrating swales of uniform 0.3m depth with passive overflow structures. Three progressively more permeable configurations, each increasing neighborhood permeable area, are tested at runoff interception fractions of 25%, 50%, 75%, and 100%, which divert the stated percentage to the swales.

3rd scenario (Bioswales with RTC-governed, active overflow release) –
Assess the impact of RTC-controlled valves at the base of each swale, which preemptively drain forecasted runoff within a 12-hour lead time, to smooth overflow volume over time, reducing flood risk by distributing the immediate overflow seen in Scenario 2 over the lead time, thereby also reducing CSO volume and frequency.

These scenarios enable the separate analysis of the effects of BGI and RTC, both individually and in combination, to better understand their potential for improving stormwater management and reducing flooding in this study location. Scenario 1 provides a baseline for understanding the current system’s performance. Scenario 2 isolates the impact of BGI, using bioswales with passive overflow release to assess how varying permeability and increasing neighborhood permeable area affects CSO volumes and uncontrolled overflow volumes. Scenario 3 introduces RTC to actively manage runoff by preemptively draining forecasted volumes from the swales, distributing variable and intense overflow over time, providing a smoothing effect that reduces local flood risk. Three different swale configurations will likewise be run using these scenarios, where the baseline will always be used to compare Scenarios 2 and 3. The interception fractions, of 25%, 50%, 75%, 100%, simply represent how much runoff is diverted to the swales, with the rest as runoff to the CSS. These percentages are achieved by closing the corresponding percentage of total street-level drains. For example, Spangen can achieve the 25% fraction by closing 25% of street-level drains, especially around the swales, while keeping 75% still open.

5.3 Introduction to proposed bioswale designs and RTC

5.3.1 Physical bioswale design

A common depth and common profile are assigned to each bioswale to simplify the modeling process. The cross-sectional profile is represented by the following drawing in figure 17.

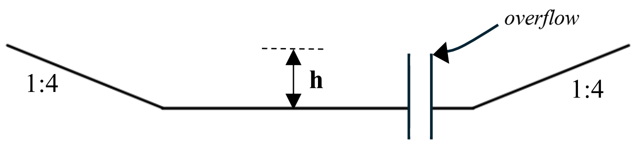

Figure 17 - *Proposed swale cross section.*

The derivation of the formula for swale volume is located in Appendix III. All calculated values, including areas of the swales (designed and set in ArcGIS), depth calculations, and neighborhood area swales are located in the complementary Excel and ArcGIS files sent upon submission of this paper, also available by contacting the author. This Excel workbook is likewise one of the required inputs for the hydrological model, discussed shortly. Values for the proposed swale design, including the recommended infiltration rate and 1:4 side slope are referenced from the Dutch swale design guidelines set by Stichting RIONED, a leading Dutch urban water management and sewage organization.

For modeling purposes, all bioswales are assigned a common depth of 0.3 meters and are collectively modeled as a single, large swale by adding their [dry] volumes together. This simplification follows the principles of linear reservoir modeling, where distributed storage elements can be aggregated into a unified system with a shared capacity. By treating all swales as a single reservoir, the model efficiently captures the overall storage dynamics, infiltration behavior, and overflow occurrences without requiring individual tracking of each swale. This approach allows for a streamlined simulation of runoff interception, ensuring that inflow, infiltration, and overflow processes are consistently applied across all bioswales. When pre-drainage via RTC is triggered, the equivalent overflow volume is removed proportionally from the collective storage, rather than from individual swales, maintaining computational efficiency while preserving hydrological accuracy.

5.3.2 Proposed use of RTC

Each bioswale is equipped with an overflow structure as seen in Figure 17. The overflow system consists of a vertical overflow pipe positioned at the swale's designed depth, allowing excess water to drain once full. These form a proposed dedicated network of pipes draining directly from the swales to the receiving water body, entirely bypassing the CSS. At the base of this pipe, a movable valve is proposed, which serves two primary functions.

Under normal conditions with no forecasted overflow, the valve as pictured in Figure 18 remains closed, allowing water to accumulate in the swale and infiltrate naturally. However, in the RTC scenario, this valve can be actively controlled and opened to preemptively drain the projected overflow volume over a lead time. This increases available storage before an expected storm event, and better distributes overflow over a longer time period, significantly reducing local flood risk caused by sharp outflow peaks with high volume released over a very short time. If the swale lacks sufficient stored water at the time of pre-drainage, no pre-outflow occurs, and any overflow will still be discharged via the overflow pipe. Thus, while RTC can optimize swale performance under forecasted conditions, passive "fail-safe" overflow structures must remain in place. Figure 18 dramatizes the overflow pipes; it is one overflow pipe explicitly showing that overflow can travel through the overflow pipe if the valve is opened.

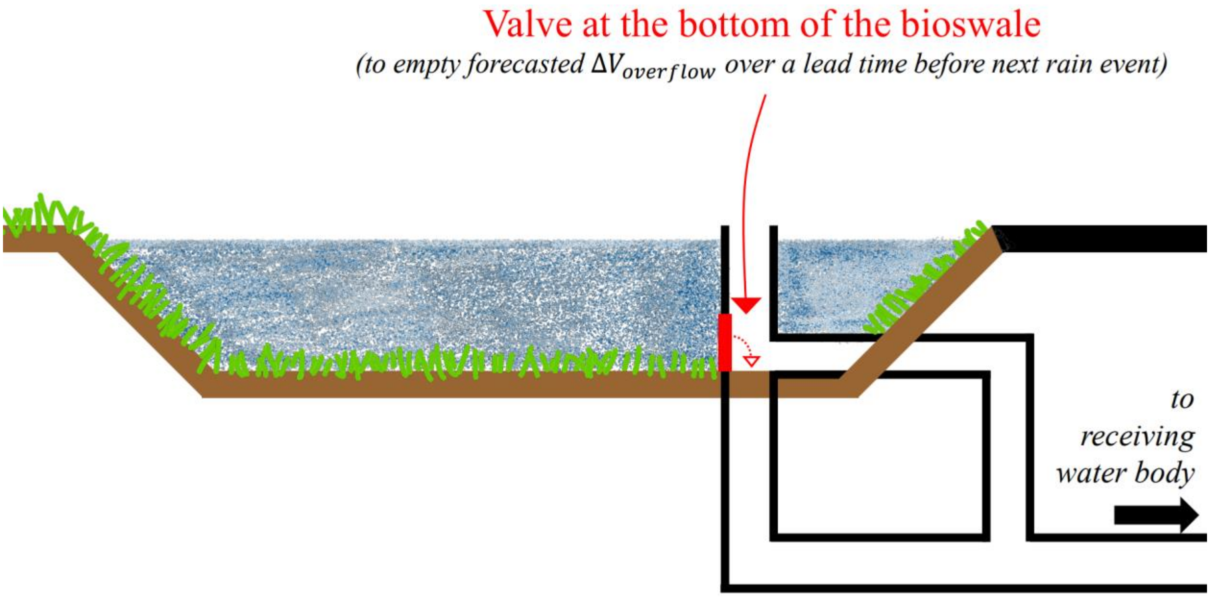

Figure 18 - Proposed RTC valves at bottom of swales (red), which can open to release a forecasted overflow volume over a lead time before the next overflow event.

5.4 Swale configurations

In developing bioswales for the neighborhood, three unique configurations are proposed to address local hydrological challenges, improve urban aesthetics, and provide a functional proof-of-concept for future large-scale bioswale implementation, seen in Configuration #3. Each configuration was tailored to integrate within the neighborhood's existing spatial layout, focusing on small, quieter streets, and street corners to maximize both functionality, green space accessibility, and visual appeal. The following sections detail the first configuration, Configuration #1 (Config_1), which acts as a steppingstone for the municipality to trial bioswale implementation.

5.4.1 Configuration 1: Initial Pilot Implementation

The first configuration represents a relatively low commitment, phased approach designed to test the efficacy of bioswales in select locations throughout Spangen. Swales are strategically placed in select streets, corners, and open spaces to balance hydrological function with public acceptance. A total of 56 swales were proposed for this configuration, and their locations were carefully selected based on the following considerations:

1. **Small Neighborhood Roads and Intro to Public Spaces**
   Swales are positioned primarily along neighborhood roads, where lower traffic and pedestrian volumes allow for a more controlled and less disruptive testing environment compared to a main thoroughfare. These quieter residential streets provide an optimal setting to evaluate bioswale performance without significant interference from vehicular activity. Key open spaces, such as the large paved plein at the intersection of Bilderdijkstraat and Spaansebocht, are reimagined with bioswales to enhance both functionality and aesthetic value. The bioswales in this large pleins specifically is designed with curvature and aesthetic appeal to better integrate into the local residential environment, adding architectural flair to the proposed bioswales.

2. **Intro to Street Corners**
   Recognizing the underutilization of street corners is a capstone similarity between all configurations, and this configuration begins by integrating these smaller bioswales at several intersections, transforming these spaces into functional, visually appealing features that pack a hydrological punch, serving as key locations improving stormwater capture. These corner swales further aim to enhance the pedestrian experience and contribute to urban greening.

<u>*Key Locations*</u>

1. **Spangesekade to Mathenesserbrug (Keystone Location)**
   One of the most significant elements of Configuration 1 are the proposed, continuous bioswales along the entire length of Spangesekade from Spaansebocht to Mathenesserbrug. This location was chosen for its proximity to the Delfshavense Schie canal, allowing overflow structures to connect directly to the waterway in a close proximity via a separated system. The straightforward construction feasibility of this separated system makes these bioswales on the Spangesekade a cornerstone of the pilot.

2. **Van Lennepstraat (Test Street)**
   Van Lennepstraat is selected as another primary test location for this configuration, with swales placed along its length and smaller corner bioswales proposed at intersections. This street experiences light neighborhood traffic, providing an opportunity to evaluate swales' effectiveness under different hydrological and urban scenarios. Key sections include:

   - A bioswale from the intersection of Spartastraat and Van Lennepstraat to Bilderdijkstraat, testing its functionality along a busier neighborhood street.
   - A continuation from Bellamystraat to Van Harenstraat, focusing on street corner swales to assess performance and public reception in quieter residential areas.

3. **P.C. Hooftplein & Da Costastraat**
   The intersection near P.C. Hooftplein and Da Costastraat was chosen for its high foot traffic, particularly due to its proximity to tram stops and Sparta Stadion. Here, street corner bioswales were implemented to enhance pedestrian spaces while capturing runoff. This site serves as a critical testing ground for how bioswales perform in areas with significant pedestrian activity.

4. **Multatulistraat**
   Bioswales along Multatulistraat and its intersections, including Nicolaas Beetsstraat and Vosmaerstraat, provide additional testing areas. These swales further diversify the configuration, offering insights into how bioswales can be adapted for different street geometries and urban contexts.

Configuration 1 lays the groundwork for future phases, emphasizing the adaptability and multifunctionality of bioswales in transforming urban spaces. This configuration is designed to serve as proof-of-concept for the municipality of Rotterdam. By incorporating swales into varied urban contexts—from moderately busy streets to quiet residential areas and underutilized public spaces, this configuration enables the testing of hydrological, environmental, and social outcomes. Its low commitment nature minimizes risks while fostering public and municipal acceptance of BGI over time. By focusing on key areas like Spangesekade and Van Lennepstraat, the pilot ensures measurable results that can inform subsequent configurations and broader adoption.

5.4.2 Configuration 2: Expanded Urban Integration & Strategic Green Retrofitting

Configuration 2 (Config_2) builds upon the initial pilot implementation phase of Configuration 1 by introducing an additional 75 local bioswales (bringing the total to 131), significantly increasing permeable surface area and improving stormwater management capabilities. This phase of bioswale integration focuses on further optimizing underutilized green spaces and strategically expanding infiltration zones across the entirety of Spangen, a step higher from the localized test phase of Config_1. While of course, also considering social and practical implications for public use. The most notable improvements in Configuration 2 include:

- **Enhanced intersection bioswales:** More corner bioswales have been incorporated at key intersections throughout the neighborhood, increasing localized infiltration and reducing surface runoff at crucial runoff convergence points.

- **Park transformation @Piet Paaltjensplein**: The existing park is reimagined with a depressed bioswale system by eliminating curbs and lowering the green space around the existing trees, allowing it to naturally collect and filter runoff while maintaining its green character.

- **Potential bioswale integration at Staringplein**: The open green space at Staringplein presents an opportunity to be lowered into a shallow depression for improved stormwater retention, with added vegetation to enhance ecological function. However, due to its current use as a play area for children and relief area for dogs, further municipal evaluation and community engagement are necessary before full implementation. This is why Staringplein is included in Configuration 2, as its feasibility requires additional considerations.

- **Full-length street bioswales along Vosmaerstraat and Mathenesserstraat:** To further optimize runoff reduction, continuous bioswales are introduced along Vosmaerstraat and Mathenesserstraat, creating a larger network of stormwater-capturing infrastructure while enhancing the urban streetscape with additional greenery.

This phase represents a significant leap toward flood resilience, balancing hydrological performance with community usability. The thoughtful placement of bioswales in key public spaces ensures functional stormwater management while respecting existing social and recreational dynamics. Configuration 2 serves as a critical intermediary stage, setting the groundwork for further expansion and refinement in Configuration 3.

5.4.3 Configuration 3: Solidifying BGI-Based Climate Resilience

Building upon the incremental adaptations introduced in Configurations 1 and 2, Configuration 3 represents the most comprehensive and enduring phase of climate adaptation in Spangen. This final stage fully integrates blue-green infrastructure (BGI) within the urban fabric, ensuring the long-term sustainability and resilience of the neighborhood against pluvial flooding. The key advancement in this configuration is the solidification of BGI through the strategic retrofitting of enclosed residential gardens into bioswales, capitalizing on municipal land ownership and existing spatial opportunities to further enhance stormwater retention.

This climate-adaptive transformation is not just a technical improvement, it is a necessary step toward future-proofing Spangen, reinforcing its ability to withstand the increasing impacts of climate change. The integration of bioswales into these enclosed green spaces is both feasible and strategically aligned with Rotterdam's broader sustainability goals, provided that appropriate legal considerations and municipal coordination are undertaken.

Plan: Key Enhancements & Considerations

1. **Retrofitting Enclosed Residential Gardens for Stormwater Management**
   The most defining feature of Configuration 3 is the strategic enhancement of BGI through the integration of enclosed communal gardens into the bioswale network. These areas, owned by Gemeente Rotterdam, are underutilized but strategically located to serve as critical stormwater retention zones. By incorporating bioswales within these spaces, stormwater can be effectively intercepted from a catchment area, and stored and infiltrated before reaching the CSS, significantly improving flood resilience while maintaining the social and ecological value of these gardens. From a legal and zoning perspective, this intervention is both feasible and well-supported under existing municipal regulations:

   - *Land Use & Ownership Considerations*
     The Programma Noordzee 2022-2027 (Rijksoverheid, Structuurvisie, vastgesteld 2022-03-18 [Ruimtelijkeplanning.nl]) confirms that at a communal garden such as at Justus van Effenstraat fall under Artikel 18 Tuin - 2, designating them as communal gardens with permissible uses including green space, pathways, and terraces. As bioswale implementation does not constitute a building project but rather a landscape modification, it aligns with the existing purpose of these areas. Furthermore, the Water Board (Waterschap) can be involved to ensure compliance with hydrological regulations and facilitate necessary modifications, such as mild depressions in the terrain.

   - *Archaeological Considerations*
     Every enclosed garden identified for bioswale integration is also subject to Artikel 35 Waarde - Archeologie - 3, which protects archaeological values inherent to the land. This means that before any intervention, an archeological assessment report must be submitted to the municipality, confirming that no significant archeological disturbances will occur. However, as bioswale construction involves shallow surface modifications rather than deep excavation, it is unlikely to conflict with these regulations, provided that necessary permits are secured.

   - *Cultural & Historical Considerations – Justus van Effen Complex*
     The gardens within the Justus van Effen Complex are designated under Artikel 37 Waarde - Cultuurhistorie - 1, which emphasizes the preservation of the historical green structure of the neighborhood. Any modifications require municipal approval, particularly to ensure that interventions do not compromise historical or cultural integrity. However, as bioswales enhance the natural function of these gardens, maintaining them as green spaces while improving stormwater absorption, the proposal aligns with the intent of preserving the green structure rather than altering it.

2. **Final Expansion of the Street Bioswale Network**
   Building upon previous implementations, continuous bioswales along Mathenesserstraat and Vosmaerstraat are fully extended, reinforcing these corridors as high-capacity infiltration zones that reduce surface runoff, mitigate heat stress, and enhance local biodiversity.

3. **Stormwater Management at Maximum Efficiency**
   With nearly one-third of Spangen's impermeable surfaces now converted into permeable, water-absorbing infrastructure, this configuration ensures optimal water retention, peak flow reduction, and the complete elimination of CSO events. The strategic placement of bioswales at previously overlooked garden spaces means that stormwater is intercepted at multiple points across the neighborhood, reducing sewer dependency and minimizing flood risk.

4. **Institutional Collaboration & Policy Integration**
   As this phase involves modifications to municipal and historically designated land, successful implementation will require collaboration between Gemeente Rotterdam, the Water Board (Waterschap), archeological experts, and historical preservation committees. Given Rotterdam's proactive stance on climate adaptation and urban water management, this plan aligns with the city's long-term objectives, reinforcing Spangen's role as a resilient, future-proof urban district.

Configuration 3 represents the pinnacle of Spangen's transformation into a climate-resilient urban district. By integrating bioswales within enclosed residential gardens and fully optimizing the neighborhood's permeable surface area, this phase solidifies flood resilience through strategic green retrofitting. The legal and zoning feasibility of these interventions ensures that implementation is both practical and scalable, providing a replicable model for other flood-prone urban areas. With this final adaptation, Spangen transitions from a vulnerable, flood-prone neighborhood to a fully future-proof, climate-resilient urban landscape, reinforcing Rotterdam's leadership in adaptive water management and sustainable urban design.

5.5 Hydrological model

A custom, hydrological model of the project area is developed from scratch in Python to simulate local stormwater runoff, sewer system behavior, and the impact of bioswale installations on CSO outflows and uncontrolled vs. controlled swale outflows. The model follows a structured workflow and is run iteratively for the three bioswale configurations, each tested under four runoff interception levels (25%, 50%, 75%, and 100%).

5.5.1 Modeling introduction – Linear reservoir modeling

Linear reservoir modeling, best described by the US Army Corps of Engineers' HEC-HMS Technical Reference Manual as using multiple reservoirs to model different hydrologic processes of a system, is employed in this research to model the processes of the Spangen neighborhood. In addition to being the foundational concept for many water modeling softwares including HEC-HMS and WaterCAD, this type of modeling has been extensively used in water management studies to achieve maximum similarity between nature and model by numerically representing the current situation as a model to estimate responses to physical processes and changes in the physical environment (Span & Kuhn, 2003; Buytaert et al., 2004; Lázaro et al., 2015).

Depicted in Figure 19, four reservoirs ("buckets") have been drafted to represent and model the hydrologic processes of the Spangen neighborhood, all with common connections to each other. Reservoirs #2 (sewer system) and #3 are intensively analyzed and modeled in this study, using numerous inputs to model the behavior of both of them. CSO volumes and frequencies are analyzed from Reservoir #2, and outflow volumes and frequencies are analyzed from Reservoir #3, both having impacts on Reservoir #4. The hydrological model developed later in the study uses given and researched inputs for the sewer reservoir, and many inputs were designed to represent the swale reservoir. Regarding Reservoirs #1 (unsaturated zone) and #4, only "flow volumes into" these buckets were modeled, and the rest of the bucket was not, as they were not explicitly modeled as they were not the focus of this study. More on this at the end of this paper. However, as discussed, the flow volumes into these reservoirs was modeled, therefore their interaction in the system is not completely discounted. Given more time, these reservoirs can be modeled to an extremely fine degree, considering different phenomena such as local soil infiltration capacity, favorable flow paths, and plant uptake for Reservoir #1, or local pump activity from the surface water to the Maas River for Reservoir #4.

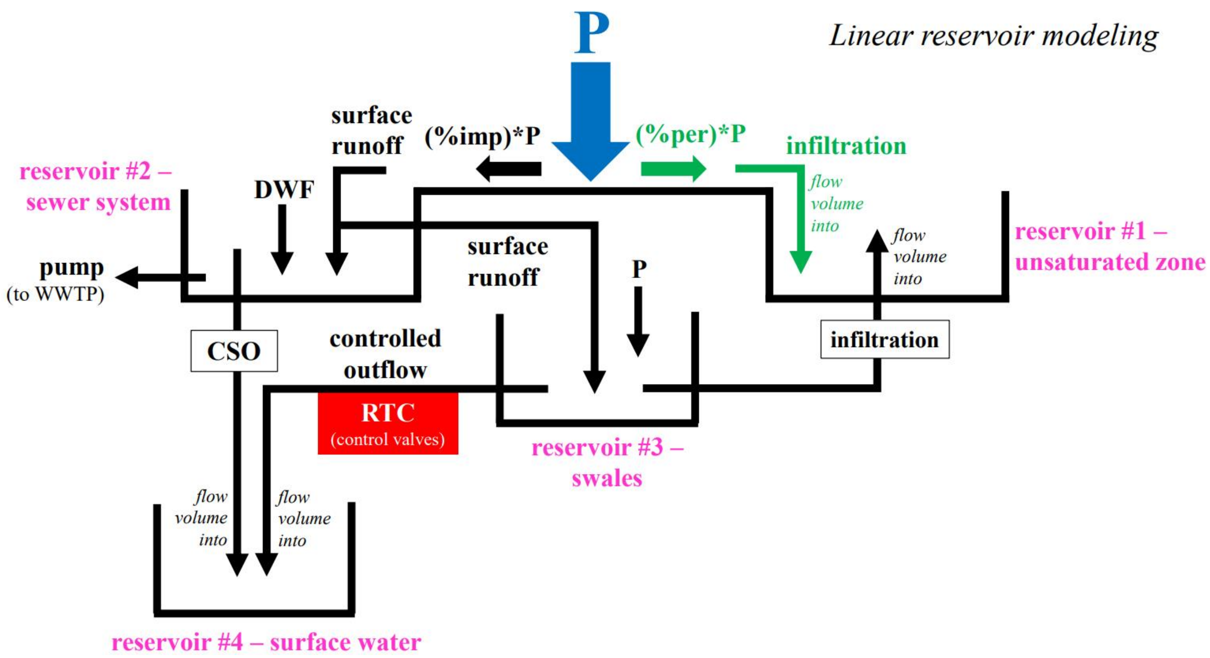

Figure 19 *- A conceptual visualization of the modeling framework employed by this research, with the RTC link in a red flag between the swale and surface water reservoirs, symbolizing the control valves at the base of the swale outflow drainage pipe, connected to a separated system conveying swale overflow directly to the local receiving water body.*

The main driver to the Spangen system is precipitation (P), which is parsed at the onset and can be followed in the figure above. Surface runoff travels to the left towards the sewer system reservoir, but can also travel to the third reservoir, the proposed swales. This junction represents the interception fractions discussed later, where this junction can be controlled by closing a set number of sewer inlets and instead directing the flow to the swales. Furthermore, P also falls directly on the swales, as this is another element that must be added for higher model accuracy. For the first reservoir, assisted by ArcGIS analysis, all areas of any element in the Spangen neighborhood are known, thus precipitation (P) can be also split into and infiltrated_amount=(%pervious_area)*P. Finally, the RTC is shows as a connection from the swale reservoir to the surface water reservoir in the form of control valves pre-emptying a stored volume from the swales as discussed later via a dedicated swale overflow network, totally bypassing the CSS altogether.

5.5.2 Modeling workflow

Precipitation data spanning nearly 20 years is processed into a Pandas DataFrame, formatted for time-series analysis to ensure compatibility with hydrological modeling. The study area is categorized into pervious and impervious surfaces, with sewer system parameters—including dry weather flow, pumping capacity, and storage volume—factored into the simulation. The baseline scenario models runoff generation by computing surface flow from impervious areas and tracking sewer system performance at 10-minute intervals. If sewer capacity is exceeded, excess flow is registered as a Combined Sewer Overflow (CSO) event. To regulate flow, pumping activity follows a stepwise function based on sewer storage thresholds: at low storage (<1946.6 m^3), the pump operates at full capacity (96.7 m^3/10 min) to clear excess water rapidly; at mid-range storage (1946.6 – 2426.3 m^3), the rate reduces to 63.4 m^3/10 min, balancing efficiency while preventing excessive drawdown; and at high storage (2426.3 - 2500 m^3), the pump runs at 29.2 m^3/10 min, maintaining steady flow without prematurely depleting available storage. These values are derived from the control logic currently implemented in Rotterdam's stormwater infrastructure. The pump curve used in this model is based on the existing operational parameters of the installed system, as provided by Imber, a company specializing in hydrodynamic modeling and urban water management. Imber developed the 0D hydrodynamic model of Rotterdam, which serves as a representative simulation of the city's drainage operations. By incorporating these parameters, the model ensures that the simulated pumping behavior aligns with real-world system performance, maintaining consistency with actual drainage operations in Spangen.

Bioswale implementation is analyzed across three configurations, progressively increasing the number of swales to evaluate their effect on stormwater retention, infiltration, and sewer system load reduction. This layered approach offers insight into the marginal benefits of expanding bioswale networks, helping determine optimal integration strategies within the urban landscape. By modifying the impervious-to-pervious ratio, bioswales function as surface detention features that reduce direct runoff, providing additional stormwater retention capacity. If bioswale storage is exceeded, overflow is directed toward the sewer system or adjacent water bodies, simulating real-world hydrological responses.

Real-time control (RTC) optimization is introduced in the final scenario (Scenario 3), incorporating pre-drainage strategies to empty swales before incoming rainfall events. The model evaluates whether an uncontrolled overflow will occur within the next 12 hours by assessing the collective storage of all swales. If an overflow is detected and there is sufficient water stored, the system gradually drains the equivalent overflow volume from the current swale volume over the 12-hour period using movable valves located near the base of each swale's overflow pipe. These valves regulate outflow, allowing for controlled pre-release to maximize swale capacity before rainfall. However, if insufficient water is available at the time of detection, no pre-drainage can occur, and excess runoff will still be discharged via the overflow structures. This approach optimizes stormwater retention, reducing sharp overflow spikes and distributing discharges more evenly over time. By dynamically adjusting outflow rates based on projected rainfall, RTC enhances bioswale efficiency, mitigates CSO occurrences, and reduces stress on the CSS. 12 hours is chosen as a lead time based on urban drainage response timescales, balancing pre-drainage efficiency with forecasting reliability and infrastructure constraints. Stormwater retention in urban environments typically occurs over several hours, making 12 hours a practical window to optimize swale capacity before peak inflows. Shorter lead times, such as 3-6 hours, may react too late, leading to insufficient storage availability, while longer lead times, such as >24 hours, introduce greater forecasting uncertainty and risk unnecessary drainage. Additionally, the pre-drainage valves operate at a controlled discharge rate, requiring sufficient time to gradually release water without overwhelming the sewer system or adjacent water bodies. By choosing a 12-hour window, the system ensures a balance between effective pre-release, reliable forecasting, and operational feasibility.

Overall, the modular structure of the model allows for flexible parameter adjustments, facilitating scenario testing for alternative stormwater management strategies, as well as simple restructuring to integrate forecasted weather into the model instead of historical forecasts. The model's computational structure is likewise clearly labeled, with well-defined sections ensuring seamless navigation and reproducibility of results.

5.6 Data acquisition

5.6.1 Geodata & Area Information

Details about the current stormwater infrastructure in Spangen are provided at the start of the study, including storage volume of the CSS, dry weather flow (DWF), and pumping capacity:

- Storage volume of local CSS: 2500 m^3 → *equivalent: ~8.4 mm*
- DWF: 108 m^3/h → *equivalent: ~0.1 mm/10 min*
- Pumping capacity: 580 m^3/h (WWF to WWTP, CSO pumping removed) → *equivalent: ~0.3 mm/10min*

Neighborhood boundaries and existing green areas will be mapped and calculated using ArcGIS Pro, utilizing the following hosted datasets from ArcGIS Online:

- Neighborhood Boundaries: *Buurten in Rotterdam* (Esri_NL_Onderwijs)
- General Greenery:
    - *Overige groene elementen* from the hosted feature layer "groen 010 v9_WFL1" (bsr_esri)
    - *Groene_daken_Rotterdam_Totaal* from the hosted feature layer "Inventarisatie Groene Daken Rotterdam" (rvanderwel_rotterdam)
    - *EGTTuinenStats_RotterdamV2* from the hosted feature layer "Tuinen_Rotterdam_GroenIndex" (mboelhouwer_rotterdam)

These datasets will be used to generate spatial layers and calculate areas for neighborhood extent visualization, green spaces, and swale configurations, forming the foundation for scenario development and analysis.

5.6.2 Meteorological data

Precipitation data for this study comes from KNMI's Precipitation - duration, amount and intensity at a 10 minute interval dataset, which provides 10-minute meteorological observations from automatic weather stations across the Netherlands. The data is obtained by using the Python script in Appendix IV. The dataset includes high-resolution measurements of various atmospheric parameters, including precipitation intensity recorded by different sensors. This short-interval dataset offers a clear and focused record of precipitation on a detailed resolution, despite being without the additional meteorological variables found in broader datasets such as KNMI's daily climatology records (Daggegevens KNMI) or KNMI's hourly climatology dataset (Uurgegevens KNMI). While daily, or even hourly datasets like these provide detailed meteorological information, including temperature, wind, and humidity, they lack the granularity needed to analyze short-duration storm events. This makes them unsuitable for studies like this, which are focused on near-instantaneous urban hydrology and sewer system performance, where rainfall variability on a minute-scale directly influences system behavior.

RI_REGENM_10 is the primary precipitation variable used to calculate precipitation values from the dataset. This variable represents the precipitation intensity recorded by the electronic rain gauge, measured in millimeters per hour. The electronic rain gauge operates through direct collection and quantification, physically capturing and measuring rainfall to ensure a high degree of accuracy. In contrast, optical present weather sensors estimate precipitation intensity based on particle detection and scattering, which can introduce inaccuracies due to environmental factors such as fog, mist, or airborne particles unrelated to actual rainfall. The accuracy of precipitation measurements is crucial in hydrological applications, where small deviations can significantly impact runoff modeling, infiltration estimates, and water balance calculations. Given these considerations, the electronic rain gauge provides the most reliable data source for this hydrological analysis. This dataset reports precipitation intensity in mm/hr. Since this study operates on a 10-minute timescale, the RI_REGENM_10 values are divided by six, distributing the recorded hourly intensity evenly across six 10-minute intervals.

Precipitation (P) = (RI_REGENM_10) / 6

This level of temporal detail is particularly valuable for analyzing combined sewer overflow (CSO) events, which can develop within minutes or even seconds in response to sudden rainfall. By utilizing this dataset, the study ensures that precipitation data aligns with the timescales at which CSO events and urban drainage responses occur.

5.7 Soil analysis

A soil analysis is conducted to gain insight into subsurface conditions, specifically to determine whether infiltration through the soil is feasible for BGI implementation in this district. Since surface water must pass through the soil to reach groundwater, understanding soil stratification at different depths is essential for understanding whether swales can effectively connect surface runoff to the subsurface to a degree. The goal is not to perform a highly detailed geotechnical assessment but rather to confirm that infiltration is possible to some degree and that the subsurface is not entirely impermeable.

Subsurface data for the Netherlands is openly available through DINOloket, which provides Dutch subsurface data, such as geological drilling records or geotechnical testing data. For this study, Geologisch Booronderzoek (GDN) data has been selected and filtered to obtain drilled soil profiles at 14 locations within and around the Spangen neighborhood. These profiles provide a general visualization of soil stratification, indicating whether permeable layers exist that could facilitate infiltration. The analysis focuses on mapping and visualizing these soil profiles rather than conducting an in-depth geotechnical evaluation. The resulting assessment simply demonstrates that some infiltration capacity exists in the subsurface, supporting the viability of BGI in this area to a degree.

6 – Results

6.1 Project Area and Soil Findings

This section provides an overview of Spangen's spatial and subsurface characteristics, laying the groundwork for subsequent bioswale implementation and modeling. An ArcGIS-based analysis highlights the neighborhood's green spaces and basic elevation features, and data from 14 boreholes reveals the local soil stratification, shedding light on infiltration potential and any subsurface constraints. Together, these insights introduce how bioswales can be most effectively integrated into Spangen's urban environment.

6.1.1 Spatial Overview

As discussed in the introduction of the paper, Spangen (1) suffers from a lack of public green spaces, especially on local streets, and (2) sits on a low relative elevation. Regarding green space distribution, as can be seen by Figure 20, an aerial image of an index from 0 (no plant cover) – 200 (best plant cover), many of the streets in Spangen have very low/lack of green cover, resulting in a low index score and a darker red color for the street. This dataset, from Gemeente Rotterdam's Data Platform, encompasses "an analysis that calculates the % of green areas, # and size of trees, and the presence of adjacent gardens" from an aerial perspective. Even though the dataset is not representative of permeable areas on ground-level and could be influenced by green cover "covering" the street, it is still a depiction of the current state of green space distribution in the neighborhood. As can be seen by maps and results later, in section 6.3, the baseline "current" situation results in 50.2% of the neighborhood area as permeable, and 49.8% impermeable. This is deceivingly high, as many of the green spaces in the neighborhood are private, with the majority of public areas being impervious, or in the case of the map below, a darker red color.

Figure 20 - *An aerial depiction of the vegetation cover of Spangen, quantified by overhead coverage of green, with a range of 0 (no plant coverage) to 200 (best plant coverage).*

Further examining the project area in isolation, Figure 21 (below) provides a representation of the local elevation profile, highlighting the flat and low-lying nature of the area. The map, created in ArcGIS using elevation raster data sourced from the [AHN4 dataset](#), visually depicts the elevation range of the project area, which falls below sea level. This characteristic is a critical factor in the area's flood vulnerability, as the lack of significant elevation gradient prevents water from naturally draining or evacuating the area once it is flooded. Furthermore, as previously discussed, the Delfshavense Schie runs directly along the project area, and there is minimal natural elevation difference between its water level and the Spangen elevation, leading to the control of its water level to be essential. If bioswales are to be proposed built with overflows draining directly to this catchment, as this paper proposes, it becomes critical to model flows into this receiving water body to understand the effects of swale overflows and CSO interactions on this water body. This hydrological vulnerability highlights the necessity for robust flood prevention strategies within the Spangen district; in the context of this paper, proposed bioswales. Improving water management infrastructure therefore is vital for bolstering local climate resilience and minimizing the adverse impacts of high impervious area in the neighborhood.

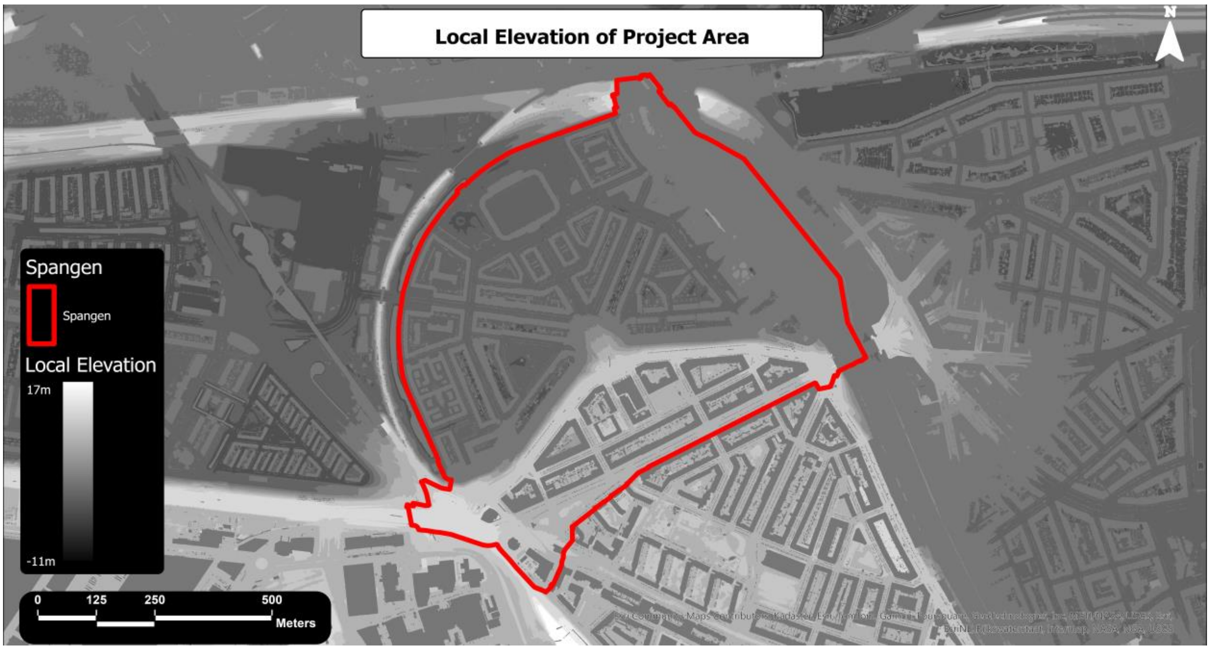

***Figure 21** - Local elevation of the project area in Spangen, sourced from [AHN4's elevation raster data](#), revealing a relatively flat and low-lying topography. One portion of the project area is higher than the rest, however, this portion was not necessarily the focus of this study. The lack of an elevation gradient further limits natural water evacuation, making infrastructure including BGI and RTC even more necessary.*

6.1.2 Soil Profiles

The borehole data in Spangen (Figure 22) is primarily concentrated around: the westernmost periphery canal (boreholes 4, 7, 9, 10), the area surrounding Sparta Stadion (boreholes 1, 2, 3, 5, 6, 8), and somewhat in the

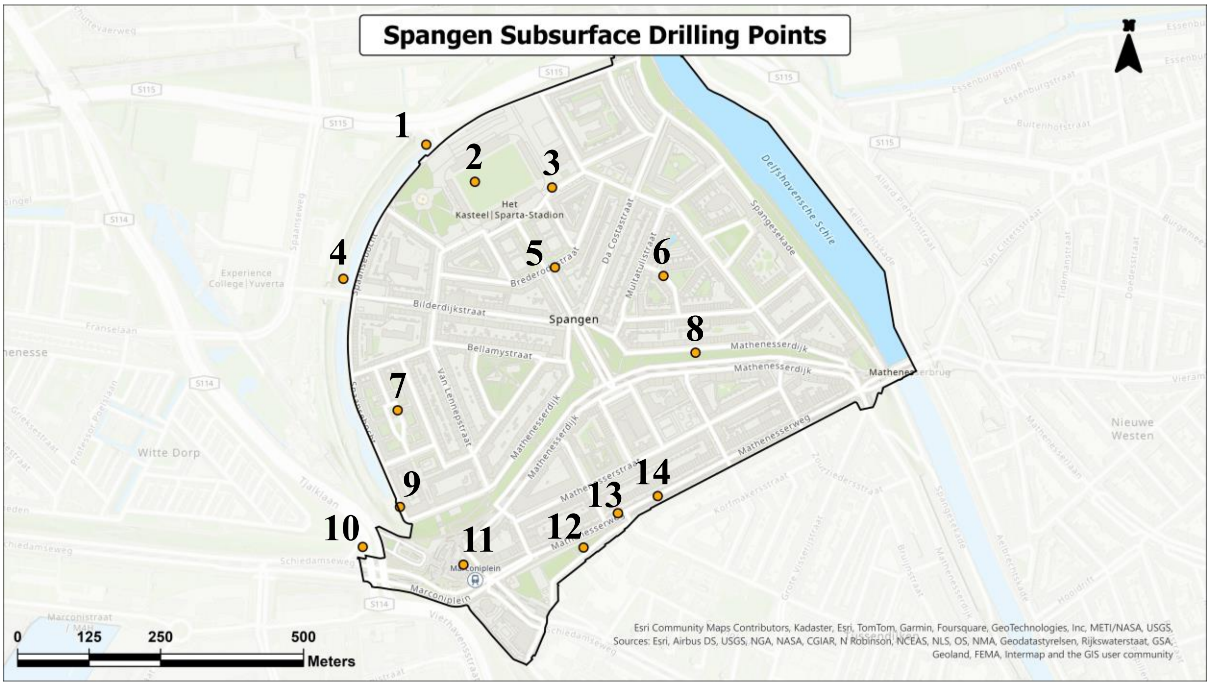

***Figure 22** - Geological drilling research points in and immediately around Spangen, seen as orange dots. These points yield soil lithology data. They have been numbered for standard reference.*

Southern part of the neighborhood (boreholes 11-14). However, there are noticeable gaps in coverage, particularly in the southwestern middle section of the neighborhood around the green triangle (Bellamypark), near the Delfshavense Schie and Spangesekade, and in the Southeasternmost part of the map. These areas lack direct subsurface data, which could introduce some uncertainty when extrapolating lithological characteristics across the entire neighborhood. Future research should consider expanding borehole coverage in these underrepresented areas, as a denser dataset would allow for a more precise assessment of local soil permeability variations.

Despite these gaps, the 14 borehole locations provide a foundational understanding of local subsurface conditions, offering some insight into soil stratification and infiltration potential. While not exhaustive, this dataset helps establish a preliminary lithological profile (Fig. 21) that supports decision-making for bioswale implementation. The lithological data reveals that in more land-surrounded borehole locations, further from the nearby canals, draining sand layers of varying thicknesses are present within the upper five meters of the subsurface. This suggests that at least some areas in Spangen have sufficient infiltration capacity to support bioswale implementation. Given that the proposed bioswales have a designed depth of 0.3 meters, even with supporting backfill layers of the bioswales, they are positioned within the range of these sand layers, allowing for potential infiltration. This provided sufficient justification to proceed with modeling in this study, under the assumption that bioswales could function effectively in parts of the neighborhood. However, the limited borehole coverage does not allow for a definitive neighborhood-scale determination of infiltration potential. Additional borehole data, particularly in the underrepresented areas as discussed, is recommended and would be necessary for a more comprehensive hydrogeological assessment.

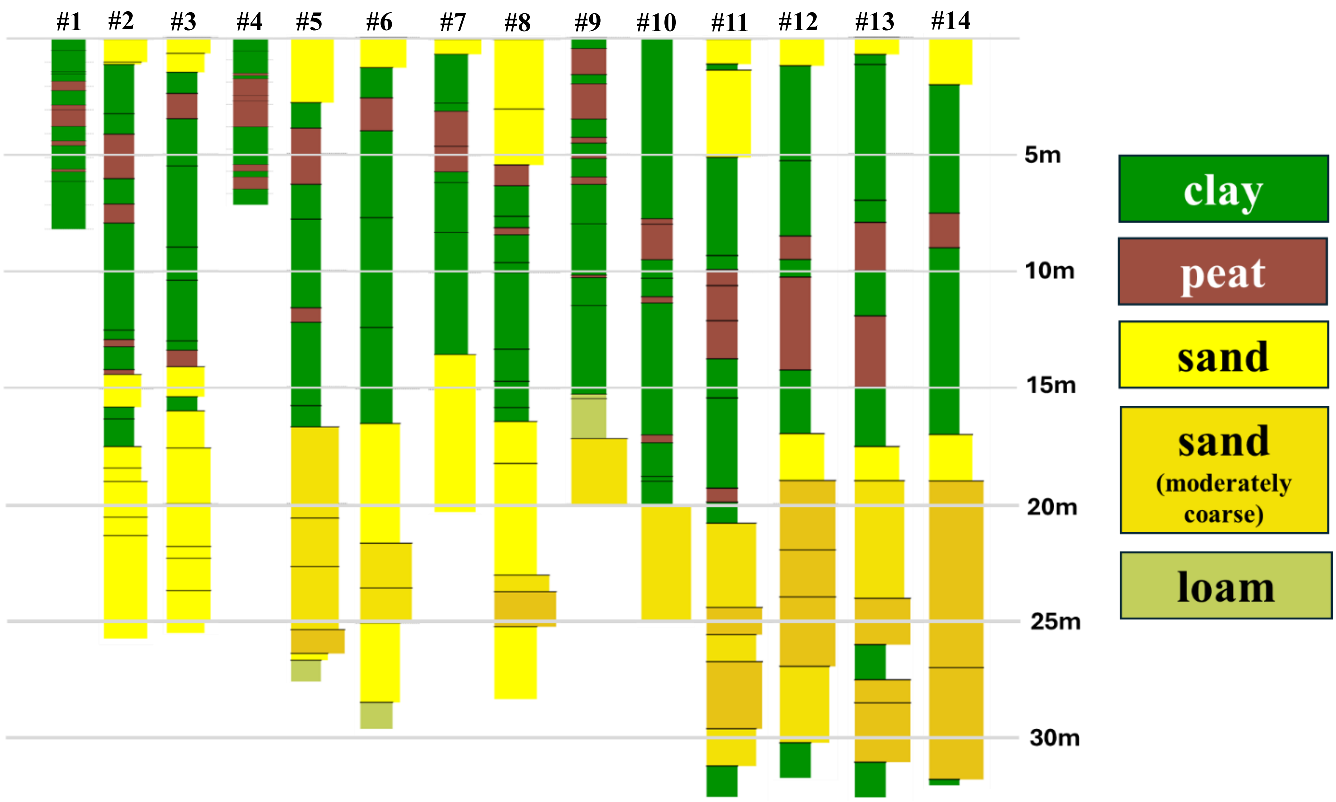

Figure 23 - *Lithological profile of Spangen derived from the 14 boreholes, with sandy topsoil in land-based areas, indicating subsurface infiltration potential.*

Another distinct result from the lithological profiles is the presence of a thick, continuous layer of clay and peat across all boreholes, forming a largely impermeable aquitard that restricts deeper percolation. This suggests that bioswales in Spangen would primarily function as surface retention and infiltration features rather than direct conduits for groundwater recharge, a limitation discussed at the end of the report. However, beneath this layer, extensive sand deposits starting at around 15m below the surface indicate a confined aquifer with high infiltration potential. While this study focused on surface-level stormwater management, future research is recommended to explore methods to activate these deeper sand layers by identifying pathways for water to percolate from the bioswales downwards, beyond the clay and peat barrier. Further investigation into this potential would help optimize local, long-term hydrological performance and render Spangen even more climate resilient.

6.2 Meteorological Data

This section presents the precipitation characteristics observed in Spangen over the study period of around 20 years, based on high-resolution meteorological data from KNMI. The analysis includes both a time-series representation of rainfall and a frequency distribution of rainfall intensities over 10-minute intervals.

Results: Meteo data

Study Period	Nov. 01, 2004 00:00 - 01 Oct. 2024 00:00
Total Precipitation (mm)	18,593.7

Table 1 - *Precipitation data over the study period.*

A total of 18,593.7 mm of precipitation was recorded during the study period as seen in Table 1, over 3,700 individual rain events, defined as exceeding 2.5 mm (0.1 inches) rainfall in a single interval. These precipitation characteristics provide the basis for stormwater modeling, allowing for the evaluation of bioswale performance under varying rainfall conditions.

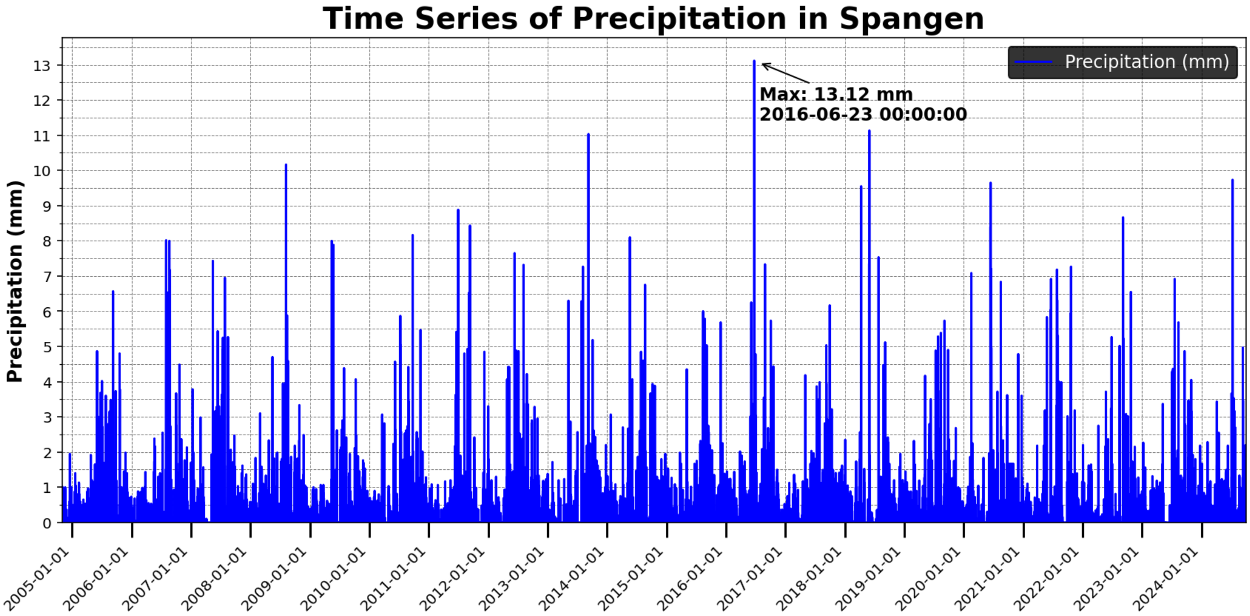

Figure 24 - *Time-series of precipitation in Spangen over the study period, with a total recorded precipitation of 18,593.72 mm. The highest single event was 13.12 mm on June 23, 2016.*

Figure 24 presents the time-series of precipitation in Spangen across the study period, providing a fine-scale representation of rainfall variability and storm events at a 10-minute resolution. The dataset reveals distinct seasonal and interannual fluctuations, with frequent low-to-moderate intensity events interspersed by high-intensity spikes. The most extreme recorded rainfall event occurred on June 23, 2016, with a peak 10-minute accumulation of 13.1 mm. These high-intensity spikes are particularly significant for urban drainage management, as the combined sewer system (CSS) and combined sewer overflows (CSOs) respond in near real-time to sudden stormwater surges, often within minutes or even seconds. The ability of the system to handle such abrupt increases in inflow is a critical factor in flood prevention and CSO mitigation. However, while extreme storm events represent the most visible stressors on the drainage system, the dataset also shows that sustained moderate rainfall plays a key role in influencing CSO occurrences. Frequent, smaller storm events contribute to cumulative runoff, gradually saturating the drainage network and increasing the likelihood of overflow events even in the absence of extreme precipitation. The presence of extended dry periods further underscores the variability of the local climate, highlighting the need for adaptive stormwater management solutions that account for both extreme peaks and prolonged sequences of moderate rainfall. To refine the analysis and focus on hydrologically relevant events, minor precipitation occurrences—such as drizzles and mist—were filtered out, ensuring that the study captures only meaningful storm events that contribute to surface runoff and system loading. By eliminating this noise, the dataset provides a clearer picture of precipitation-driven stormwater challenges in Spangen, reinforcing the necessity of BGI interventions that can accommodate both high-intensity and cumulative rainfall dynamics.

Figure 25 illustrates the frequency distribution of rainfall intensities per 10-minute interval across the study period, showing a steep, logarithmic decline in occurrence as event rainfall intensity increases. The histogram reveals that low-intensity precipitation events (>0.5 mm/10 minutes) dominate, with 1,038,801 instances recorded. Precipitation events exceeding 5.5 mm/10 minutes are much less frequent, occurring only 65 times, and those exceeding 10 mm/10 minutes are rare, with just 5 occurrences. This distribution emphasizes that while extreme rainfall events are infrequent and appear small in frequency, they still present a significant concern for stormwater management, as they have the potential to overwhelm the CSS and trigger CSOs.

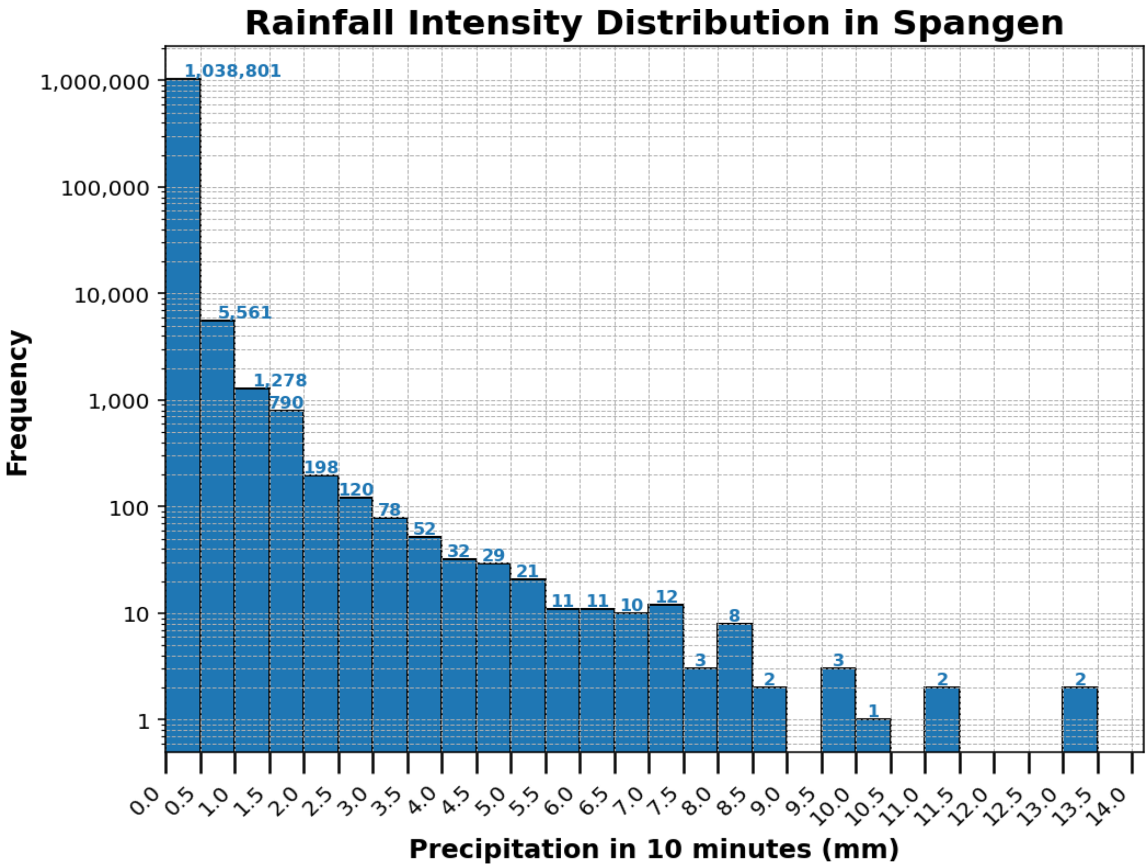

Figure 25 - *Distribution of rainfall intensity in Spangen over the study period, showing a high (1.038 x 10^6) frequency of lighter rainfall events and a steep, logarithmic decline in occurrence as intensity of rainfall events increases.*

6.3 Scenario 1 - Baseline scenario

Scenario 1 models the performance of the existing stormwater management infrastructure in Spangen as of October 2024, using calculations based on the local sewer system's characteristics, along with the current distribution of permeable and impermeable surfaces. The table below provides key baseline values, and the figure following, Figure 26, demonstrates the existing layout of urban greenery as can be seen as of October 2024.

Results: Scenario 1 - Baseline

Per. Area *(ArcGIS)*	***Imp. Area*** *(ArcGIS)*	***Total Runoff***	***CSO Events***	***CSO Volume***
30.2 ha	29.9 ha	9,251.3 mm	188	582.5 mm
50.3%	49.8%	~5.6×10^6 m^3		~3.5×10^5 m^3

Table 2 - *Results of the Baseline scenario (Scenario 1) modeling.*

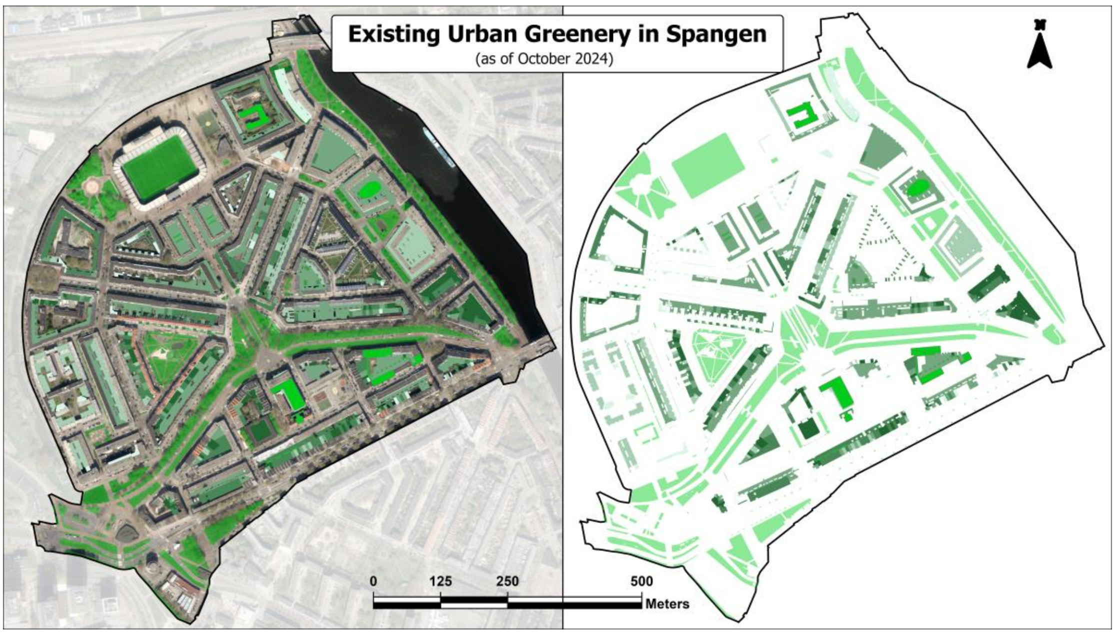

Figure 26 - *Aerial overviews of the existing greenery in Spangen as of October 2024. Imagery basemap: left | Isolated greenery: right*

Figure 27 (below) depicts modeled pump activity over the study period, with pump power displayed in m3/10min. The pump behavior in this model is storage-based, meaning the system adjusts its operation depending on the available sewer storage. As storage approaches its limits, the pump operates at higher capacities to discharge excess sewage and prevent overflow at a faster rate, making more storage available. During times of higher storage levels, the pump runs at a reduced capacity, equal to the DWF. The periods of inactivity in the graph, white spaces, correspond to times when there was little to no rainfall, or when the system was not under stress. This dynamic pump response ensures that the sewer system adapts to varying runoff conditions. The model's simulation of pump activity is based on parameters from the aforementioned Imber hydrodynamic model, which reflects real-world stormwater infrastructure in Rotterdam, ensuring that the model is consistent with real-life drainage operations.

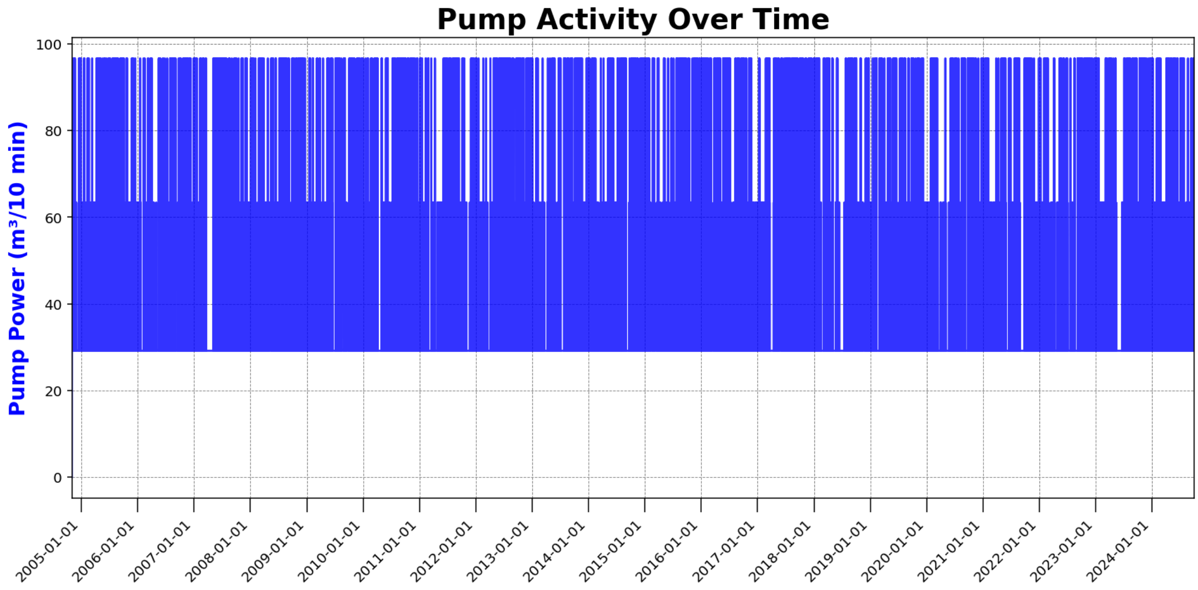

Figure 27 *- Modeled activity of the WWTP pump of the Spangen CSS.*

Figure 28 (below) highlights the fluctuations in sewer storage, which frequently reaches its capacity during intense rainfall events. Very often the CSS almost overflows as well, reaching almost full capacity before retreating back in volume, with the help of the extremely powerful local pump (580m^3/hr @max power). When the storage exceeds its limit, CSO overflow, indicated in red, occurs, representing the excess runoff that the sewer system cannot accommodate. Unfortunately for the local ecology, the existing CSO flows are then directed to the nearby Delfshavense Schie, releasing sewage into the local receiving water body. These overflow events align with the most significant rainfall events, emphasizing the need for enhanced storage capacity or alternative solutions to manage runoff effectively and prevent CSOs. The peaks in overflow are a clear indication of the system's vulnerability during high-intensity or frequent moderate-intensity rainfall events, underscoring the necessity for improvements in stormwater management and flood mitigation strategies.

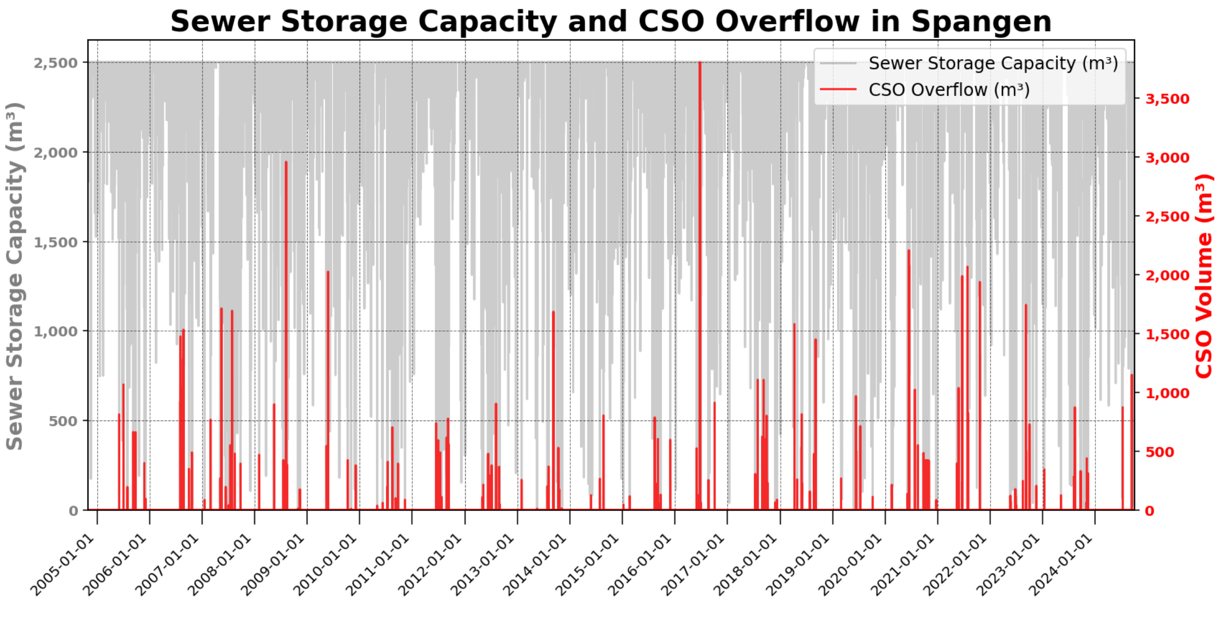

Figure 28 *- The response of the sewer storage capacity and CSO overflow volumes in Spangen throughout the study period.*

Figure 29 (below) shows the detailed hydrological situation during the highest-yielding rain event in the dataset. When the heavy rainfall events hit, peaking the precipitation plot, a mirroring surge in surface flow (runoff) is seen, and an immediate decrease in sewer storage follows, demonstrated by a sharp drop in the black line of the third subplot, until CSOs are activated, a sharp increase in the red line. The final subplot demonstrates the pumping power with a pink line, showing how the pump operates in a stepwise fashion as discussed earlier, operating at an extremely high power when the sewer storage is at the lowest, until the system is able to recover, whereby the pump power drops back to the DWF.

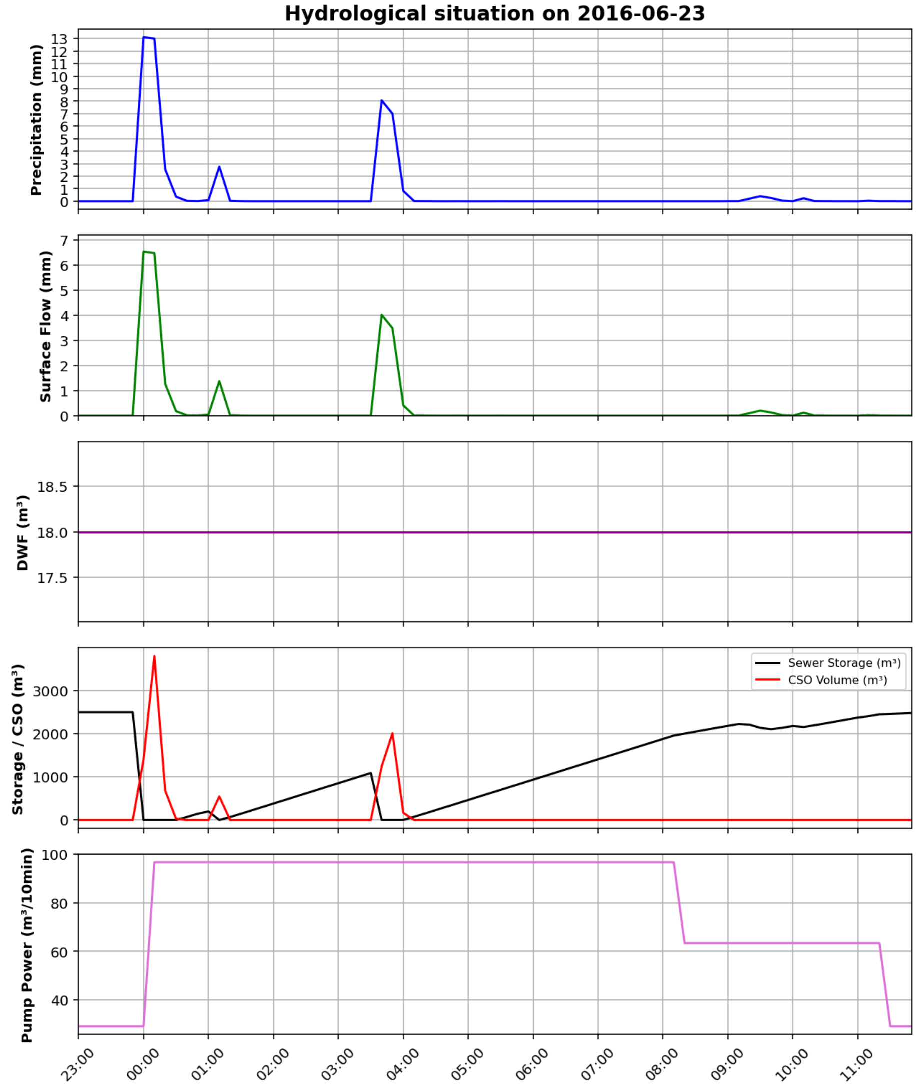

Figure 29 - *The hydrological situation on June 23, 2016.*

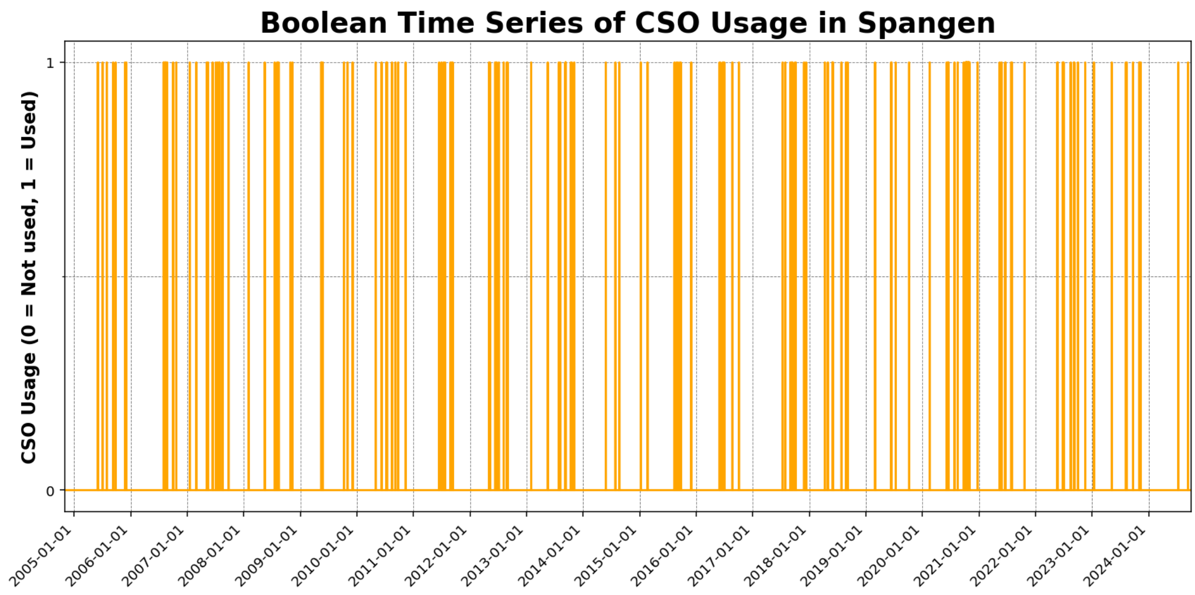

Figure 30 – *The "barcode plot": a Boolean time series of CSO usage, where 0 represents no CSO use and 1 indicates the activation of CSOs.*

Figure 30 identifies the specific instances when the sewer system exceeded its capacity, necessitating the activation of CSOs to prevent system failure. The data reveals the frequency of CSO use corresponding with the plots from earlier, with events largely concentrated during heavy rainfall episodes. This reinforces the finding that while extreme storm events are relatively rare, their impact on the sewer system is substantial enough to trigger CSO events. Ideally, zero CSO events should be seen in a neighborhood with a strong hydrological system, however, the 188 CSO events in the baseline scenario totaling 582.5mm suggest that the current system can be much improved, as it is vulnerable during peak stormwater runoff periods. The question is, how to improve it?

6.4 Configuration 1

6.4.1 Scenario 2 – Bioswales with Passive, Uncontrolled Overflow

Section 6.4 presents the results (Table 3) of Configuration #1 (Config_1) of bioswales, the first, and lightest, implementation of swales in Spangen as shown in Figure 31. As a reminder, in this configuration, all 56 proposed swales have a uniform depth of 0.3 meters and have been volumetrically combined into a single large swale for modeling purposes. The model evaluates four interception fractions: 25%, 50%, 75%, and 100%.

Results: Scenario 2 – Configuration 1

	Swales Added	***Swale Storage Volume***	***Local Per. Area***	***Interception Fraction*** *(% Runoff to Swales)*	***Total Runoff (mm)***	***CSO Overflow Volume (mm)***	***# of CSO Overflow Events***	***Uncontrolled Bioswale Overflow Volume (mm)***	***# of Uncontrolled Bioswale Overflow Events***	***Net flow out (mm)***
	56	10.0 mm	31.1 ha	25%	2,237.6	220.4	81	20.3	38	240.7
		2,892.0 m^3	51.9%	50%	4,475.3	39.0	26	217.3	190	256.3
				75%	6,712.9	0	0	718.4	551	718.4
				100%	8,950.5	0	0	1,642.7	1,158	1,642.7
Totals (Compared to Baseline)	*+56*	*+10.0 mm*	*+1.0ha or +1.6%*	-	*-300.8mm in the 100% case*	*25%: -362.1 50%: -543.5 75&100%: -all*	*25%: -107 50%: -162 75&100: -all*	-	-	*25%: -341.9 50%: -326.2 75%: +135.9 100%: +1,060.2*

Table 3 - *Results of Scenario 2 for Configuration 1, split into 2 sub-tables: spatial results (left) and flow impacts (right, from "int. frac's").*

Table 3 demonstrates the impacts of Configuration 1 on the neighborhood's spatial and flow totals. The very bottom row of the table compares results of the baseline scenario, to show the differences this swale configuration makes compared to the current (baseline) state. For the 25% interception scenario, the bioswales intercept 25% of runoff, reducing CSO overflow by 362.1mm over 81 events to 220.4mm, drastically reducing CSOs in volume and frequency. At 50% interception, CSO volume is further reduced by 543.5mm over 26 events, and very important to note, the net flow out is very close to the 25% fraction despite the large CSO decrease, as the source of overflow switches from the CSS to the swales. Finally, with the 75% and 100% scenarios, although they eliminates CSOs, these scenarios see uncontrolled overflow rise to 718.4mm and 1,642.7mm, drastically exceeding baseline outflow. The 75% and 100% are not justified implementations from a volumetric perspective, despite the swales in these cases effectively redirecting the overflow source from CSOs to a much cleaner overflow source of treated stormwater from the swales, an improvement in water quality and public health effects.

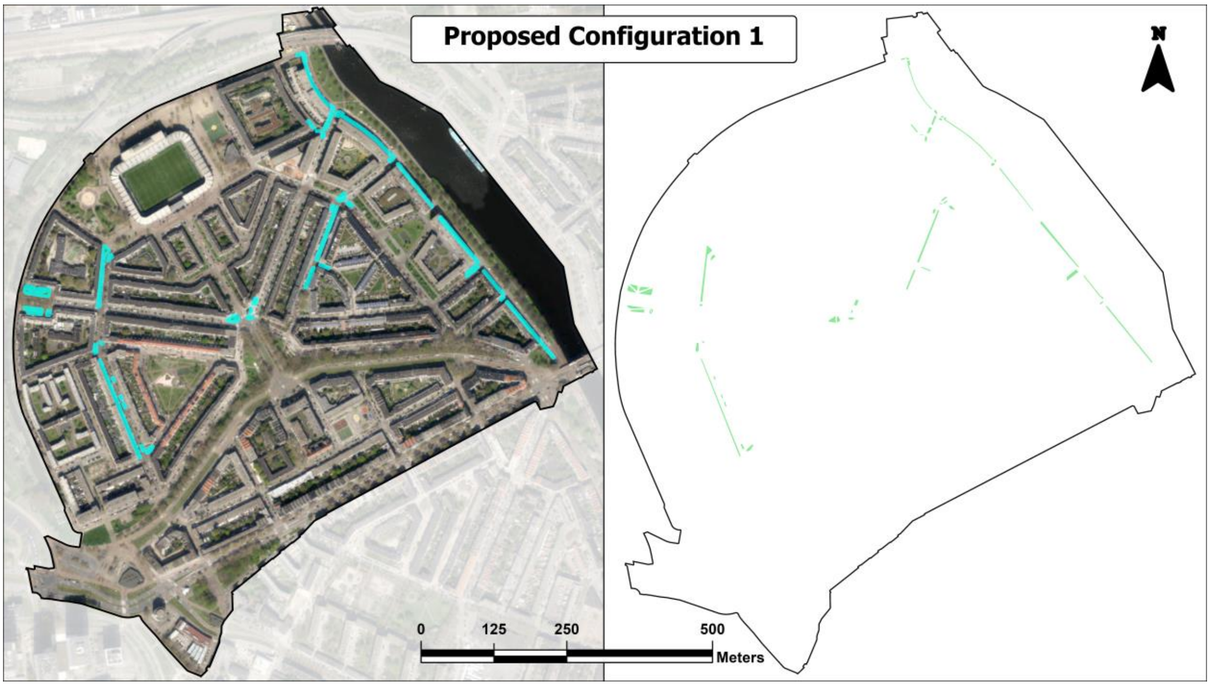

Figure 31 - *Configuration 1, depicting an aerial satellite overview (left) of proposed bioswales, highlighted blue. Right: isolated bioswales.*

Figure 32 shows sewer storage capacity over time in the top plot, with colored lines representing different interception scenarios. The bottom plot shows the CSO overflow under the same interception fractions. The 100% interception scenario leads to no CSO overflow by definition, and the full CSS sewer storage is always available, because no runoff goes into the sewer. Whereas the lower interception fractions (25%, 50%, and 75%, especially 25%) show varying degrees of overflow. The most striking visualization is how the top plot overflows visually into CSOs, visually depicting when the CSS overflows. This figure highlights the importance of increasing bioswale interception to reduce the strain on the sewer system.

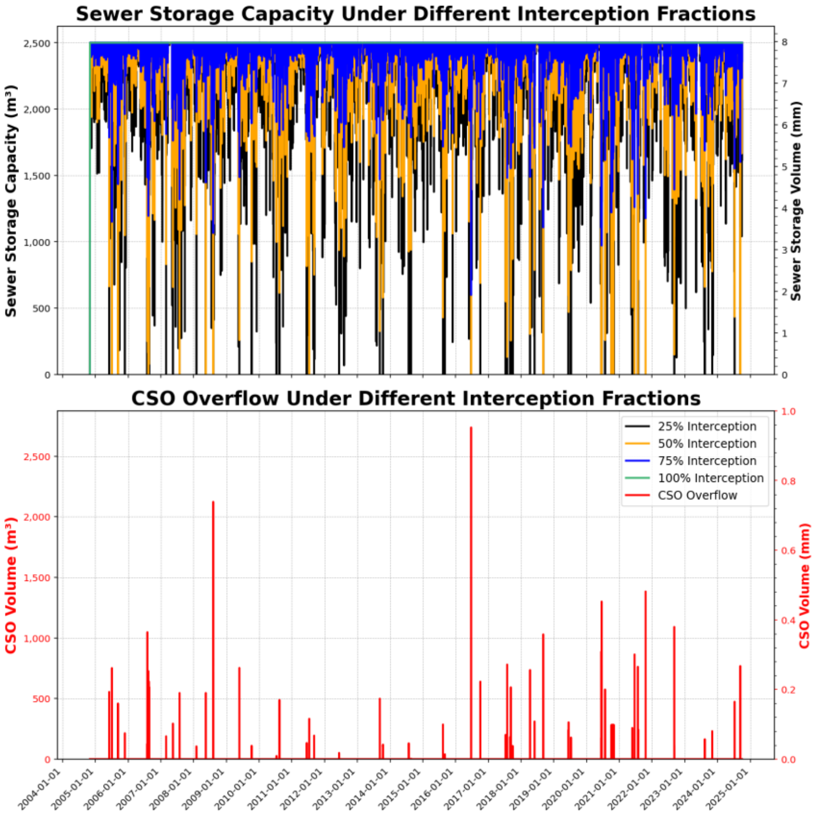

Figure 32 - *The sewer storage capacity observed under the different interception and the corresponding CSO overflow volumes and events.*

Figure 33 provides two detailed time series of (1) overflow and (2) stored volume in the swales over time across the different interception fractions. The upper plot visually isolates and illustrates the uncontrolled overflow volume instances, in terms of frequency and volume, for Configuration 1 of swales. Increasing overflow volumes can be observed as the interception fraction increases, meaning as more runoff is captured by the swales, there is more uncontrolled overflow because their relatively shallow cumulative depth is not able to infiltrate all of the runoff they capture. Meaning, the more runoff diverted to the swales, the more likely the swales are to overflow.

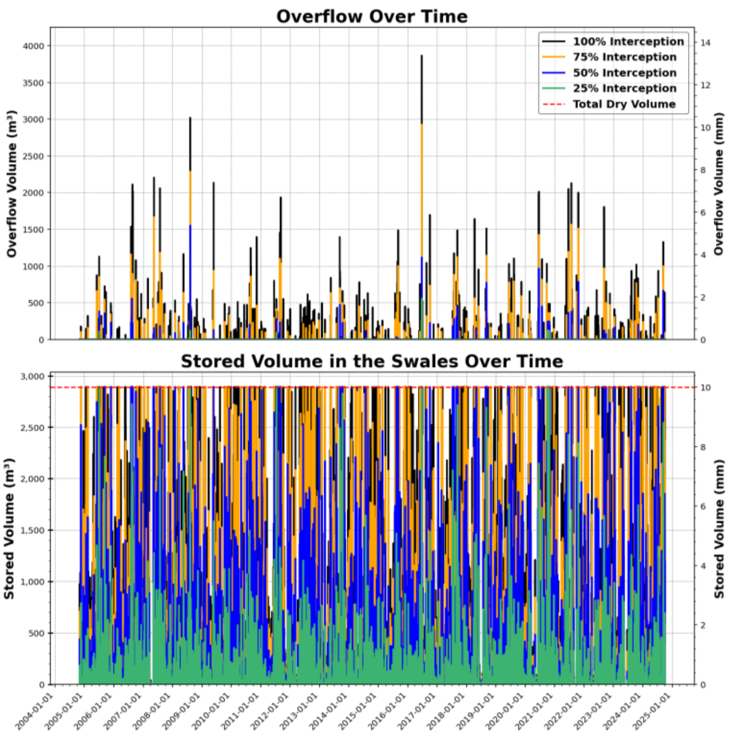

Figure 33 *– Uncontrolled overflow and stored volume over time for the different interception fractions.*

The lower plot shows a rather congested time series of stored volume in the swales, depicting peaks from swales storing and infiltrating stored volume. However, once the swales' dry volume is reached, they will overflow, visually depicted by the top plot. This plot is especially important to link Scenarios 2 and 3, as it demonstrates that Scenario 2 has significant uncontrolled overflow events, and the question becomes, how to manage these high-volume, rapid overflow events to smooth their peak outflow over a longer time, using RTC?

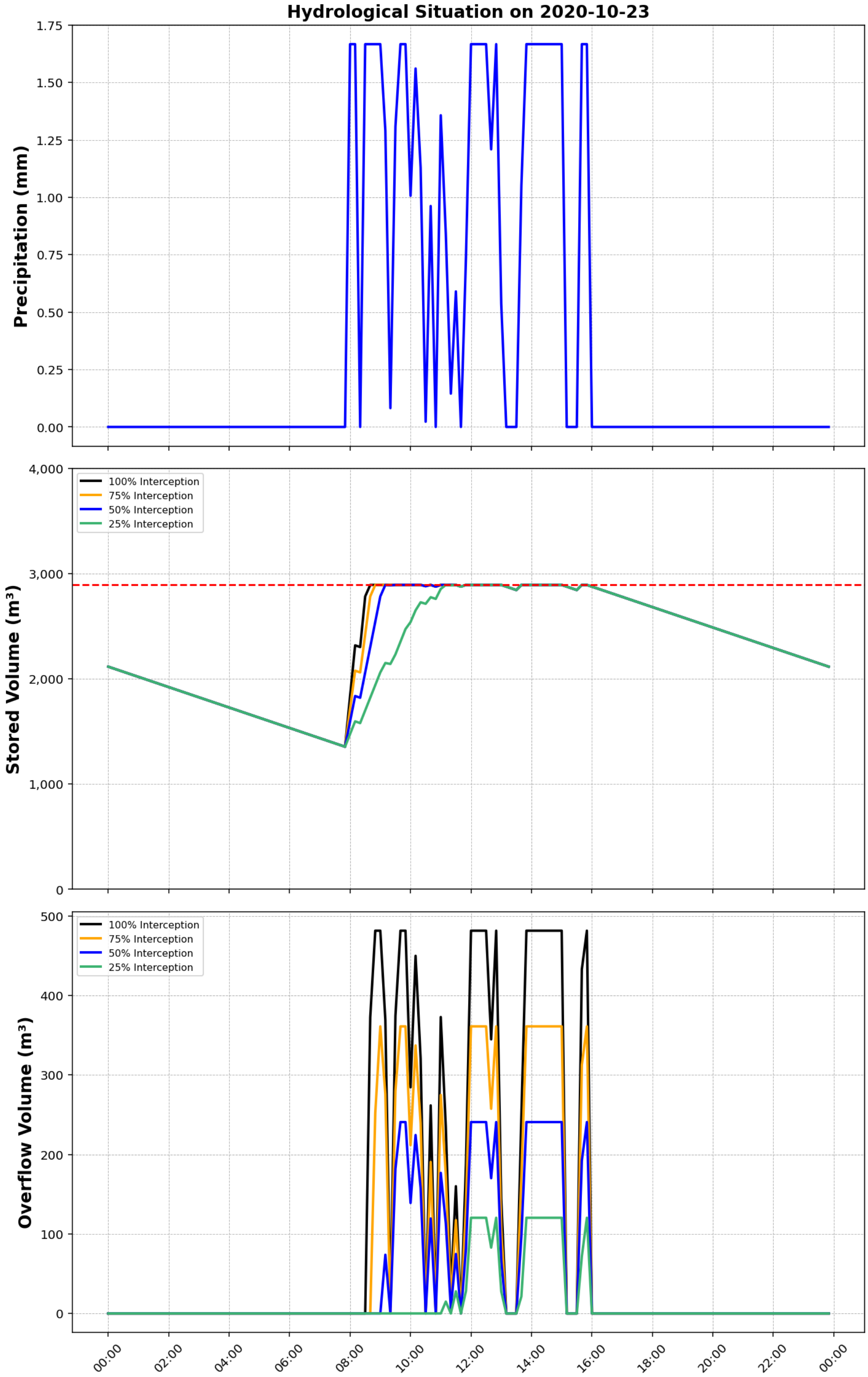

Figure 34 *– The modeled hydrological situation during a significant rainfall event on 2020-10-23, under the uncontrolled overflow scenario.*

Figure 34 illustrates the local hydrological response during one of the most significant rainfall events during the study period, 2020-10-23. The local hydrological response is displayed across three subplots. The first subplot shows a 24-hour time series of the precipitation event, in which multiple high-volume rainfall events occur within a short time frame, with 11 peaks in precipitation (8 of them over 1.5mm) in about 8 total hours. These bursts are shown to overwhelm the proposed bioswale system, leading to overflow, which occurs when the swale volume exceeds the total dry volume, or the red line. The second subplot presents the stored volume in the swales, which rapidly fills up with every precipitation burst, demonstrating the swales' rapid response to intercept runoff.

However, as the final subplot shows, the swales are unable to handle all overflow volume, leading to multiple distinct peaks representing the extreme surges of uncontrolled overflow from the swales, most surpassing several hundred cubic meters. These sharp overflow peaks emphasize the system's vulnerability to intense, rapid rainfall events, highlighting the challenges in managing large amounts of runoff in such a short time. Without a control scheme to govern swale overflow, there are large peaks of overflow deposited into the local receiving water body.

6.4.2 Scenario 3 - RTC-Controlled Bioswales

In this section, the impact of RTC on the proposed bioswales is analyzed, focusing on the capacity of RTC to mitigate swale overflow by pre-emptively adjusting stored volumes across the swales. The RTC system dynamically releases a calculated volume of stored water over a lead time of 12 hours to optimize stormwater management in the context of peak forecasted precipitation events, which builds on the uncontrolled overflow scenario, in which the bioswales were unable to regulate stormwater volume in real time. Now, the RTC adds the ability for the bioswales to dynamically manage their stored volume, giving the municipality of Rotterdam (Gemeente Rotterdam) the upper hand to control the new bioswales directly. The figures following especially illustrate the hydrological impact of RTC in Spangen for October 23, 2020, and the differences between Scenario 2 and 3 are then compared in histograms and probability density function (PDF) plots.

Results: Scenario 3 (RTC) – Configuration 1

Interception Fraction	*Pre-emptively removed volume by RTC (mm)*	*Remaining uncontrolled overflow volume*	*Uncontrolled overflow reduction, compared to Scenario 2*
25%	*14.1*	*6.2*	*-14.1 mm*
50%	*122.0*	*152.2*	*-65.1 mm*
75%	*395.3*	*511.2*	*-207.2 mm*
100%	*902.2*	*1,138.8*	*-503.9 mm*

Table 4 *- Scenario 3 (RTC) results for Configuration 1.*

Table 4 demonstrates that implementing RTC drastically reduces the uncontrolled overflow volume directed to the receiving water body from the swales. However, the net volume is not necessarily lower, just distributed over time (see rightmost column, Table 3). However, the 75% and 100% fractions still show that despite RTC, the sum of pre-emptively removed plus remaining uncontrolled is still higher than the baseline scenario, leading to these two fractions not being recommended. In these specific fractions, the swales simply have too limited net storage capacity in this configuration. Therefore, the investment for RTC is justified for the 25% and 50% compared to Baseline, and not for the 75% or 100% interception fractions.

Figure 35 again displays the hydrological situation on October 23, 2020 as was shown in the previous section (Config 1, Scenario 2), this time with RTC applied. The RTC system's effectiveness is evident here. In the updated volume subplot, the RTC mechanism shows its ability to pre-emptively evacuate stormwater stored in the bioswales in a lead-time of 12 hours, before an overflow is projected. This ensures that overflow is re-distributed over a longer time period before the intercepted runoff exceeds the storage capacity. Specifically, in the previous graph (Figure 34), the black, yellow, and blue lines reached overflow rather quickly together (~09:00) with the green line following a bit behind. However, in Figure 35, the delay between lines is pronounced much more, with all lines spread further apart to when they will reach overflow. The green line (25% fraction) demonstrates a prime demonstration of the effect of RTC, as RTC successfully pre-emptied just enough volume for the swale to reach its maximum volume before then retreating in volume and not overflowing. However, the 100%, 75%, and 50% fractions will still have overflows despite RTC pre-removing all of the volume stored in these fractions, because in the plot, the red line is reached and the fraction lines plateau, suggesting overflows that go past the red line. This is not a limitation of the RTC but rather a physical limitation of swale capacity, as the RTC cannot remove more volume than is physically possible before the overflow, rendering the bioswales not able to handle extreme loads in the current configuration (Configuration 1). However, the large reduction in uncontrolled overflow volume in the outflow subplot demonstrates that RTC successfully mitigates flooding risk, allowing for stronger peak attenuation during events of high rainfall. The pattern of overflow volume is therefore significantly smoother, with fewer peaks exceeding the system's capacity compared to what was seen in the uncontrolled overflow case in Figure 34. The RTC-controlled overflow is a major improvement in comparison to uncontrolled overflow because it shifts overflow events into smaller, sustained, more frequent releases, ensuring that the system can handle more rainfall over time.

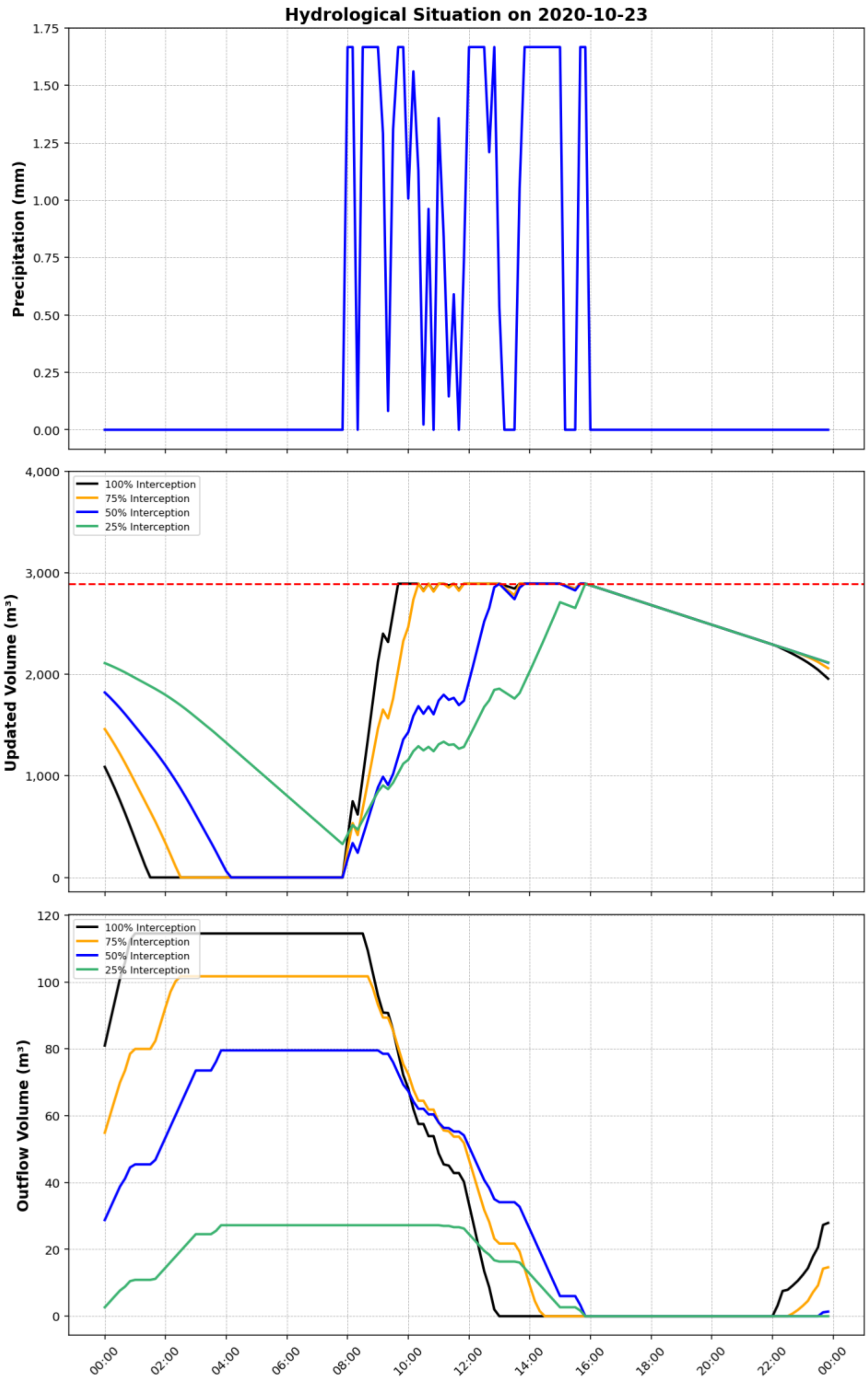

***Figure 35** – Again, the modeled hydrological situation on 2020-10-23, now under the comparison of RTC-controlled bioswale overflow.*

6.4.3 Visual comparison of Scenario 2 and Scenario 3

This section directly compares the results of Scenario 2 (uncontrolled overflow) with Scenario 3 (RTC-controlled overflow). Red plots represent Scenario 2, while blue plots correspond to Scenario 3, allowing for a clear visual contrast between the two approaches. The plots focus specifically on the 100% interception fraction, as this configuration directs the entire runoff volume to the swales, providing the most comprehensive and interpretable comparison of swale performance. By evaluating the extreme case where all runoff is intercepted, the effectiveness of RTC in managing stormwater volumes can be most clearly demonstrated.

Figure 36 provides a side-by-side comparison of the outflow events of the uncontrolled and RTC-controlled overflow scenarios, with overflow volume (m^3 per 10 minutes) plotted on the x-axis, and log frequency on the y-axis. The most striking difference immediately seen between the scenarios is in the x-axis scale. On the left, the red histogram demonstrates the unpredictable and random nature of uncontrolled overflow, with overflow events occurring at varying magnitudes, and only even occurring once at extreme volumes. The spread of the data is much larger compared to the blue plot, reflecting the high variability in, and magnitude of overflow volumes. In light of climate change bringing more intense precipitation events at a higher frequency, logically, the outliers of the histogram will only increase in frequency and volume, spreading the data even further. These high peaks are major risk factors for urban water management systems, as the unpredictability and high volume discharged in a short time span leads to higher risk of flooding, especially in Spangen, located in an area with high annual rainfall yields, and geographical vulnerabilities. It then becomes especially important to implement a system like RTC to better predict and manage these events, the results of which are already hinted at in the right histogram.

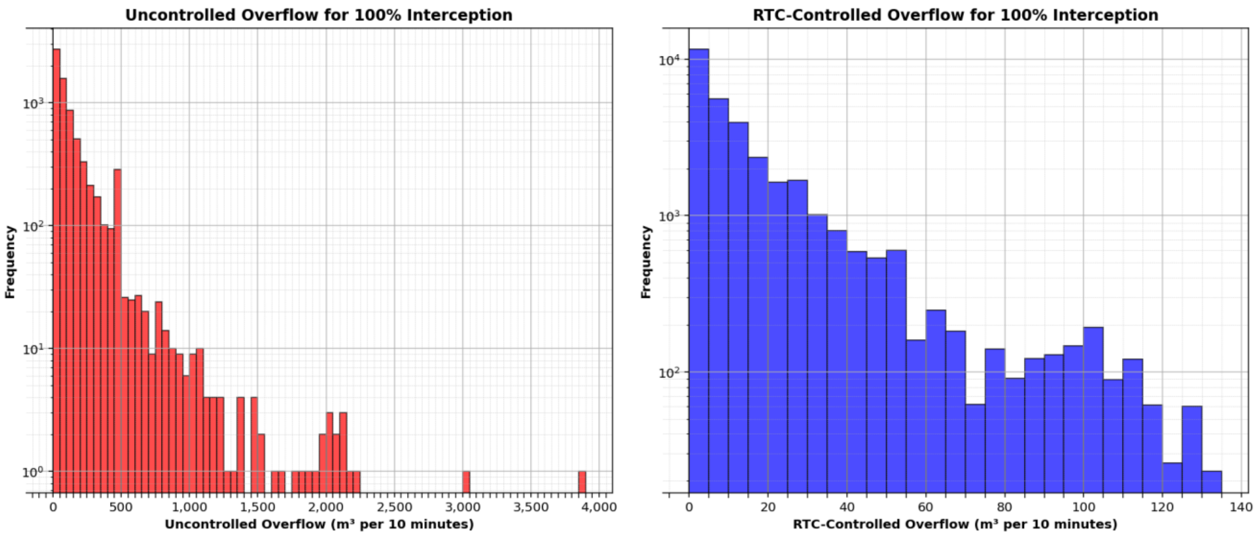

Figure 36 - *A side-by-side comparison of Scenario 2 (uncontrolled) overflow compared to Scenario 3 (RTC-controlled) overflow results.*

On the right, the blue histogram demonstrates the RTC-controlled overflow scenario. The x-axis, and the data distribution are notably different compared to the uncontrolled (red) plot. The frequency of overflow events in the RTC scenario is much higher in the lower volume ranges, indicating that the RTC system effectively reduces the magnitude of peak overflow events by redistributing large overflow peaks into more manageable, smaller-scale outflow events, even past 10^4 as a frequency for lower-volume RTC flows. This gives the municipality more control over the effects of the bioswales on the local receiving water body, because the RTC system effectively reduces the occurrence of peak, high-volume overflow events by translating them into more frequent, low-volume events, ensuring that the system remains within manageable limits. The comparison reveals the stark contrast between the unpredictable and erratic nature of uncontrolled overflow and the much more consistent behavior of the RTC-controlled system.

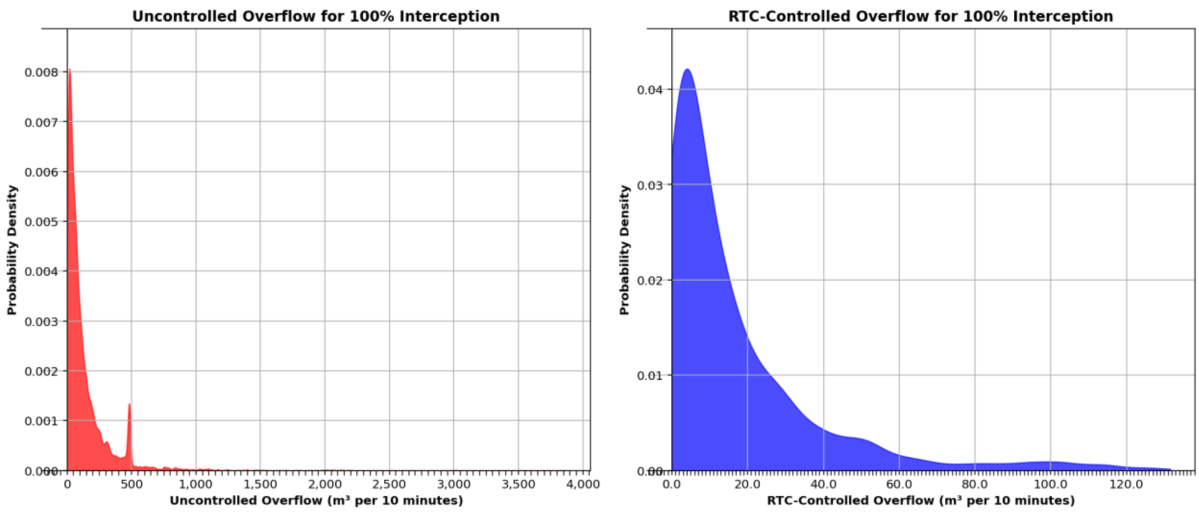

Figure 37 - *Probability Density Function (PDF) comparison of uncontrolled and RTC-controlled overflow event distributions.*

The final figure, Figure 37, further demonstrates the difference between Scenarios 2 and 3 using a Probability Density Function (PDF) plot. The red PDF (uncontrolled overflow, left) is again characterized by the large x-axis, and the very low probability densities at higher overflow volumes with large and irregular peaks, reflecting the high unpredictability of overflow events. Whereas, the blue PDF (RTC-controlled overflow) exhibits a much tighter x-axis, and a wider, smoother curve with a higher probability density in the lower overflow ranges, reflecting the RTC system's ability to consistently manage and mitigate overflow events. In summary, the PDFs reinforce the results observed in the histograms discussed earlier. The uncontrolled overflow shows a highly irregular and unpredictable nature, translating to peak outflow events with a short duration and high volume, while the RTC-controlled overflow is more stable, with a higher likelihood of smaller overflow events, demonstrating the efficiency of RTC in reducing peak overflows.

6.5 Configuration 2

6.5.1 Scenario 2 – Bioswales with Passive, Uncontrolled Overflow

This section presents the results of Scenario 2 of bioswale Configuration #2 (Config_2), focusing on the second, more prominent implementation of swales in Spangen as shown in Figure 38. Table 5 summarizes the key results for each interception fraction.

Results: Scenario 2 – Configuration 2

	Swales Added	*Swale Storage Volume*	*Local Per. Area*	*Interception Fraction (% Runoff to Swales)*	*Total Runoff (mm)*	*CSO Overflow Volume (mm)*	*# of CSO Overflow Events*	*Uncontrolled Bioswale Overflow Volume (mm)*	*# of Uncontrolled Bioswale Overflow Events*	*Net flow out (mm)*
	131	20.5 mm	32.1 ha	25%	2,163.5	196.6	78	0	0	196.6
		5,737.3 m³	53.46%	50%	4,326.9	32.0	24	35.8	34	67.8
				75%	6,490.4	0	0	171.8	99	171.8
				100%	8,653.9	0	0	401.7	181	401.7
Totals (Compared to Baseline)	*+131 swales*	*+20.5 mm*	*+1.9ha or +3.2%*	-	*-597.4mm in the 100% case*	*25%: -385.9 50%: -550.5 75&100%: -all*	*25%: -110 50%: -164 75&100%: -all*	-	-	*25%: -385.9 50%: -514.7 75%: -410.7 100%: -180.8*
Totals (Compared to Config_1)	*+75 swales*	*+10.5 mm*	*+1.0ha or +1.6%*	-	*-296.7mm in the 100% case*	*25%: -23.8 50%: -7.0 75&100%: same*	*25%: -3 50%: -2 75&100: same*	*25%: -20.3 50%: -181.6 75%: -546.6 100%: -1,241.0*	*25%: -38 50%: -156 75%: -452 100%: -977*	*25%: -44.1 50%: -188.5 75%: -546.6 100%: -1,241.0*

Table 5 - *Results of Configuration #2 of bioswales, the middle, more-intensive configuration.*

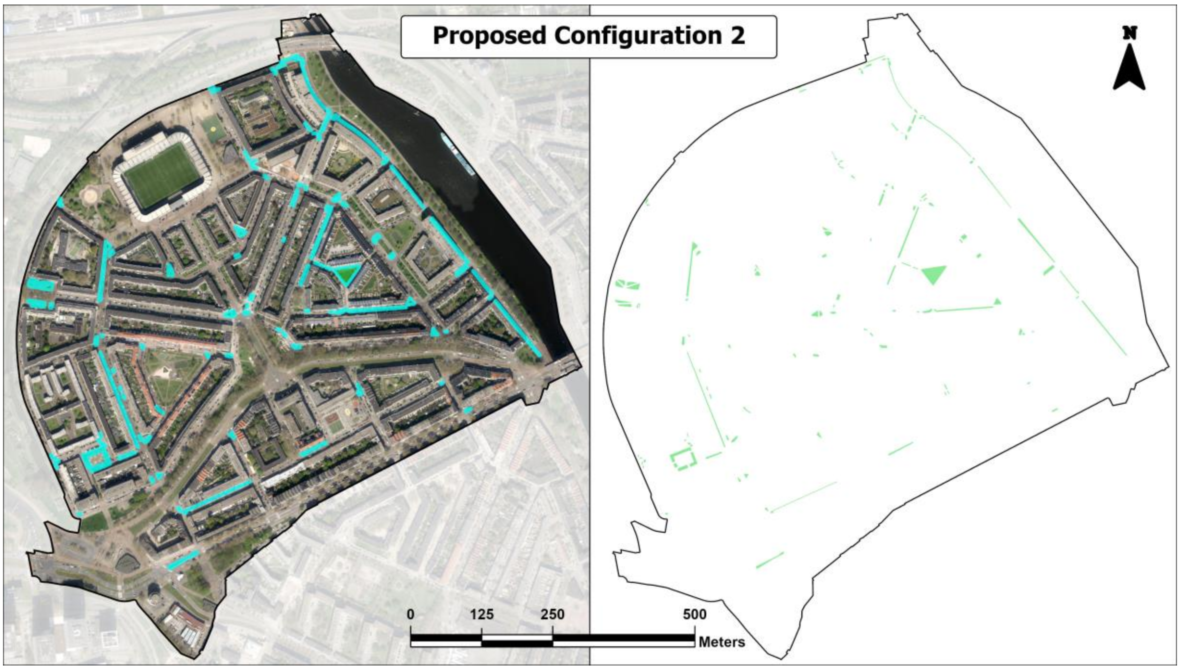

Figure 38 - *The proposed Configuration 2, with proposed bioswales highlighted in blue on the left and isolated on the right.*

Table 5 shows many consistent and intuitive patterns in the results of Configuration 2. Total runoff, CSO overflow volume and frequency, uncontrolled volume and frequency, and net flow out all show decreases compared to both the baseline (Scenario 1) and Configuration 1. Most strikingly, the 50% interception fraction shows the strongest results, decreasing the “net flow out” the most, despite it not having the best CSO or uncontrolled overflow results. The combination of both performs the best compared to the other interception fractions. This interception fraction resulted in the configuration-lowest 67.8mm of net flow out, the best result in the configuration. With swales now located across the entire neighborhood, their effects are very evident in this fraction, with drastic decreases seen especially for the 100% fraction. With more storage, the 100% fraction decreased over 1,000mm for the uncontrolled overflow volume, and almost 1,000 lesser events of uncontrolled overflow compared to Configuration 1.

Similar to Config 1, Figure 39 shows sewer storage capacity on the top subplot, and CSO overflow on the bottom.

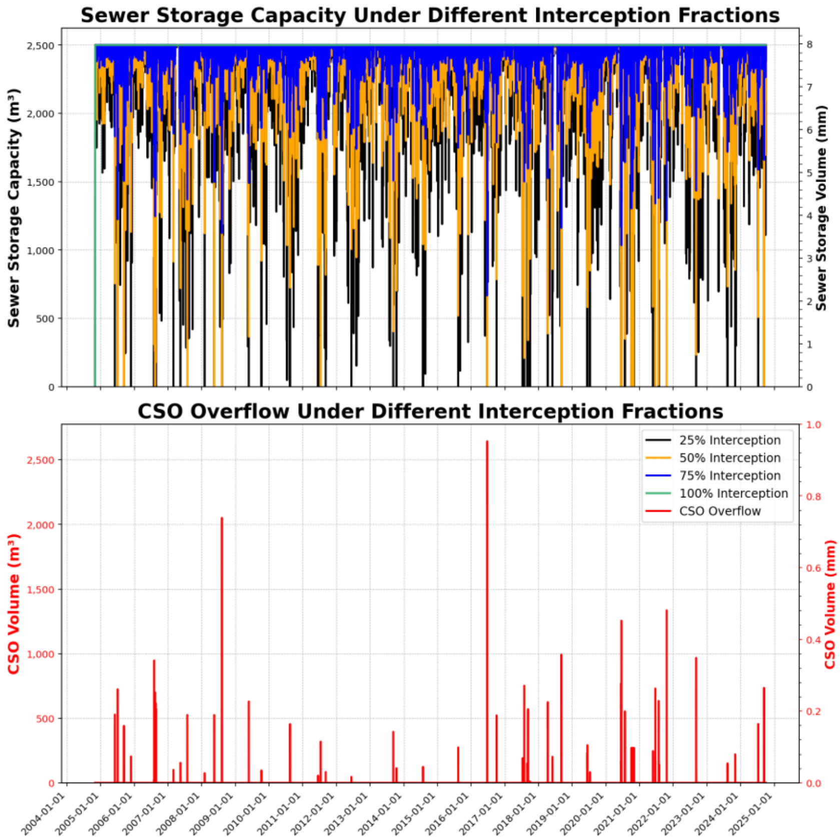

Figure 39 - *The sewer storage capacity and corresponding CSO overflows observed for the interception fractions for Config_2.*

Compared to the same graph in the analysis of Config 1, significant reductions in CSO overflow and CSO events are seen for all interception fractions, except for 100%, because the 100% fraction redirects all runoff away from the swales, physically making sewer storage always available. Compared to the same plot in Config 1, the most striking difference is the improvement that more sewer storage volume is now always available, with significantly less peaks dipping close to maximum sewer storage, especially compared to baseline. This figure further highlights

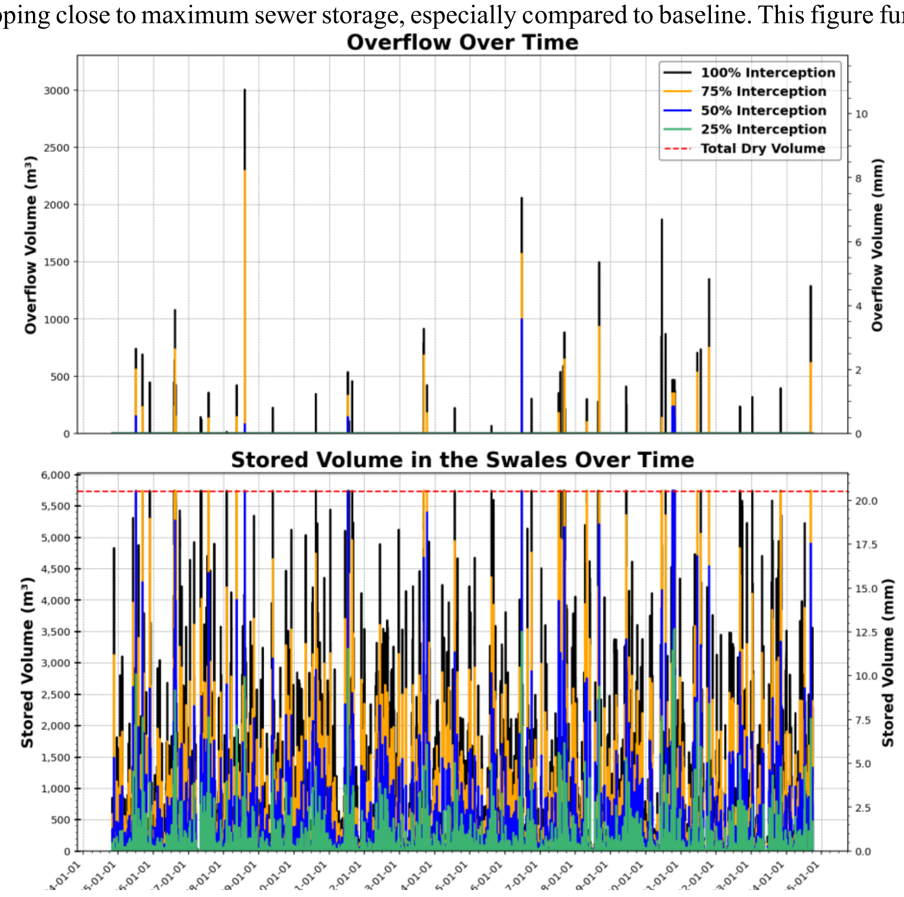

Figure 40 - *Uncontrolled overflow and stored volume over time for the different interception fractions.*

the importance of increasing bioswale storage to reduce the strain on the sewer system. Figure 40 provides two detailed time series of (1) overflow and (2) stored volume in the swales over time across the different interception fractions. The upper plot visually isolates and illustrates the uncontrolled overflow volume instances, in terms of frequency and volume, for Configuration 2 of swales. Compared to the same plot in Config 1, visually, less overflow events, in terms of frequency, and volume can be seen. Whereas uncontrolled overflow volumes can still be observed as the interception fraction increases, the magnitudes of these uncontrolled overflow volumes are much less, largely in part due to the 75 more swales with over double combined storage capacity compared to Config 1. The doubling of storage capacity can be seen on the right hand side y axis of the bottom subplot, which shows the red line at over double as high as it was in the previous plot, Figure 33.

Below, Figure 41 again illustrates the local hydrological response on 2020-10-23, updated for Config 2 and displayed across three subplots. The first subplot shows the 24-hour time series of the precipitation event. However, with this configuration, the system is not so overwhelmed compared to the baseline or first configuration. These intense rainfall bursts are still shown to overwhelm the proposed bioswale system, leading to overflow, however, with the higher red line (increased swale storage), the peaks of uncontrolled overflow are reduced in magnitude and frequency. For the 100% fraction (black line) the peaks remain at 10, but with noticeable decreases in volume. For the 75% fraction (yellow line), the peaks decrease from 10 to 9, with decrease in volume. For the 50% fraction (blue line), the peaks decrease from 10 to 4, and for the green line (25% fraction), peaks decrease from 6 to 0. The line of the 25% fraction is a product of the increased number of swales throughout the neighborhood with a higher overall storage volume, as in Configuration 1, this same rainfall event would have led to overflows, however now, the swales can handle this amount of runoff. Overall, the configuration decreases the system's vulnerability to intense, rapid rainfall events such as the one on October 23rd, 2020, highlighting the effectiveness of this configuration's proposal to distribute more swales throughout the entirety of Spangen.

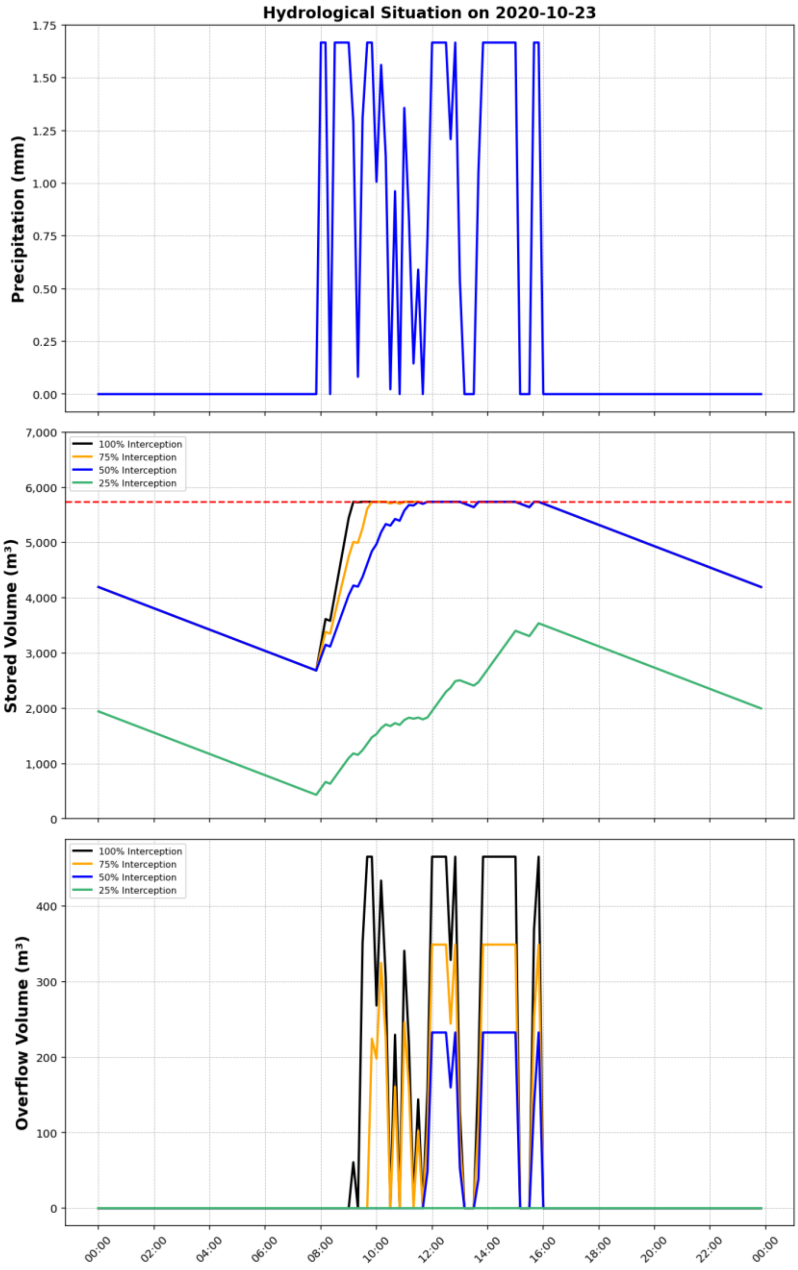

Figure 41 *- The modeled hydrological situation during a significant rainfall event on 2020-10-23, under the uncontrolled overflow scenario.*

6.5.2 Scenario 3 - RTC-Controlled Bioswales

In this section, the impact of RTC on the proposed swales is analyzed, focusing on the capacity of RTC to mitigate swale overflow by pre-emptively adjusting stored volumes across the swales. The figures below especially illustrate the hydrological impact of RTC in Spangen for two separate days: October 23, 2020, and June 23, 2016, demonstrating the potential and limitations of RTC to manage stormwater and overflows. The differences between Scenarios 2 and 3 are then compared in histograms and probability density function (PDF) plots.

Results: Scenario 3 (RTC) – Configuration 2

Interception Fraction	***Pre-emptively removed volume by RTC (mm)***	***Remaining uncontrolled overflow volume (mm)***	***Uncontrolled overflow reduction, compared to Scenario 2 (mm)***
25%	0	0	0
50%	25.9	9.9	-25.9
75%	98.7	91.8	-80.0
100%	227.4	277.8	-123.9

Table 6 - *Scenario 3 (RTC) results for Configuration 2.*

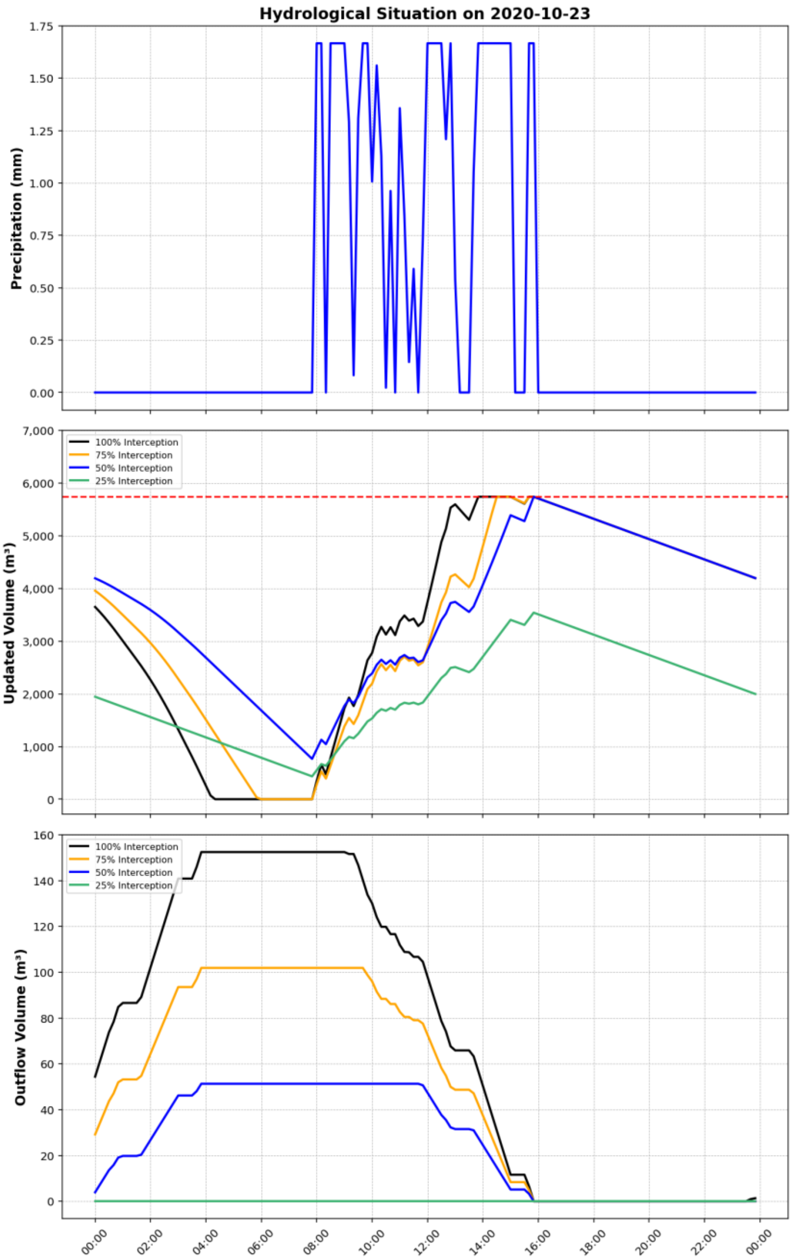

Figure 42 - *Again, the modeled hydrological situation on 2020-10-23, now under the comparison of RTC-controlled bioswale overflow.*

Table 6 demonstrates that RTC, similar to Configuration 1, plays a role in removing even more uncontrolled overflows from the 50%, 75%, and 100% fractions, with net flow out decreases as seen in Table 5. RTC successfully attenuated these peaks over the lead time.

Figure 42 again displays the hydrological situation on October 23, 2020 as was shown in the previous section (Config 2, Scenario 2). RTC's effectiveness is even more evident here. Compared to Config 1 using the same date with RTC, now, when the RTC pre-emptively evacuates stormwater stored in the bioswales in a lead-time of 12 hours, there are significantly less plateaus at the dotted red line. For the 25% fraction, this rainfall event is no threat to overflowing, and the RTC does not have to pre-empty any volume as seen by the bottom-most subplot green line remaining flat, as the swales can handle all of runoff without overflowing. The 50% fraction behaves elegantly in this figure, with the RTC pre-emptying the projected overflow volume over the lead time – depicted by an increased negative slope around 02:00 - and the swales just reaching their peak full volume at the very end of the event, never overflowing. The yellow (75% fraction) and black (100% fraction) also demonstrate an activation of RTC, with the pre-emptying seen in the bottom subplot, however, these fractions still overflow and plateau at the red line. Despite their full volumes being pre-emptied, this rain event led too much runoff into the swales, with the swales not being able to handle so much, thus overflowing. However, overall, with 75 more swales added in Configuration 2, net storage volume was more than doubled, and uncontrolled overflow significantly decreased. Further adding RTC, uncontrolled overflow decreased even more (ref. Table 6), successfully demonstrating that RTC mitigated flooding risk on this day, especially in the 50% fraction.

6.5.3 Visual comparison of Scenario 2 and Scenario 3

In this section, red histograms and plots represent Scenario 2, while blue histograms and plots correspond to Scenario 3, allowing for a clear visual contrast between the two approaches. The plots focus specifically on the 100% interception fraction, as this configuration captures the entire runoff volume, providing the most comprehensive and interpretable comparison of system performance.

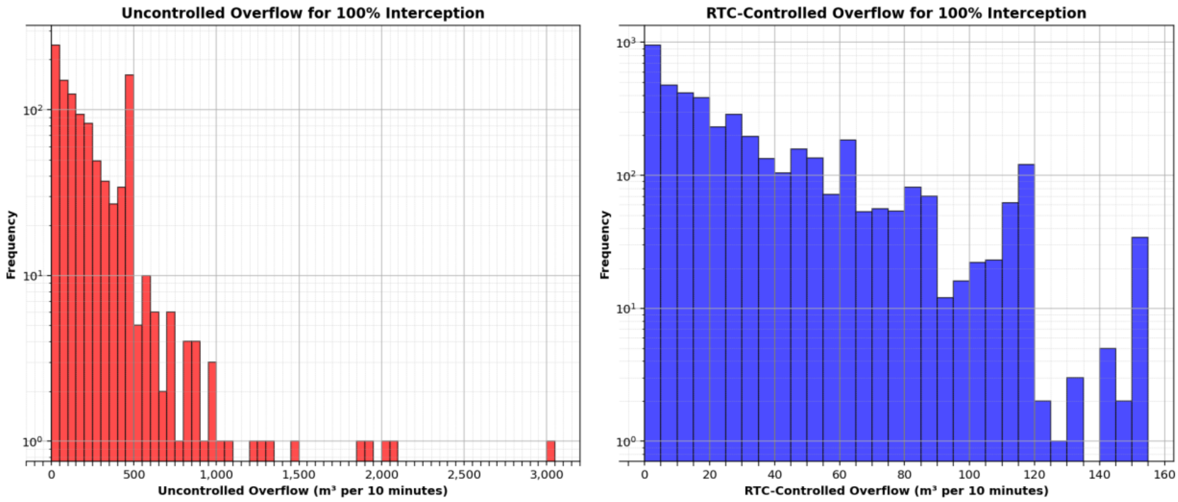

Figure 43 - *A side-by-side comparison of Scenario 2 (uncontrolled) overflow compared to Scenario 3 (RTC-controlled) overflow results.*

Figure 43 provides a side-by-side comparison of the uncontrolled and RTC-controlled overflow scenarios. Again, the most striking comparison between the plots continues to be the x-axis scale. On the left, the red histogram demonstrates overflow events occurring at varying magnitudes, again showing an irregular distribution similar to that of Config 1. The x-axis, while having an improved, lower x-axis limit of 3,200 compared to 4,050 in Config 1 due to the larger storage capacity of the swales, is still spread out almost 20 times higher than that of the right.

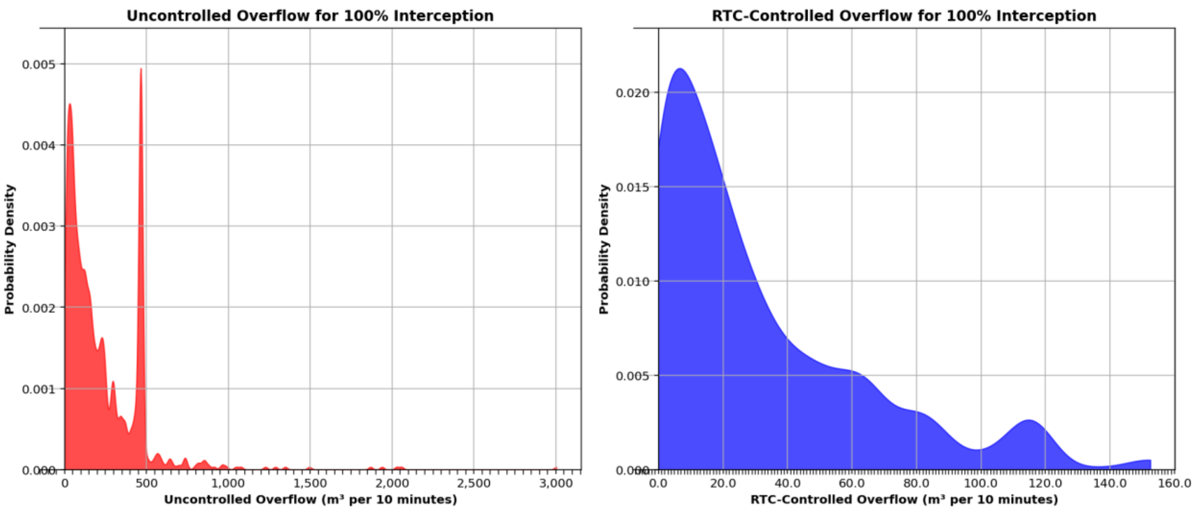

Figure 44 - *Probability Density Function (PDF) comparison of uncontrolled and RTC-controlled overflow event distributions.*

On the right, the blue histogram demonstrates the RTC-controlled overflow scenario, this time with an order of magnitude less than the same plot of Config 1, reaching a high of 10^3, not 10^4. The distribution is even more evenly spread out compared to both the red plot of this configuration, as well as to the same histogram (blue) of Config 1. Overall, this plot demonstrates that the RTC is functioning well, redistributing projected overflow.

The final figure, Figure 44, further exemplifies the differences seen in the comparative histogram between Scenarios 2 and 3 using PDF plots, used to outline the shape of the data. Even more pronounced spikes compared to the same plot in Config 1, and the continued large spread of data can be seen in the red PDF, whereas the blue PDF (RTC-controlled overflow) exhibits a much smoother curve with a more even distribution, even in comparison to the same plot from Config 1. For the blue PDF plot, the concentration of overflow in lower volumes and the gradual distribution across the range reflect the RTC system's ability to consistently manage and mitigate overflow events. In summary, the uncontrolled overflow PDF shows an irregular plot outline, while the RTC-controlled overflow plot is more evenly distributed, demonstrating efficiency of RTC in reducing peak overflows.

6.6 Configuration 3

6.6.1 Scenario 2 – Bioswales with Passive, Uncontrolled Overflow

This section presents the results of Scenario 2 of bioswale Configuration #3 (Config_3), focusing on the third, most intensive implementation of swales in Spangen as depicted in Figure 45. This configuration features 144 swales with a uniform depth of 0.3 meters. Table 7 summarizes key results for each interception fraction.

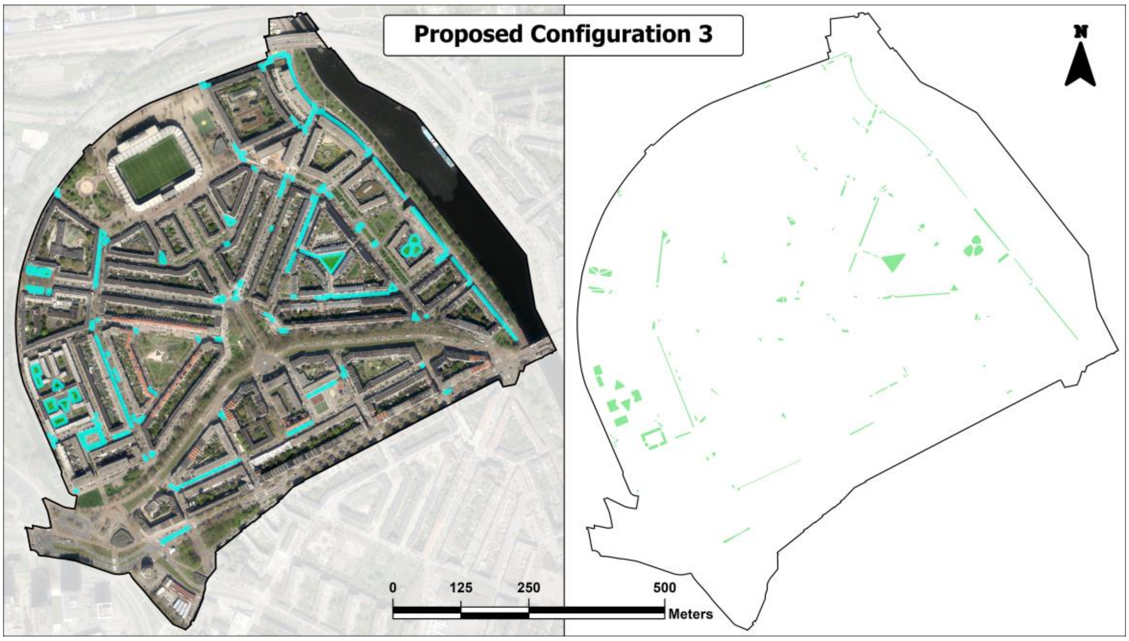

***Figure 45** – The proposed, most-intensive Configuration 3, with proposed bioswales highlighted in blue on the left and isolated on the right.*

Results: Scenario 2 – Configuration 3

	Swales Added	*Swale Storage Volume*	*Local Per. Area*	*Interception Fraction (% Runoff to Swales)*	*Total Runoff (mm)*	*CSO Overflow Volume (mm)*	*# of CSO Overflow Events*	*Uncontrolled Bioswale Overflow Volume (mm)*	*# of Uncontrolled Bioswale Overflow Events*	*Net flow out (mm)*
	144	28.6 mm	32.8 ha	25%	2,110.5	180.4	72	0	0	180.4
		7,784.6m³	54.6%	50%	4,221.0	27.3	22	4.0	4	31.3
				75%	6,331.4	0	0	68.0	45	68.0
				100%	8,441.9	0	0	203.9	95	203.9
Totals (Compared to Baseline)	*+144 swales*	*+28.6 mm*	*+2.6ha or +4.4%*	-	*-809.4mm in the 100% case*	*25%: -402.2 50%: -555.2 75&100: -all*	*25%: -116 50%: -166 75&100: -all*	-	-	*25%: -402.2 50%: -551.2 75%: -514.5 100%: -378.6*
Totals (Compared to Config_1)	*+88 swales*	*+18.6 mm*	*+1.6ha or +2.7%*	-	*-508.6mm in the 100% case*	*25%: -40.0 50%: -11.7 75&100%: same*	*25%: -9 50%: -4 75&100: same*	*25%: -20.3 50%: -213.3 75%: -650.4 100%: -1,438.8*	*25%: -38 50%: -186 75%: -506 100%: -1,063*	*25%: -60.3 50%: -225.0 75%: -650.4 100%: -1,438.8*
Totals (Compared to Config_2)	*+13 swales*	*+8.0 mm*	*+0.7ha or +1.1%*	-	*-211.9mm in the 100% case*	*25%: -16.3 50%: -4.7 75&100%: same*	*25%: -6 50%: -2 75&100: same*	*25%: same 50%: -31.8 75%: -103.8 100%: -197.8*	*25%: same 50%: -30 75%: -54 100%: -86*	*25%: -16.3 50%: -36.5 75%: -103.8 100%: -197.8*

***Table 7** - Results for Scenario 2 for Configuration #3, the most-intensive swale configuration.*

Compared to Config 2, the addition of only 13 new bioswales intercept a substantial extra portion of the runoff, an additional 211.9mm in the 100% case compared to Config_2. However, CSO overflow still occurs. Interestingly, similar to Config 2, the 50% interception fraction again shows the most promising results, with the lowest net flow out of all of the analyzed interception fractions. While the 75% and 100% cases eliminate CSO entirely, they also lead to volumes of uncontrolled bioswale overflows that cannot be ignored, indicating a need for controlled release mechanisms. This highlights a key tradeoff: while more interception reduces CSOs, excessive retention may cause local surcharges in uncontrolled overflow.

Similar to Configs 1 and 2, Figure 46 shows updated sewer storage capacity over time in the top plot, with colored lines representing the different interception fractions. The bottom plot shows the CSO overflow under the same interception fractions. Compared to the baseline, Config 1, and Config 2, reductions in CSO overflow volumes can be seen for all interception fractions. Visually, compared to the same plots in the Baseline, Config 1, and Config 2, the most striking difference is the improvement that more sewer storage volume is now always available, with significantly less peaks dipping close to maximum sewer storage use. It is a visually less cluttered plot compared to the same of those in previous configurations. Columns 7 and 8 in Table 7 support this as less CSO overflow and instances are seen in this configuration compared to the Baseline, Config 1, and Config 2.

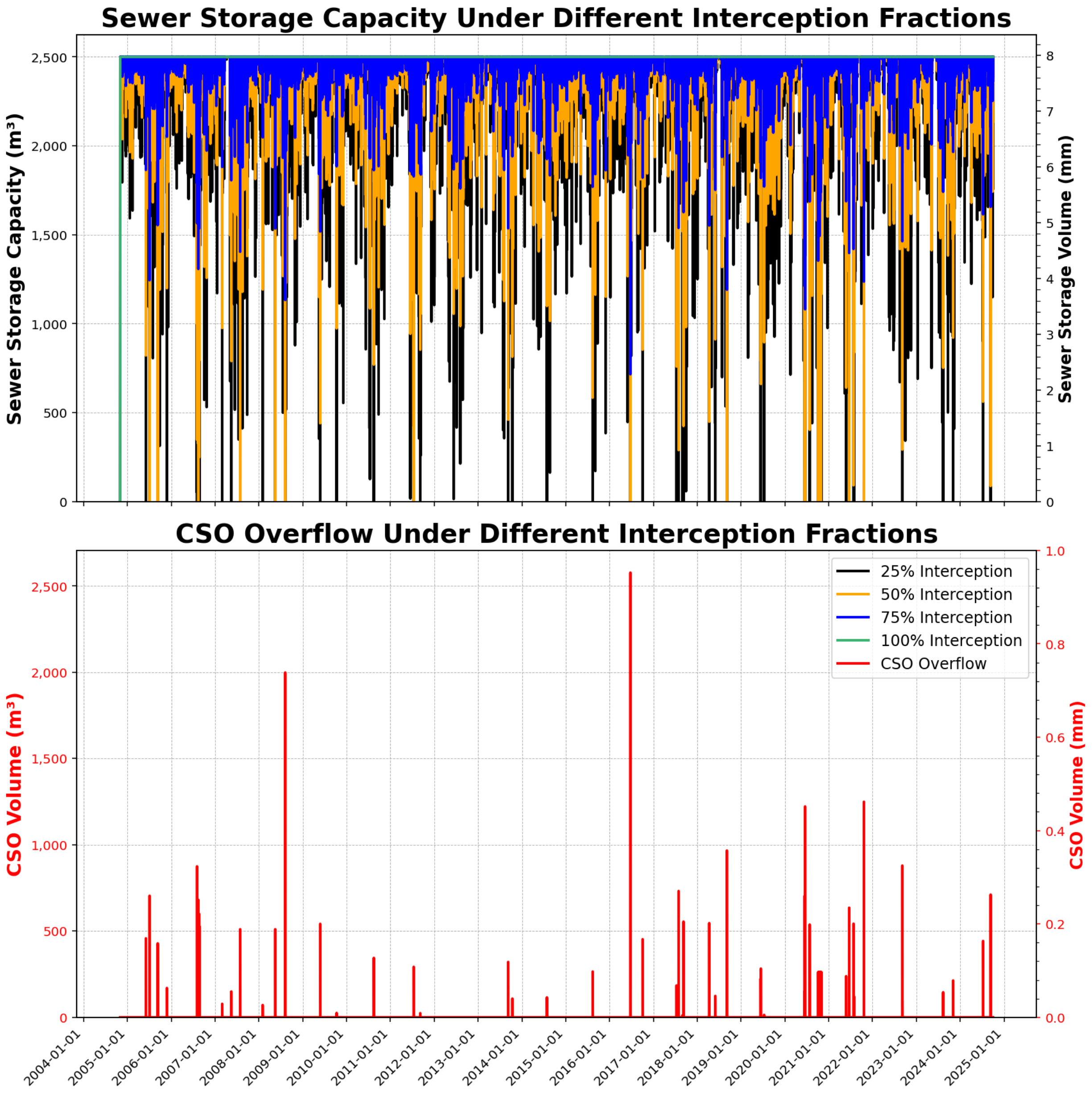

Figure 46 - *The sewer storage capacity and corresponding CSO overflows and events observed for the interception fractions for Config_3.*

Figure 47 (following page) provides two detailed time series of (1) overflow and (2) stored volume in the swales over time across the different interception fractions for Config 3. Compared to the same plots in Config 1 and 2, visually, significantly less overflow events, in terms of frequency and volume are seen, now with only 4, 45, and 95 events in the 50%, 75%, and 100% fractions, respectively. Whereas uncontrolled overflow volumes can still be observed even in this most-intensive swale configuration, the magnitude of these uncontrolled overflow volumes are much less, especially compared to Figure 33. Importantly, in the face of climate change bringing more frequent, higher-yielding precipitation events, it is important to always have redundancy in overflow structures, as there can be such a high-yielding (or frequent succession of) rainfall event that no matter if there are double the swales added which are proposed by this paper, there is always the chance that they will overflow, as the event on October 23, 2020 will shortly demonstrate, below.

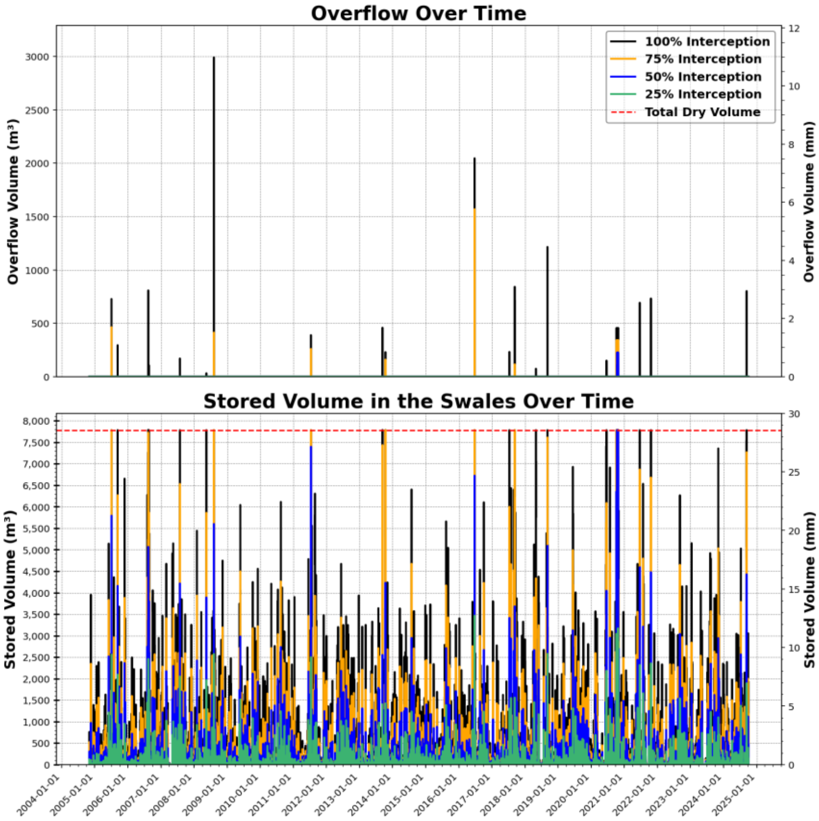

Figure 47 - *Uncontrolled overflow and stored volume over time for the different interception fractions.*

Figure 48 (below) demonstrates the hydrological situation on October 23, 2020. Uncontrolled overflows are still prominent, however less in volume, and as can be seen by the blue line (50% fraction), there is a more pronounced

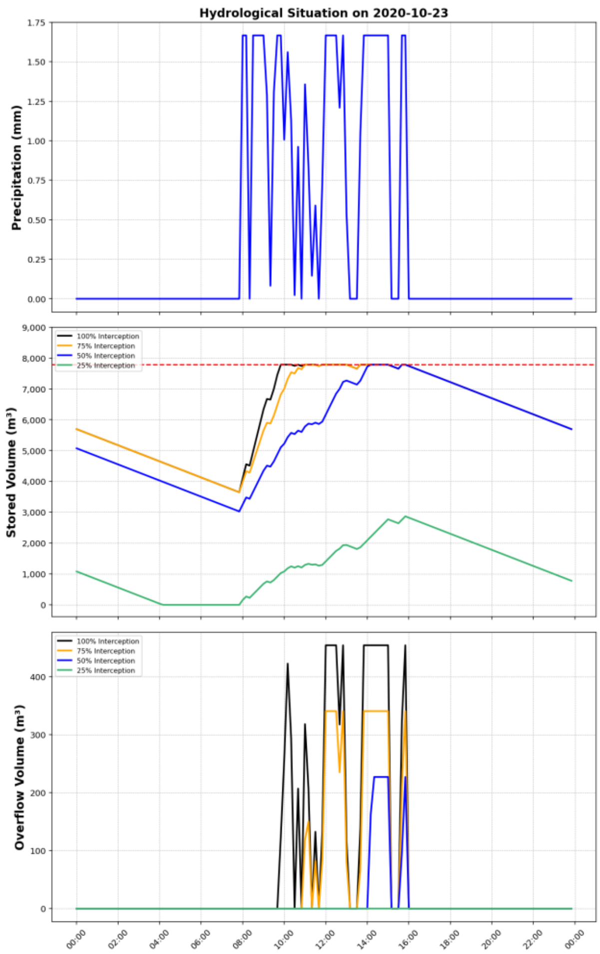

Figure 48 - *The modeled hydrological situation during a significant rainfall event on 2020-10-23, under the uncontrolled overflow scenario.*

delay in when the overflow happens, attesting to the swale's even higher storage capacity in Config 3. This most intensive bioswale configuration, featuring 144 bioswales with the highest overall storage volume analyzed in this paper, bolsters the local hydrological system's vulnerability against intense, rapid rainfall events such as the one on October 23rd, 2020.

6.6.2 Scenario 3 - RTC-Controlled Bioswales

In this section, the impact of RTC on the proposed bioswales is analyzed, focusing on the capacity of RTC to mitigate swale overflow by pre-emptively adjusting stored volumes across the swales.

Results: Scenario 3 (RTC) – Configuration 3

Interception Fraction	*Pre-emptively removed volume by RTC (mm)*	*Remaining uncontrolled overflow volume (mm)*	*Uncontrolled overflow reduction, compared to Scenario 2 (mm)*
25%	0	0	0
50%	4.0	0	-4.0
75%	44.8	23.2	-44.8
100%	117.1	103.9	-100.1

Table 8 *– Results for Scenario 3 (RTC) for Configuration #3.*

Table 8 demonstrates that for the 50% fraction, RTC is completely successful in its role to attenuate and distribute the peak outflows to the canal over time, completely shifting the entire uncontrolled overflow volume to pre-emptied volume. In the rest of the fractions, the RTC successfully reduced the uncontrolled overflows even more, instead re-distributing it over the lead time, as is observed in the following figure.

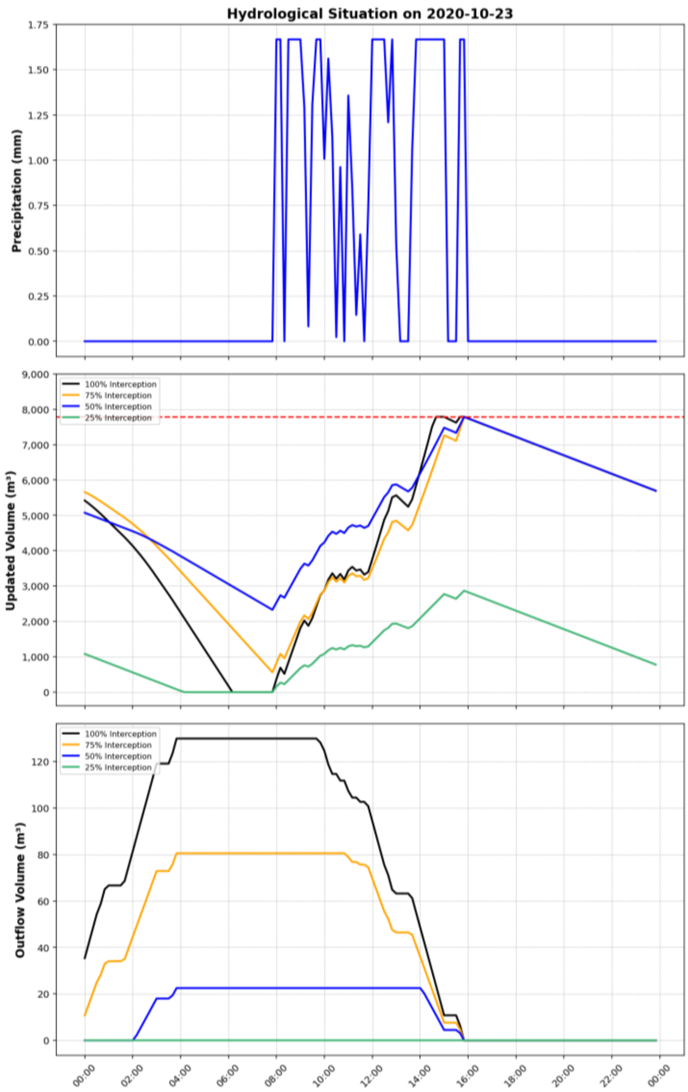

Figure 49 - *Again, the modeled hydrological situation on 2020-10-23, now under the comparison of RTC-controlled bioswale overflow.*

Figure 49 again displays the hydrological situation on October 23, 2020 as was shown in the previous section (Config 3, Scenario 2), but now with the effects of RTC. The RTC system's effectiveness is extremely evident in this specific plot. Similar to Config 2, the 25% fraction requires no pre-emptying, and does not register on the bottom-most subplot. For the yellow (75%) and blue (50%) lines, the RTC behaves as predicted, pre-emptying the perfect stored volume from the swales over the lead time, equivalent to the projected overflow. Both lines gently reach their respective maximums for the swale volumes and do not overflow, decreasing in volume after the precipitation event. There is still uncontrolled overflow for the 100% interception fraction on this day, as despite the RTC pre-emptying all of the stored volume from the swale, the swale is physically not large enough to handle all of the incoming runoff. Overall, this demonstrates an extremely successful (1) forecast done by the model, and (2) re-distribution of existing stored swale volume done by the RTC to use the proposed BGI in the most efficient manner possible. The design of the swales on a neighborhood level have done well to intercept a majority of local stormwater runoff, and the RTC complemented by redistributing projected uncontrolled overflow over time, decreasing local flood risk, allowing for stronger peak attenuation during this rainfall event.

6.6.3 Visual comparison of Scenario 2 and Scenario 3

Similar to the previous configurations, differences between Scenarios 2 and 3 are explored for Config 3, where red histograms and plots represent Scenario 2, while blue histograms and plots correspond to Scenario 3, allowing for a clear visual contrast between the two approaches.

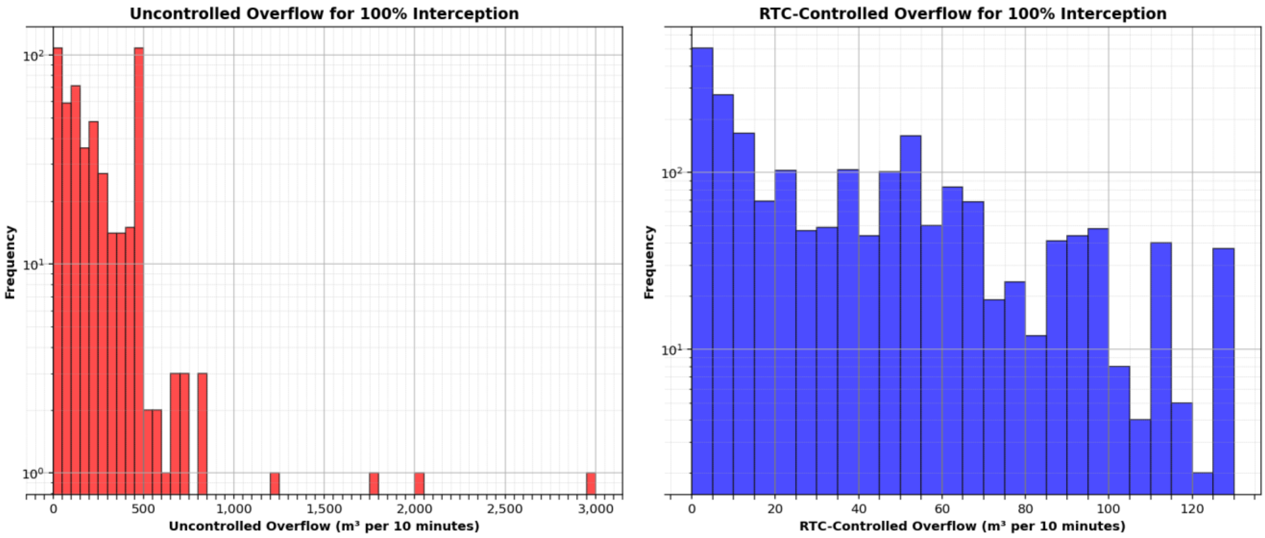

***Figure 50 -** A side-by-side comparison of Scenario 2 (uncontrolled) overflow compared to Scenario 3 (RTC-controlled) overflow results.*

Similar to the same plot in the previous configurations, the left histogram in Figure 50 (uncontrolled overflow) continues to depict a wide spread of data with a very wide x-axis, and with irregular peaks occurring throughout. Comparatively, the right plot (RTC-controlled overflow) continues to spread overflow over time, now with an even lower y-axis than seen for the same plot in Config 2, but with a higher frequency of higher overflow volumes now. The final figure, Figure 51, proves this concept in the same way, demonstrating the difference between Scenarios 2 and 3 using a PDF plot, for both uncontrolled and RTC-controlled overflow. The results are similar to the results of Configs 1 and 2, in that the uncontrolled plot features large volumes on the x-axis with peak events of very large volumes, whereas the RTC-controlled plot features a much lower magnitude x-axis with more consistent releases, demonstrating a smoother distribution of overflow compared to the peaky red plot.

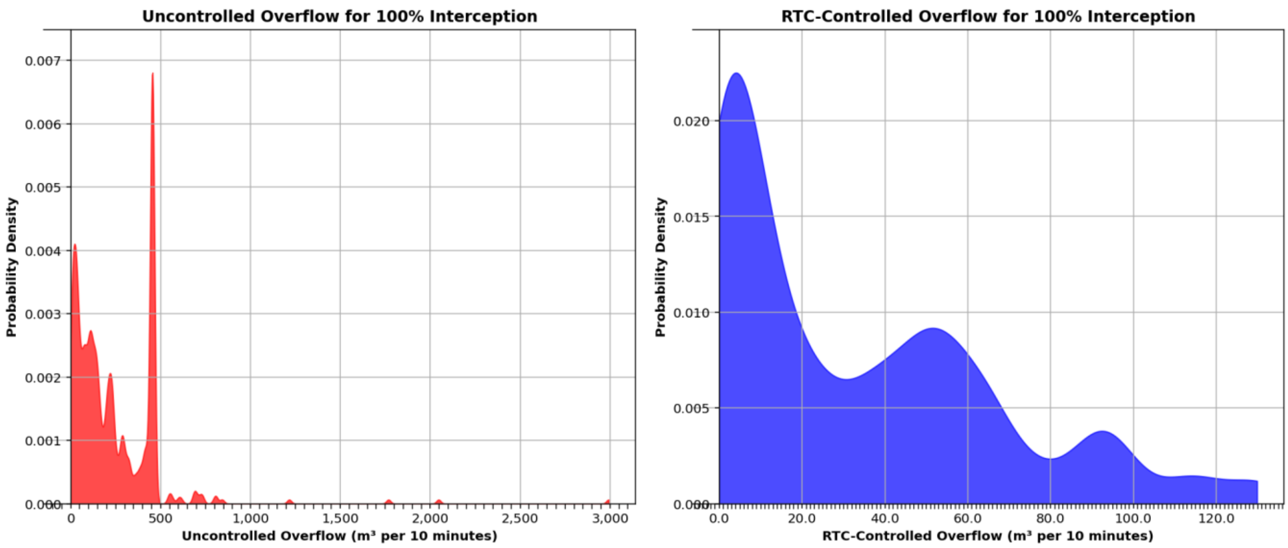

***Figure 51 -** Probability Density Function (PDF) comparison of uncontrolled and RTC-controlled overflow event distributions.*

7 – Discussion

Many factors must be considered when thinking about implementing BGI and RTC in Spangen. On the human side, the attitude of the community towards helping maintain these infrastructures is known from the interview as locals not being invested in maintenance of public greenery. To address this, efforts should focus on leveraging Spangen's existing social institutions to develop and possibly reverse this attitude: the community center "Westervolkshuis", the premier football club "FC Sparta Rotterdam", and local schools including "Kasteel Spangen". The community center can play a key role in coordinating outreach programs and fostering dialogue about the benefits of BGI between citizens and from the municipality to the citizens. Programs such as volunteer work can be drafted through the community center, encouraging local residents of all ages to help develop the green spaces of Spangen. Schools, in particular, could integrate educational programs where children could participate in maintaining green spaces, fostering awareness of stormwater management from a young age. Perhaps even integrating a local garden or bioswale nearby the school could be enough to interest children already, with a large educational board nearby and opportunities for hands-on maintenance. Meanwhile, the football club, with its strong ties to the community and Rotterdam as a city, could serve as a platform for engagement initiatives. Fans could be encouraged to help think about the significance of BGI, and FC Sparta Rotterdam could give back to the community by organizing hands-on BGI maintenance sessions. These locally embedded approaches ensure that BGI maintenance is not solely dependent on municipal maintenance but instead becomes a shared responsibility within the community. Overall, the attitudes of local residents towards changing the existing use of space, and their perception vs. reality of the co-benefits brought about by BGI, must be considered come time for implementation.

For RTC, the benefits need to be tangible and seen, such as through cost savings in sewer maintenance, cost reductions in pump operations, or other real benefits for all stakeholders, like the water board Hoogheemraadschap van Delfland seeing results in local water levels. Furthermore, feasibility of implementation and long-term upkeep must likewise be considered, asking questions such as, "Who will pay for the new BGI and RTC?" or "What kind of maintenance is required by the Gemeente for the BGI/RTC, and what happens if they will not maintain it?".

7.1 Co-benefits of BGI and RTC

As mentioned throughout the report, implementing BGI and RTC will go beyond their intended purposes of local water management. On a more global scale of thinking, the BGI themselves can be looked at as tools to help Rotterdam on the way towards becoming a more climate-resilient city, tools that Rotterdam can implement to help achieve wider sustainability strategies. For example, if the municipality of Rotterdam strives towards a goal of improving green space accessibility, they could use BGI in Spangen to achieve at least five goals in one: (1) planting BGI, (2) perhaps by gathering local residents to help plant them, will (3) increase the green spaces and (4) in turn local livability by providing shade and pleasant green spaces on the streets of Spangen, in order to ultimately (5) help manage stormwater flows and decrease CSS load.

The larger thinking behind this approach is using BGI and RTC as vehicles for change in urban climate resilience, embedding them within Rotterdam's sustainability goals, rather than treating them as standalone interventions with no further purpose than managing stormwater. The very process of integration as well as long term adoption and care, fosters community engagement and strengthens Rotterdam's long-term climate adaptation efforts. The BGI can likewise be looked at as a similar tool come time for Gemeente Rotterdam will look to achieve other goals such as:

- Increasing public green access (in this study, by +1.6%, +3.2%, and up to +4.4%).
- Decreasing urban noise.
- Creating urban habitat space for animals such as birds, insects, and small animals.
- Mitigating urban heat stress by absorbing solar radiation; instead utilizing it for natural purposes such as evapotranspiration, unlike impervious surfaces, which reflect heat back into the atmosphere (Zhang et al., 2021).
- Improving neighborhood appearance thereby increasing property values.
- Increasing engagement of residents and local social organizations to improve and care for their neighborhood.

In the case of the RTC, the RTC can be a step towards integrating technology which is not totally common on a larger scale, connecting the sewer and drainage systems to more effectively and efficiently handle increasing runoff volumes instead of depending on a central source (WWTP) or collection system (CSS) to handle all the runoff. Once the RTC is tested and delivers promising results, as modeled in this thesis, the technology can serve as a method of linking surface to subsurface activity, increasing efficiency in sewer and WWTP operations by providing more insight into the local urban fabric.

7.2 Results in context

This study highlights the potential of integrating real-time control (RTC) with blue-green infrastructure (BGI) to significantly improve urban stormwater management in Spangen. Results demonstrate a two-part improvement: (1) implementing BGI in the neighborhood improves local stormwater management alone by intercepting runoff volumes, reducing CSO volumes and frequency, and (2) implementing RTC control in the form of a valve at the base of the swale overflow structure successfully distributes swale overflow volume over a long time span, reducing local flood risk. The results of this study align with a broader body of scientific literature.

The results align with the work of Moghanlo and Raimondi (2024), who demonstrated that integrating BGI can reduce runoff volumes and peak discharges by 20–50%. Results from this study supports their findings, with the least-intensive proposed configuration of bioswales in Spangen, Configuration 1, reducing the net flow (CSO volume + uncontrolled swale overflow volume) to the local receiving water body from a baseline of 582.5mm to just 240.7mm, a 58.7% reduction, showcasing the standalone effectiveness of BGI in intercepting runoff. This was also seen for the other two proposed configurations as well, further decreasing to 67.8mm and 31.3mm of net flow to the receiving water body. For the runoff, the least-intensive configuration reduced runoff by 3.3%, with the next two configurations reducing the baseline runoff by 6.5% and 8.7%, respectively. However, these decreases are idealized. The model used in this study over-simplified local dynamics (discussed later), likely leading to slightly inflated results, however still demonstrating an alignment in ideas to Moghanlo and Raimondi's 2024 study. Comparatively setting the results of this study against those of Moghanlo and Raimondi, this study found that RTC successfully pre-empties a forecasted volume from the swales over a lead time of 12 hours, however, also that the efficiency of RTC is limited by physical swale size and storage capacity. When RTC was added to Configuration 1 in this study, in the case of the maximum interception fraction, while the RTC successfully pre-emptied 902.2mm from the swales, the system experienced an overall 250.5% increase in total flow to the receiving water body, from 582.5mm to 2,041.1mm. Whereas CSOs were completely removed in this 100% fraction for Configuration 1, this shows that storage volume is a critical factor in designing BGI and RTC systems, and CSO cannot only be looked at to measure the effectiveness of RTC. Effectively, the total volume of outflow (net flow out) to the receiving water body was drastically increased while CSO flow was drastically reduced. Which is an interesting result, in that the overflow type is switched from CSO effluent to clean outflow – treated swale outflow water – however still increasing flood risk from the 250+% increase of net flow out for Configuration 1. For the other two configurations, which had much higher storage volumes compared to Configuration 1, RTC was able to successfully reduce net flow out, by 13.3% from 582.5mm to 505.2mm in Configuration 2, and by 62.1% from 582.5mm to 221mm in Configuration 3. Moghanlo and Raimondi also highlight ecological and societal benefits brought about by BGI, such as enhanced biodiversity, urban beautification, and improved water quality. These findings align with the outcomes observed in Spangen, where bioswales would provide added value by improving urban livability and increasing green space access. Furthermore, bioswales can be adapted as tools in Spangen to accomplish other municipal goals as previously discussed, such as taking back parking spaces, crafting the bioswales in unique designs to tailor to local use of space, and providing shade and green space access.

The ability of RTC to dynamically optimize stormwater systems further aligns with findings of Xu et al. (2020), who demonstrated that RTC could reduce peak discharges in detention basins by up to 30%, with significant improvements in system capacity utilization during storm events. They noted that preemptive releases enabled the systems to handle more rainfall without overwhelming the infrastructure. For Configuration 1, the uncontrolled overflow was reduced from 1,642.7mm to 1,138.8mm with RTC, a 30.7% reduction. For Configuration 2, RTC reduced uncontrolled overflow from 401.7mm to 277.8mm, a 30.8% reduction, and for Configuration 3, from 203.9mm to 103.9mm, a large, 49.1% reduction. However, both Xu et al, and this study observed limitations during consecutive storms, where systems struggled to fully drain before the next rainfall. In the context of this study, further investigation is needed to optimize lead times, outflow rates of the RTC, and physical swale design to increase drainage before the next overflow event. Further investigation is recommended to fine-tune the RTC logic of the valves, investigating combinations of leaving the valves open while more inflow is intercepted, doubly accelerating outflow rates to the nearby water body, something this study did not consider. This study further observed that RTC was not able to pre-empty volume before a projected overflow event if there was no stored volume in the swales, another key limitation. These parallels highlight both the effectiveness and limitations of RTC in managing stormwater volumes but emphasize the need for accurate forecasting and widespread adoption to maximize its potential during storm sequences.

Results of this study are challenged by Almaaitah et al. (2021), who critique the reliance on generalized modeling approaches in BGI research and emphasize the importance of real-world testing. While this study demonstrates significant reductions in CSO volumes, these results are based on a linear reservoir modeling approach that simplifies local hydrodynamics. Almaaitah et al. pointed out that such oversimplifications often fail to capture critical topographic features, such as minor depressions, curb heights, and localized low points even caused by a heavy vehicle rutting the road, which can dramatically influence stormwater flow paths and pooling. This study did not incorporate such highly detailed local elevation data to analyze precise runoff concentration points, potentially introducing errors in stormwater flow modeling and intercepted volume captured by the swales. Future work must address this limitation by integrating finer-scale topographic data to improve hydrological accuracy. Furthermore, Almaaitah et al. identified a broader gap in research focused on smaller urban scales, arguing that most BGI studies prioritize large-scale implementations. Although this study somewhat addresses this gap by introducing different configurations, specifically the low-commitment Configuration 1, it does so without validating findings through real-world testing. Almaaitah et al.'s critique highlights the importance of grounding modeling results in reality and evaluating the feasibility of implementing BGI and RTC systems under practical constraints, also including aspects such as budget and stakeholder coordination, points this study did not explicitly address.

In summary, the results of this study are built upon and can be challenged by findings in broader, related scientific literature, demonstrating that RTC-enhanced BGI systems represent a very feasible and adaptable solution for urban water management, particularly in Spangen. The ability of RTC to complement BGI's inherent benefits, primarily reducing runoff volumes, makes this integration a promising strategy for addressing the dual challenges of flood mitigation and climate resilience. Spangen's results not only validate the effectiveness of these systems but also provide a valuable case study for scaling similar interventions in other urban environments.

7.3 Research limitations

Data limitations are the first research limitation. Namely, (1) the use of meteorological data from a weather station not in Spangen, and (2) the availability of only 14 borehole points to construct the local lithological profile. The meteorological data used in this research was sourced from KNMI weather station #344 – Rotterdam The Hague AP (Station ID: 915096001), approximately 5km from Spangen. This location was chosen over unregulated crowdsourced data, because it is the closest official KNMI weather station to Spangen capable of measuring every type of meteorological data with extreme accuracy. Using crowdsourced station data is risky and could even be completely wrong. Despite this, by using the data gathered from station #344, the model still became slightly less reliable as the actual meteorological amounts in Spangen likely differ due to spatial variability processes. Chaubey et al., (1999) asserts that large uncertainties in estimated model parameter values can be expected if detailed spatial variations in the input rainfall are not considered, which is applicable to this research. The results could have been even drastically different if spatial variability of rainfall had been completely accounted for. Regarding the lithological profile, while the 14 boreholes provided a general understanding of subsurface conditions, this dataset lacked the resolution needed to capture spatial variations in soil composition, permeability, and other factors. It was assumed that swales could be built in the neighborhood given the presence of an unsaturated layer. However, given the heterogeneous nature of urban soils, particularly in historically developed areas like Spangen, a more detailed borehole dataset would have significantly improved the accuracy of the research.

Another critical limitation of this study is the use of simplifications. More specifically: the simplification that all rainfall landing on permeable areas is entirely infiltrated, without accounting for dynamic soil saturation processes, infiltration limitations, or subsequent runoff redistribution. While this compartmentalized approach allowed for a more straightforward modeling framework as was used in this paper, it does not fully reflect the complexities of urban hydrology. In reality, soil infiltration capacity is not static—it decreases as the soil becomes saturated, leading to an increase in surface runoff that may be redirected toward impervious surfaces or into the sewer system. Horton's infiltration theory (Horton, 1933) and subsequent refinements (Philip, 1969) describe how infiltration rates decline exponentially over time as the soil transitions from an initial dry state to a saturated condition. Studies by Beven and Germann (1982) and Smith et al. (1995) further demonstrate that as soil reaches saturation, excess water will generate surface runoff rather than continuing to infiltrate, which is particularly relevant in urban environments where saturated conditions can develop rapidly due to frequent rainfall events and limited deep percolation. The implications of this limitation are significant: rather than serving exclusively as infiltration zones, vegetated areas may intermittently function as secondary runoff sources, directing excess water onto adjacent paved surfaces or into the sewer network. This limitation is particularly relevant when considering the effectiveness of bioswales in mitigating combined sewer overflow (CSO) events. If portions of stormwater that were assumed to infiltrate instead contribute to runoff, the estimated reduction in CSO discharge may be lower than initially modeled.

A third limitation of this research was the interview process. Being that the study was conducted in Rotterdam, NL, a Dutch-speaking city, only one interview was carried out, as the author does not speak Dutch and relied on two translators. Although the interview was insightful and provided valuable results, this is definitely not a representative sample size, and conducting more interviews in the local language with a wider range of residents—varying in age and profile—would provide a better understanding of urban greenery in Spangen. Questions such as, "why is urban greenery not fully maintained by local residents?", "how are green spaces currently used?", and "do residents wish there were more or better green spaces in Spangen?" could uncover different attitudes and preferences. Conducting interviews in English limits participants in expressing their thoughts, which in turn limits the results. Future research should prioritize conducting interviews in Dutch to gain more detailed and representative insights into community perspectives.

A fourth limitation of the research was the oversight to avoid modeling the saturated zone. Whereas a local lithological profile was built, revealing some information about the subsurface, nothing was developed using the saturated zone. With such a promising confined aquifer sitting below the neighborhood, perhaps constructing bioswales could make pumping from surface to the aquifer possible. It is recommended to incorporate terms in the model to better understand the impacts that the saturated groundwater zone has on the rest of the hydrologic system of Spangen, and to explore how BGI and RTC can link to the confined aquifer under the neighborhood.

A final limitation relates to the legal and regulatory constraints surrounding Configuration 3. In this configuration, a key proposal involved reclaiming the green spaces in the historical Van Effen complex in Spangen for the implementation of bioswales by simply depressing the existing green spaces. However, as outlined with various legal sources in the methodology, this approach can be a very gray area, potentially conflicting with existing urban planning policies and heritage preservation regulations. The Van Effen complex is a protected historical site, meaning that any significant modifications to its layout are subject to strict legal scrutiny. This restriction can considerably limit the feasibility of Configuration 3, as it prevents the full realization of a potentially effective intervention. Additionally, the legal barriers highlight a broader challenge in urban water management: balancing innovative stormwater solutions with heritage conservation and existing land-use regulations. Moving forward, a viable strategy could involve negotiating with local authorities to explore the feasibility of implementing bioswales that align with the site's historical character to still be functional BGI, in the end.

7.4 Societal relevance for knowledge users

RTC is an interesting method to fully utilize the available capacity of existing and proposed infrastructure especially in the fields of hydrology and water management. One of the more traditional uses of RTC is to distribute water in a connected system from a place where water level is high/full to a place where water level is low/empty/underutilized, thereby more evenly distributing the water in the system. In this paper, RTC proposed to do similar, to pre-empty a forecasted uncontrolled overflow volume from the existing storage level of the bioswales over a lead time of 12 hours in order to make this volume available to capture incoming runoff. This paper used a perfect forecast over the past 20 years; however, this model can be flipped, fed with live forecasted rainfall in the real-time future. The idea of RTC stands, as instead of keeping stored runoff inside of the swales and risking large, uncontrolled overflow volumes from a future storm event, RTC can be used with a meteorological forecast to calculate overflows ahead of time and adjust stored swale volume accordingly.

The idea of this research can be scaled to any appropriate urban place in the world, especially those receiving regular amounts of yearly rainfall. The feasibility of implementing BGI would first need to be examined through geotechnical data of the subsurface, requiring boring data of the local soil lithology. Once the subsurface can be visualized and understood, a detailed analysis can be conducted in ArcGIS to design the placement of bioswales, and the local hydrological response can then be modeled using the principles and logic of the included model. RTC can be implemented across many different sewer systems in many places around the world, and this is one potential method of how.

8 – Conclusions

8.1 Answers to Research Questions

This research examined how real-time water management control (RTC) can be integrated together with blue-green infrastructure (BGI) in Spangen, Rotterdam, to mitigate local flooding risk and enhance local climate resiliency. The research was structured around four research questions working around a central question, which are explicitly addressed in this section.

The first sub-research question examined the current capacity of the existing combined sewer system (CSS) and combined sewer overflow (CSO) in handling stormwater flows in Spangen in terms of volume and frequency. Results indicated that the existing CSS was frequently overwhelmed over the past 20-year study period, leading to a total of 188 CSO occurrences with a cumulative CSO volume discharge of 582.5 mm. This demonstrates that the existing, CSS-reliant stormwater management system is not effectively able to manage stormwater peaks without overflowing. Ideally, zero CSOs should be occurring whatsoever, and to have the results from this research question reinforces the need for additional stormwater management interventions, especially in the face of climate change bringing more intense rainfall events with increased yields and frequency, only further overwhelming the existing CSS in the near future. Without modifications, the frequency and volume of CSOs will likely not only persist, but increase in volume and frequency, increasing flood risk in Spangen and degrading the local water quality of the receiving water body, threatening public health.

Bioswales could be a potential solution to this problem. The second sub-research question examined how bioswales could be implemented in Spangen across three different configurations, and how these configurations would impact the receiving water body in terms of CSO volume and frequency, and swale uncontrolled overflow volume and frequency. Results from Scenarios 2 per configuration demonstrated that increasing the number of bioswales reduced CSO frequency and volume across all configurations and all interception fractions, showing favorable results for the 25% and 50% interception fractions. However, new challenges were introduced as well. Namely, in Configuration 1, "net flow out" to the receiving water body, defined as the sum of CSO volume and uncontrolled volume, was increased in the 75% and 100% interception fractions. Since the overall storage of this configuration was low, the bioswales were not able to infiltrate all of the runoff they intercepted, discharging this extra stored volume when new inflows were captured. Since the proposed design of all swales featured overflow structures which would convey swale overflow in a dedicated network bypassing the CSS entirely, there was a shift from CSO overflows to uncontrolled overflow volumes in the 75% and 100% interception fractions of Configuration 1. In these specific instances, the decrease in volume and frequency of CSOs was accompanied by an increase in uncontrolled swale volume and frequency. This means that while bioswales are a promising measure for reducing CSO discharge into the receiving water body, they do not fully eliminate the risk of flooding or excessive water level raises unless the storage of the BGIs are sufficient enough to handle the runoff they capture. However, from a water quality perspective, this type of overflow is more favorable compared to CSO overflow, as the swales can already treat the captured stormwater in a preliminary phase, releasing comparatively cleaner overflow to the receiving water body compared to CSOs. Finally, the 25%, 50%, and 50% interception fractions showed the most promising results in the lowest "net flow out" in each configuration, respectively, demonstrating that the best integration of BGI and CSS is one that is balanced. Ideally, if swale coverage extends throughout the entire Spangen neighborhood, the best performance of the BGI and CSS would occur if 50% of runoff would be diverted to swales, and the other 50% to the CSS. This would result in lowest CSOs and lowest uncontrolled overflow, by simply taking back and activating currently impervious space.

The third sub-research question investigated how RTC could optimize peak swale uncontrolled outflows to the local receiving water body, by re-distributing the equivalent forecasted uncontrolled overflow volume over a lead time of 12 hours. In all three configurations, the RTC improved system performance by successfully pre-releasing stored volume ahead of forecasted overflow events, optimizing available swale storage capacity for incoming runoff. In Configuration 1, RTC pre-emptively emptied 902.2 mm from the swales before peak overflow, reducing the uncontrolled volume by 30.7% to 503.9 mm compared to Scenario 2 of the same configuration. By the same trend, the more extensive swale configurations also showed reductions in uncontrolled overflow volumes, with decreases of up to 30.8% and 49.1% in Configurations 2 and 3, respectively. Across all configurations and all interception fractions, RTC successfully reduced uncontrolled overflow volumes by 30–49%, reinforcing its capability to enhance flood mitigation and optimize swale functionality. However, the effectiveness of RTC was inherently limited when there was no stored volume in the swales prior to a forecasted event, meaning that RTC alone cannot mitigate excessive stormwater reaching the CSS without sufficient baseline storage. The results emphasize that RTC should not be seen or used as a standalone solution but rather as an additional tool to be integrated together with the BGI. In this study, a perfect forecast was used however, in the future, by giving BGI a dynamic capability through RTC, responses to rainfall forecasts could be possible as well by programming the RTC to pre-empty a forecasted overflow volume over a lead time. In the end, RTC not only optimizes the use of the proposed BGI but also strengthens the ability of the existing stormwater infrastructure to handle extreme weather events in the face of climate change and gives the municipality more control over CSS and CSO usage.

The final sub-research question explored how the integration of BGI and RTC influences urban livability in Spangen, particularly in relation to public health, green space accessibility, and climate resilience. The findings suggest that BGI implementation increases the accessibility and quality of green space in Spangen, with bioswale implementation increasing permeable surface coverage by up to 4.4%. Beyond stormwater management, BGI and RTC also generate broader co-benefits to improve local livability in Spangen. Tangible livability improvements offered include: (1) improved ecological connectivity by creating habitats for animals and spaces for plants to grow; (2) reduced urban heat stress from absorbing and utilizing solar energy for natural processes like evapotranspiration, instead of reflecting from impervious surfaces and heating the local surroundings to contribute to urban heat island; (3) enhanced overall environmental quality and public health, from improved runoff quality and air quality, and reduced exposure to contaminated water; (4) expanded accessible green spaces, creating more pleasant and visually appealing streets as well as providing mental health benefits; and (5) community-building opportunities, fostering a more connected and community-oriented environment, also contributing to increased mental health with a new support system by affording the opportunity to interact with others to work on a collective goal. Additionally, BGI provides passive cooling benefits, which can be particularly beneficial in dense urban settings like Spangen, reducing energy demand for artificial cooling in nearby residential and commercial buildings. The introduction of green infrastructure can also help mitigate noise pollution, as vegetation serves as a natural sound barrier that dampens urban noise, creating a quieter and more comfortable environment for residents. RTC improves quality of life by: (1) reducing peak uncontrolled overflow events in number and volume, preventing street flooding "water op straat" which improves pedestrian comfort and reduces disruptions to daily life, including commuting and business activity; and (2) limiting public contact and exposure to contaminated water urban waterways, reducing health risks associated with CSO overflows. Furthermore, RTC optimizes stormwater flow in real time, minimizing damage to infrastructure caused by excessive flooding and erosion, ultimately reducing maintenance costs and prolonging the lifespan of urban drainage systems. Beyond these immediate benefits, the implementation of BGI offers an opportunity to foster civic pride and long-term community stewardship. By involving local residents, schools, and organizations in the design, maintenance, and education around green infrastructure, BGI can encourage a stronger sense of ownership over public spaces. When residents are directly engaged in the transformation of their neighborhoods, whether through tree planting initiatives, community maintenance programs, or educational workshops, there is a higher likelihood of long-term investment and care, ensuring that the benefits of these interventions extend far beyond their initial implementation. For the municipality of Rotterdam and for Rotterdam as a whole, adopting these strategies aligns with broader climate adaptation planning, demonstrating how nature-based solutions and smart water management can work in tandem to create more livable, sustainable cities. The findings of this study emphasize the necessity of this transition, positioning BGI and RTC as essential components of Rotterdam's strategy for a more resilient, livable, and adaptive urban future.

8.2 Practical Considerations

For bioswale implementation in Spangen to be fully effective, several key steps must be taken. Future research should incorporate detailed elevation data and localized runoff concentration points in the model to validate the practical integration of BGI and RTC in a specific configuration. Costs and governance policies must also be reviewed, such as to consider the historical and archaeological worth of the neighborhood. Local residents are recommended to further be interviewed to reveal key insights into how green spaces are currently used. The most important consideration when work begins to construct bioswales, is to construct an independent bioswale overflow conveyance system, directing bioswale overflows into the surrounding singel of Spangen and the Delfshavense Schie rather than allowing them to travel back into the CSS, further contributing to CSOs. Finally, RTC must be deployed in conjunction with physical infrastructure changes to realize its full benefits, as it presents a promising method for optimizing bioswale performance. This study highlights the need for an integrated approach to urban stormwater management, balancing BGI with RTC adaptation. While bioswales reduce CSS burden, their success ultimately depends on RTC modeling, regulatory constraints, and forecast feasibility in a way that aligns with the urban landscape of Spangen. The idea of this research is to provide the Spangen neighborhood, moreover Gemeente Rotterdam, with another set of tools, RTC and BGI, to help the city achieve bigger sustainability strategies. Only time will tell if people will walk alongside bioswales on the neighborhood streets of Spangen in the next few years.

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Appendix I – Interview questions

Prepared questions for semi-structured interview
About the impacts of including more **green spaces** and **BGI** in Spangen

< Westervolkshuis >

In 2018, a new, public, interactive GW supply was built in front of the Westervolkshuis.

- Might you know why this was built?
- What kind of impacts has this infrastructure had on the Spangen community?
- Children now play on the new artificial turf football pitch next to the Westervolkshuis. Other than this impact, what kind of before/after can you think of that this project has created?
- How have residents interacted with it?

< Water management >

- What are some challenges in managing local water resources?
- Has there ever been flooding in Spangen?
  - ...caused by rainfall? (not being able to be drained)
  - ...caused by local canals?
  - ...caused by Maas?
- To what extent are you worried about flooding in Spangen?
- How prepared is the neighborhood to respond to flooding in case it happens?

< BGI >

- I want to propose more BGI in this neighborhood. (Swales along the street, re-working intersection corners to have green infiltration pits, incorporating gardens on the sidewalk, and more). How do you think local residents will respond to this?
  - Might they be hostile to this change? Or welcoming?
  - Why?
- How eager would residents be to work on new green spaces to maintain them?
- In general, are residents of Spangen engaged with the community?
  - Does everyone work together to make Spangen more beautiful?
  - Does everyone work together to help maintain Spangen's public areas?
  - What is the community engagement scheme?
- Are BGIs a necessity in Spangen?
- Have the locals complained about the lack of green spaces, or too much pervious area?
- Right next to the Westervolkshuis is a school. What kind of opportunity would exist for children to learn about, use, or work on BGI if it was built locally?

< Other >

- How well does Gemeente Rotterdam respond to maintenance requests in the area?
- How is the relationship between Gemeente Rotterdam and Spangen residents?

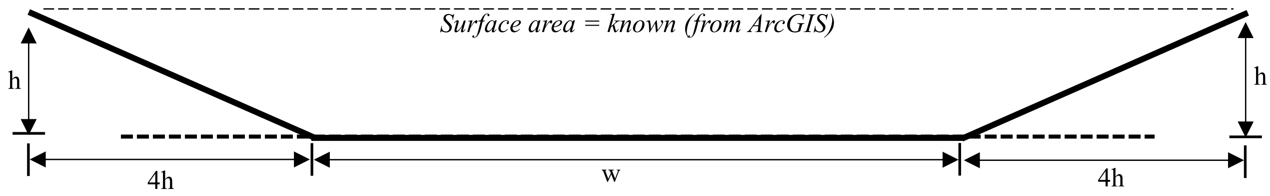
Appendix II – Interview Results

- Spartastraat makes green, tram is very Important
- Maxim tandarts to make it greener
- very wide streets, make something green, more trees
- very dirty streets
- make something streets one way, take back streets
- 40 years
- nooit wateroverlast
- never once flooding
- more plants, more trees
- water reservoir, never any water there
- nobody wants to take care of it on their own
- only one place
- is some room for green

Translator names redacted for privacy

Interviewee name redacted for privacy

Appendix III – Swale Depth Derivation



$$xc_{area} = 2\left(\frac{4h(h)}{2}\right) + w(h)$$
$$= 4h^2 + w(h)$$
$$= h(4h + w)$$

Since surface area is known (ArcGIS) and since volume = depth*(surface area)

$$volume_{swale} = (h)(surface\_area) - 2\left(\frac{4h(h)}{2}\right)$$
$$= h(surface\_area) - 4h^2$$
$$= h(surface\_area\ - 4h)$$

Appendix IV – Python Script to Access 10-minute Precipitation Data

"Meteo data - actual synoptic observations KNMI the Netherlands per 10 minutes" from
https://dataplatform.knmi.nl/dataset/actuele10mindataknmistations-2

"Precipitation - duration, amount and intensity at a 10 minute interval" from
https://dataplatform.knmi.nl/dataset/neerslaggegevens-1-0

```
import asyncio
import logging
import os
import requests
from concurrent.futures import ThreadPoolExecutor
from pathlib import Path
from typing import Any, Dict, List, Tuple
from requests import Session
#
logging.basicConfig()
logger = logging.getLogger(__name__)
logger.setLevel(os.environ.get("LOG_LEVEL", logging.INFO))
#
def download_dataset_file(
    session: Session,
    base_url: str,
    dataset_name: str,
    dataset_version: str,
    filename: str,
    directory: str,
    overwrite: bool,
) -> Tuple[bool, str]:
    #If a file from this dataset already exists, skip downloading it
    file_path = Path(directory, filename).resolve()
    if not overwrite and file_path.exists():
        logger.info(f"Dataset file '{filename}' was already downloaded.")
        return True, filename
#
    endpoint                                                                =
f"{base_url}/datasets/{dataset_name}/versions/{dataset_version}/files/{filename}/url"
    get_file_response = session.get(endpoint)
#
    if get_file_response.status_code != 200:
        logger.warning(f"Unable to get file: {filename}")
        logger.warning(get_file_response.content)
        return False, filename
#
    download_url = get_file_response.json().get("temporaryDownloadUrl")
    return download_file_from_temporary_download_url(download_url, directory, filename)
#
def download_file_from_temporary_download_url(download_url, directory, filename):
    try:
        with requests.get(download_url, stream=True) as r:
            r.raise_for_status()
            with open(f"{directory}/{filename}", "wb") as f:
                for chunk in r.iter_content(chunk_size=8192):
                    f.write(chunk)
    except Exception:
        logger.exception("Unable to download file using download URL")
        return False, filename
#
    logger.info(f"Downloaded dataset file '{filename}'")
    return True, filename
#
def list_dataset_files(
    session: Session,
    base_url: str,
    dataset_name: str,
    dataset_version: str,
    params: Dict[str, str],
) -> Tuple[List[str], Dict[str, Any]]:
    logger.info(f"Retrieve dataset files with query params: {params}")
#
    list_files_endpoint = f"{base_url}/datasets/{dataset_name}/versions/{dataset_version}/files"
    list_files_response = session.get(list_files_endpoint, params=params)
#
```

```
    if list_files_response.status_code != 200:
        raise Exception("Unable to list initial dataset files")
#
    try:
        list_files_response_json = list_files_response.json()
        dataset_files = list_files_response_json.get("files")
        dataset_filenames = [file.get("filename") for file in dataset_files]
        return dataset_filenames, list_files_response_json
    except Exception as e:
        logger.exception(e)
        raise Exception(e)
#
def get_max_worker_count(filesizes):
    size_for_threading = 10_000_000  # 10 MB
    average = sum(filesizes) / len(filesizes)
    if average > size_for_threading:
        threads = 1
    else:
        threads = 10
    return threads
#
async def main():
    api_key= "eyJvc…" #put your API key here, my full API key is redacted for privacy
    dataset_name = "neerslaggegevens"
    dataset_version = "1.0"
    base_url = "https://api.dataplatform.knmi.nl/open-data/v1"
    overwrite = False
    #
    download_directory = "./dataset-download"
    #
    session = requests.Session()
    session.headers.update({"Authorization": api_key})
    if not Path(download_directory).is_dir() or not Path(download_directory).exists():
        raise Exception(f"Invalid or non-existing directory: {download_directory}")
   #
    filenames = []
    max_keys = 500
    next_page_token = None
    file_sizes = []
    #
    while True:
        dataset_filenames, response_json = list_dataset_files(
            session,
            base_url,
            dataset_name,
            dataset_version,
            {"maxKeys": f"{max_keys}", "nextPageToken": next_page_token},
        )
        file_sizes.extend(file["size"] for file in response_json.get("files"))
        filenames += dataset_filenames
        #
        next_page_token = response_json.get("nextPageToken")
        if not next_page_token:
            logger.info("Retrieved names of all dataset files")
            break
    #
    logger.info(f"Number of files to download: {len(filenames)}")
    #
    worker_count = get_max_worker_count(file_sizes)
    loop = asyncio.get_event_loop()
    #
    executor = ThreadPoolExecutor(max_workers=worker_count)
    futures = []
    #
    for dataset_filename in filenames:
        future = loop.run_in_executor(
            executor,
            download_dataset_file,
            session,
            base_url,
            dataset_name,
            dataset_version,
            dataset_filename,
            download_directory,
            overwrite,
        )
```

```
        futures.append(future)
    #
    future_results = await asyncio.gather(*futures)
    logger.info(f"Finished '{dataset_name}' dataset download")
    #
    failed_downloads = list(filter(lambda x: not x[0], future_results))
    #
    if len(failed_downloads) > 0:
        logger.warning("Failed to download the following dataset files:")
        logger.warning(list(map(lambda x: x[1], failed_downloads)))
#
if __name__ == "__main__":
    asyncio.run(main())
```

Appendix V – Full Python Modeling Script

**Note before running: This script can take up to 140 minutes to run, typically around 90 to 95 minutes with the given precipitation and swale input data. Actual runtime depends on processing power. It was tested on a system with an AMD Ryzen 7 7730U processor with 8 cores and 16 threads, a base clock speed of 2.0 GHz and a boost clock of up to 4.5 GHz. The system has 16 GB of DDR4 RAM and a 512GB Samsung MZAL4512HBLU-00BL2 SSD.*

```
import os
import time
import math
import numpy as np
import pandas as pd
from datetime import datetime
import matplotlib.pyplot as plt
import matplotlib.image as mpimg
import matplotlib.dates as mdates
from scipy.stats import gaussian_kde
from matplotlib.ticker import AutoMinorLocator, MultipleLocator, FuncFormatter
start_clock_time = datetime.now().strftime("%H:%M:%S on %B %d, %Y")
start_time = time.time()
os.chdir('C:/Python_Thesis')
pd.set_option('display.max_columns', None)
#
#Figure 1: Spangen aerial photograph
img = mpimg.imread("Spangen Greenery.jpg")
plt.imshow(img)
plt.axis('off')
plt.show(block=False)
#
#Global variables
project_area = 600102  # total area of Spangen (m²), calculated using ArcGIS
project_area_ha = (project_area) / 10000
DWF = 108  #(m³/hr)
storage = 2500  #storage capacity of sewer (m³)
pump = 580  #pumping capacity (m³/hr)
DWF_10 = (DWF)/6
pump_10 = (pump)/6
file_name = "Rainfall_Data.csv"
data = pd.read_csv(file_name, low_memory=False)
data['DateTime'] = pd.to_datetime(data['# DTG'] + ' ' + data.iloc[:, 1], format='%m/%d/%Y
%H:%M:%S')
data = data.drop(columns=['# DTG', data.columns[1]])
data = data[['DateTime'] + [col for col in data.columns if col != 'DateTime']]  # Move
'DateTime' to the front
precipitation = data.iloc[:, 11]  # extract precipitation data from column M (12th index)
max_precipitation = precipitation.max()
max_precipitation_date = data['DateTime'][precipitation.idxmax()]
total_precipitation = data['Precipitation (mm)'].sum()
P = data['Precipitation (mm)']
rain_event_threshold_mm = 0.1 * 25.4 #Rain event is >0.1 inches (2.54mm),
https://ercweb.com/regulations/show/What-Qualifies-as-a-Storm-Event-for-Stormwater-Sampling
cumulative_rain = 0
rain_event_count = 0
for i in range(len(data)):
    if data['Precipitation (mm)'].iloc[i] > 0:
        cumulative_rain += data['Precipitation (mm)'].iloc[i]
        if cumulative_rain >= rain_event_threshold_mm:
            rain_event_count += 1
            cumulative_rain = 0
    else:
        cumulative_rain = 0
#
#Figure 2: Plotting P time series
plt.figure(figsize=(12, 6))
plt.plot(data['DateTime'], data['Precipitation (mm)'], label='Precipitation (mm)', color='blue')
plt.title('Time Series of Precipitation in Spangen', fontsize=20, fontweight='bold')
plt.ylabel('Precipitation (mm)', fontsize=13, fontweight = 'bold')
plt.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
plt.annotate(f'Max: {max_precipitation:.2f} mm\n{max_precipitation_date.strftime("%Y-%m-%d
%H:%M:%S")}',
             xy=(max_precipitation_date, max_precipitation),
             xytext=(max_precipitation_date + pd.Timedelta(days=30), max_precipitation - 1.7),
             arrowprops=dict(facecolor='black', arrowstyle='->', shrinkA=0, shrinkB=5),
             fontsize=12, fontweight='bold',
```

```
             ha='left')
plt.legend(facecolor='black', edgecolor='black', fontsize=12, loc='best', labelcolor='white',
fancybox=True)
start_date = '2004-11-01'
end_date = '2024-10-01'
ax = plt.gca()
plt.ylim(bottom=0)
plt.xlim(pd.Timestamp(start_date), pd.Timestamp(end_date))
ax.xaxis.set_major_locator(mdates.YearLocator())
ax.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
ax.tick_params(axis='x', length=10, width=1.5)
ax.yaxis.set_major_locator(MultipleLocator(1))
ax.yaxis.set_minor_locator(AutoMinorLocator(2))
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show(block=False)
#
#Figure 3: Plotting P distribution
plt.figure(figsize=(8, 6))
n, bins, patches = plt.hist(precipitation, bins=np.arange(0, max_precipitation + 0.5, 0.5),
edgecolor='black', log=True)
plt.title('Rainfall Intensity Distribution in Spangen', fontsize=16, fontweight='bold')
plt.xlabel('Precipitation in 10 minutes (mm)', fontsize=12, fontweight='bold')
plt.ylabel('Frequency', fontsize=12, fontweight='bold')
plt.grid(True, which='major', linestyle='--', linewidth=0.5)
ax = plt.gca()
ax.set_yscale('log')
ticks = [1, 10, 100, 1000] + [10**i for i in range(4, int(np.log10(ax.get_ylim()[1])) + 1)]
ax.set_yticks(ticks)
ax.get_yaxis().set_major_formatter(plt.FuncFormatter(lambda y, _: f'{y:,.0f}'))
ax.xaxis.set_major_locator(MultipleLocator(0.5))
ax.set_xlim(left=0)
ax.yaxis.grid(which='minor', linestyle='--', linewidth=0.5)
for i in range(len(patches)):
    height = n[i]
    if height > 0:
        if height > 1000:
            x_text = patches[i].get_x() + patches[i].get_width() / 2
            ha_position = 'left'
        else:
            x_text = patches[i].get_x() + patches[i].get_width() / 2
            ha_position = 'center'
        plt.text(x_text, height, f'{int(height):,}',
                 ha=ha_position, va='bottom', fontsize=8, color=patches[i].get_facecolor(),
fontweight='bold')
ax.tick_params(axis='x', length=10, width=1.25)
plt.xticks(rotation=45, ha='right')
plt.show(block=False)
#
print("Welcome to the thesis analysis of Spangen, Rotterdam, NL, by Jacob Zakrzewicz")
print("Let's begin with some basic project and area information.")
print("\n" + "="*50)
print("           PROJECT & AREA INFORMATION")
print("="*50 + "\n")
print("Figure 1 depicts Spangen, the study neighborhood, with the surroundings shaded in color,
for contrast.")
print(f"The total project area is: {project_area_ha:.2f} ha")
print("The study period of data is: November 01, 2004, 00:00 until October 01, 2024, 00:00, a
month shy of 20 years.")
print(f"Figure 2 shows a times series of the total precipitation over the study period, the
total resulting: {total_precipitation:,.2f} mm.")
print(f'Total number of rain events, defined as >0.1 inches (2.54mm), during this study period:
{rain_event_count:,}')
print("Figure 3 demonstrates the distribution of rainfall events over time.")
print("This precipitation results in the following runoff situation, CSO usage, and effects on
the surrounding surface water.")
#
#
######################### CURRENT SCENARIO (NO SWALE, EXISTING-STATE) #########################
#
per_area = 301521.94  # total pervious area of Spangen (m²), calculated using ArcGIS and Excel
by summing up areas of all green spaces in ArcGIS
imp_area = 298580.54  # total impervious area of Spangen (m²)
per_area_ha = (per_area) / 10000
per_area_percentage = per_area / project_area
imp_area_ha = (imp_area) / 10000
```

```
imp_area_percentage = imp_area / project_area
DWF_mm = (DWF)*(1/6)*(1/imp_area)*(1000)  #DWF, mm/10min
storage_mm = (storage)*(1/imp_area)*(1000)  #maximum storage capacity (mm)
pump_mm = (pump)*(1/6)*(1/imp_area)*(1000)  #max pumping in mm/10min
surface_flow = P * imp_area_percentage
transformed_surface_flow = surface_flow * (1 / 1000) * project_area #runoff in m³
data['Surface_Flow'] = surface_flow
data['Runoff (m³)'] = transformed_surface_flow
total_sf = data['Surface_Flow'].sum() #net runoff in mm
total_runoff = data['Runoff (m³)'].sum()
#
print("\n" + "="*50)
print("                 SCENARIO 1")
print("="*50 + "\n")
print("Scenario 1 represents the current situation, with existing permeable and impermeable
areas as of October 2024.")
print("We will use these numbers to calculate the runoff, CSO usage, and other variables over
the 20-year study period from November 1, 2004 to October 1, 2024.")
print("")
print(f"Referencing ArcGIS data, the calculated pervious, green area of Spangen is:
{per_area_ha:.2f} ha.")
print(f"That's {per_area_percentage * 100:.2f}% of the total area.")
print(f"The analyzed impervious area of Spangen is: {imp_area_ha:.2f} ha")
print(f"That's {imp_area_percentage * 100:.2f}% of the total area.")
print("")
print("Now, let's look at some info about the local sewer system.")
print(f"The DWF of the local CSS is {DWF} m³/hr.")
print(f"Or, {DWF_10:.0f} m³/10min, which is equal to {DWF_mm:.2f} mm/10 min.")
print(f"The maximum storage capacity of the local CSS is {storage} m³.")
print(f"Or, {storage_mm:.2f} mm.")
print(f"The maximum WWTP pumping capacity is {pump} m³/hr.")
print(f"Or, {pump_10:.2f} m³/10min, which is equal to {pump_mm:.2f} mm/10min.")
print(f'The total runoff over this time was: {total_sf:,.2f} mm, equivalent to
{total_runoff:,.2f} m³.')
print("")
#
#Figure 4: Dual-axis graph of surface runoff in mm and m³
def format_func(value, tick_number):
    if value.is_integer():
        return f'{int(value)}'
    else:
        return f'{value:,.2f}'
fig, ax1 = plt.subplots(figsize=(12, 6))
ax1.plot(data['DateTime'], surface_flow, label='Runoff (mm)', color='green')
ax1.set_ylabel('Runoff (mm)', fontsize=13, fontweight='bold')
ax1.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
ax1.set_xlim(data['DateTime'].min(), data['DateTime'].max())
ax1.xaxis.set_major_locator(mdates.YearLocator())
ax1.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
ax1.tick_params(axis='x', rotation=45)
plt.xticks(rotation=45, ha='right')
ax1.tick_params(axis='x', which='major', length=10)
ax1.set_ylim(bottom=0)
ax2 = ax1.twinx()
ax2.set_ylabel('Runoff (m³)', fontsize=13, fontweight='bold')
ax2.set_ylim(0, transformed_surface_flow.max())
ax2.yaxis.set_major_formatter(FuncFormatter(format_func))
plt.title('Time Series of Runoff in Spangen', fontsize=20, fontweight='bold')
max_surface_flow = surface_flow.max()
max_surface_flow_date = data['DateTime'][surface_flow.idxmax()]
max_transformed_surface_flow = transformed_surface_flow[surface_flow.idxmax()]
ax1.annotate(f'Max: {max_surface_flow:.2f} mm / {max_transformed_surface_flow:,.2f}
m³\n{max_surface_flow_date.strftime("%Y-%m-%d %H:%M:%S")}',
             xy=(max_surface_flow_date, max_surface_flow),
             xytext=(max_surface_flow_date + pd.Timedelta(days=25), max_surface_flow - 0.9),
             arrowprops=dict(facecolor='black', arrowstyle='->', shrinkA=0, shrinkB=5),
             fontsize=12, fontweight='bold', ha='left')
plt.tight_layout()
plt.show(block=False)
#
####CSO modeling
data['DWF'] = DWF_10
data['Sewer_Storage_Capacity'] = float(storage)
data['Pump_Power'] = 0.0
data['CSO_Volume'] = 0.0
total_cso_volume_1 = 0.0
```

```
group_count_1 = 0
is_in_group = False
time_step_minutes = 10
group_time_window = 5 * 60 // time_step_minutes

for i in range(1, len(data)):
    if data.loc[i - 1, 'Sewer_Storage_Capacity'] > 2426.3:
        pump_power = 29.16 #this is DWF cap in 10min
    elif data.loc[i-1, 'Sewer_Storage_Capacity'] > 1946.6: #if the capacity left is more than
1946, but less than 2426
        pump_power = 63.4 #New step in the pump curve in 10min
    else:
        pump_power = 96.66 #Make use of all capacity active
    data.loc[i, 'Pump_Power'] = pump_power
    previous_capacity = data.loc[i - 1, 'Sewer_Storage_Capacity']
    runoff = data.loc[i, 'Runoff (m³)']
    new_capacity = previous_capacity + pump_power - runoff - DWF_10
    if new_capacity < 0:
        data.loc[i, 'CSO_Volume'] = abs(new_capacity)
        total_cso_volume_1 += abs(new_capacity)
        new_capacity = 0
        if not is_in_group:
            is_in_group = True
            group_count_1 += 1
            last_cso_time = i
        elif i - last_cso_time > group_time_window:
            group_count_1 += 1
            last_cso_time = i
    else:
        if is_in_group and i - last_cso_time > group_time_window:
            is_in_group = False
    data.loc[i, 'Sewer_Storage_Capacity'] = min(new_capacity, storage)
print(f"Total CSO overflow volume: {total_cso_volume_1:,.2f} m³")
print(f"CSO overflow volume in mm: {(total_cso_volume_1/project_area)*1000:,.2f} mm")
print(f"Number of times CSO use occurred: {group_count_1}")
#
#Figure 5: Plot pumping activity
fig, ax = plt.subplots(figsize=(12, 6))
plt.title('Pump Activity Over Time', fontsize=20, fontweight='bold')
ax.plot(data['DateTime'], data['Pump_Power'], color='blue', linestyle='-', label='Pump Power
(m³/10 min)', alpha=0.8)
ax.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
ax.set_ylabel('Pump Power (m³/10 min)', fontsize=15, color='blue', fontweight='bold')
ax.set_xlim(data['DateTime'].min(), data['DateTime'].max())
ax.xaxis.set_major_locator(mdates.YearLocator())
ax.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
ax.tick_params(axis='x', rotation=45)
plt.xticks(rotation=45, ha='right')
ax.tick_params(axis='x', which='major', length=10)
plt.tight_layout()
plt.show(block=False)
#
#Figure 6: Plot sewer storage time series
data['CSO_Overflow'] = data['Sewer_Storage_Capacity'].apply(lambda x: -x if x < 0 else 0)
fig, ax1 = plt.subplots(figsize=(12, 6))
ax1.plot(data['DateTime'], data['Sewer_Storage_Capacity'], label='Sewer Storage Capacity (m³)',
color='black', alpha=0.2)
ax1.set_ylabel('Sewer Storage Capacity (m³)', fontsize=15, color='gray', fontweight='bold')
ax1.tick_params(axis='y', labelcolor='gray')
ax1.grid(which='both', color='dimgrey', linestyle='--', linewidth=0.5)
ax2 = ax1.twinx()
ax2.plot(data['DateTime'], data['CSO_Overflow'], label='CSO Overflow (m³)', color='red',
linestyle='-', alpha=0.8)
ax2.fill_between(data['DateTime'], 0, data['CSO_Overflow'], where=(data['CSO_Overflow'] > 0),
color='red', alpha=0.3)
ax2.plot(data['DateTime'], data['CSO_Volume'], color='red', linestyle='-', alpha=0.8)
ax2.set_ylabel('CSO Volume (m³)', fontsize=15, color='red', fontweight='bold')
ax2.tick_params(axis='y', labelcolor='red')
for label in ax1.get_yticklabels():
    label.set_fontweight('bold')
for label in ax2.get_yticklabels():
    label.set_fontweight('bold')
plt.title('Sewer Storage Capacity and CSO Overflow in Spangen', fontsize=20, fontweight='bold')
ax1.set_xlim(data['DateTime'].min(), data['DateTime'].max())
ax1.xaxis.set_major_locator(mdates.YearLocator())
ax1.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
```

```
ax1.tick_params(axis='x', rotation=45, labelsize=10)
plt.setp(ax1.get_xticklabels(), ha='right')
ax1.set_ylim(bottom=0)
ax2.set_ylim(bottom=0)
ax1.yaxis.set_major_formatter(lambda x, _: f'{int(x):,}')
ax2.yaxis.set_major_formatter(lambda x, _: f'{int(x):,}')
lines_1, labels_1 = ax1.get_legend_handles_labels()
lines_2, labels_2 = ax2.get_legend_handles_labels()
ax1.tick_params(axis='x', which='major', length=10)
ax2.legend(lines_1 + lines_2, labels_1 + labels_2, loc='upper right', fontsize=12)
plt.tight_layout()
plt.show(block=False)
#
#Figure 7: Boolean chart of CSO usage
cso_usage = data['CSO_Volume'] > 0
plt.figure(figsize=(12, 6))
plt.title('Boolean Time Series of CSO Usage in Spangen', fontsize=20, fontweight='bold')
plt.plot(data['DateTime'], cso_usage.astype(int), label='CSO Usage', color='orange')
plt.ylabel('CSO Usage (0 = Not used, 1 = Used)', fontsize=13, fontweight = 'bold')
plt.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
plt.xlim(data['DateTime'].min(), data['DateTime'].max())
ax = plt.gca()
ax.xaxis.set_major_locator(mdates.YearLocator())
ax.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
ax.yaxis.set_major_locator(MultipleLocator(1))
ax.yaxis.set_minor_locator(AutoMinorLocator(2))
plt.xticks(rotation=45, ha='right')
plt.tight_layout()
plt.show(block=False)
#
#Figure 8: Zoom in on June 23, 2016, a random date with a CSO event, to examine the hydrological
situation
zoom_in_date = '2016-06-23'
start_zoom = pd.Timestamp(f'{zoom_in_date} 23:00:00') - pd.Timedelta(days=1)
end_zoom = pd.Timestamp(f'{zoom_in_date} 12:00:00')
data_zoomed = data[(data['DateTime'] >= start_zoom) & (data['DateTime'] < end_zoom)]
fig, axes = plt.subplots(5, 1, figsize=(9, 11), sharex=True)
axes[0].set_title(f'Hydrological situation on {zoom_in_date}', fontsize=14, fontweight='bold')
axes[0].plot(data_zoomed['DateTime'], data_zoomed['Precipitation (mm)'], color='blue')
axes[0].set_ylabel('Precipitation (mm)', fontsize=10, fontweight='bold')
axes[0].set_yticks(range(0, int(data_zoomed['Precipitation (mm)'].max()) + 1, 1))
axes[0].grid(True)
axes[1].plot(data_zoomed['DateTime'], data_zoomed['Surface_Flow'], color='green')
axes[1].set_ylabel('Surface Flow (mm)', fontsize=10, fontweight='bold')
axes[1].set_ylim(0, data_zoomed['Surface_Flow'].max() * 1.1)
axes[1].yaxis.set_major_locator(MultipleLocator(1))
axes[1].grid(True)
axes[2].plot(data_zoomed['DateTime'], data_zoomed['DWF'], color='purple')
axes[2].set_ylabel('DWF (m³)', fontsize=10, fontweight='bold')
axes[2].grid(True)
axes[3].plot(data_zoomed['DateTime'], data_zoomed['Sewer_Storage_Capacity'], color='black',
label='Sewer Storage (m³)')
axes[3].plot(data_zoomed['DateTime'], data_zoomed['CSO_Volume'], color='red', label='CSO Volume
(m³)')
axes[3].set_ylabel('Storage / CSO (m³)', fontsize=10, fontweight='bold')
axes[3].grid(True)
axes[3].legend(loc='best', fontsize=8)
axes[4].plot(data_zoomed['DateTime'], data_zoomed['Pump_Power'], color='orchid')
axes[4].set_ylabel('Pump Power (m³/10min)', fontsize=10, fontweight='bold')
axes[4].grid(True)
for ax in axes:
    ax.xaxis.set_major_locator(mdates.HourLocator(interval=1))
    ax.xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
    ax.tick_params(axis='x', rotation=45)
plt.xlim(data_zoomed['DateTime'].min(), data_zoomed['DateTime'].max())
axes[-1].set_xlabel('Time', fontsize=15)
plt.tight_layout()
plt.show(block=False)


print("""Now let's compare the current situation (Scenario 1, which we just analyzed) to a new
situation, Scenario 2, using the same data and time frame.
In Scenario 2, outflow volumes to the surrounding surface water will be analyzed as if 56, 131,
or 144 swales were to be built in this neighborhood.
Three different bioswale configurations will be tested, with Config_1 having the least swales
and Config_3 having the most swales.
```

```
These swales capture, store, and infiltrated stormwater volume.
Before a next rain event, the volume of the swales will be modeled as collectively being
released into the surrounding canals in an uncontrolled manner.
In order to make the full volumes of the swales available for capturing runoff from the next
rain event.
In practice, this released volume would originate from the overflow structures of the swales.
The ultimate goal is then to compare the effects on the water level of the canals using this
type of release versus the current situation.""")
#
#
########################### LOAD SWALE CONFIGURATIONS ##############################
#
#
swale_configs = {}
config_sheet_names = ["Config_1", "Config_2", "Config_3"]

for config_name in config_sheet_names:
    swale_data = pd.read_excel("Swale info.xlsx", sheet_name=config_name)
    swale_data['Area (m2)'] = pd.to_numeric(swale_data['Area (m2)'], errors='coerce')
    swale_data['Dry Volume (m3)'] = pd.to_numeric(swale_data['Dry Volume (m3)'],
errors='coerce')
    swale_configs[config_name] = swale_data
#
#
########################### RUN SCENARIOS 2 AND 3 ##############################
#
#
for config_name, swale_data in swale_configs.items():
    if config_name == "Config_1":
        new_per_area = 311229.29
    elif config_name == "Config_2":
        new_per_area = 320803.46
    elif config_name == "Config_3":
        new_per_area = 327643.480

    new_per_area = float(new_per_area)
    new_imp_area = project_area - new_per_area
    new_imp_area = float(new_imp_area)
    new_per_area_ha = new_per_area / 10000
    new_imp_area_ha = new_imp_area / 10000
    new_per_area_percentage = new_per_area / project_area
    new_imp_area_percentage = new_imp_area / project_area
    diff_percentage = (new_imp_area_percentage - imp_area_percentage) * 100
    rounded_diff = math.ceil(abs(diff_percentage))

    net_swale_area = float(swale_data['Area (m2)'].sum())
    total_dry_volume = float(swale_data['Dry Volume (m3)'].sum())
    P_swale = P / 1000 * net_swale_area
    new_surface_flow = P * new_imp_area_percentage #in mm
    new_surface_flow_m3 = new_surface_flow * (1/1000) * project_area #in m³

    data['Swale Number'] = swale_data['Swale Number']
    data['Area (m2)'] = swale_data['Area (m2)']
    data['Depth (m)'] = swale_data['Depth (m)']
    data['Dry Volume (m3)'] = swale_data['Dry Volume (m3)']
    data['New_Surface_Flow'] = new_surface_flow
    data['New_Surface_Flow_m3'] = new_surface_flow_m3

    print(f"\n{'='*70}")
    print(f"                   RUNNING SCENARIOS 2 AND 3 FOR {config_name}")
    print(f"{'='*70}\n")
    print(f"Remember, the total project area is: {project_area_ha:.2f} ha")
    print(f"Adding the new swales, the new pervious, green area of Spangen is:
{new_per_area_ha:.2f} ha.")
    print(f"That's {new_per_area_percentage * 100:.2f}% of the total area,
{(new_per_area_percentage - per_area_percentage) * 100:.2f}% of a difference!")
    print("")
    print(f"The new impervious, black area of Spangen then becomes: {new_imp_area_ha:.2f} ha.")
    print(f"That's {new_imp_area_percentage * 100:.2f}% of the total area,
{(new_imp_area_percentage - imp_area_percentage) * 100:.2f}% of a difference!")
    print(f"That's good, decreasing impervious area by about {rounded_diff}% and replacing it
with swales leads to a more climate-resilient neighborhood.")
    print("Let's understand how.")
    print("In this model, all of the swales have a common depth of 0.3m, and have all been
combined volumetrically into one large swale for modeling purposes.")
    print("")
```

```
    print(f"The total dry volume across all swales is: {total_dry_volume:,.2f} m³")
    print(f"Or, about: {((total_dry_volume)/(new_imp_area))*1000:.2f} mm")
    print(f"The net swale area is: {net_swale_area:,.2f} m²")
    print(f"Or, about: {net_swale_area/10000:,.2f} ha")
    print("Already, adding swales decreased the total impervious area of the neighborhood by
this amount, greening the streets of Spangen.")
    print("And, we now introduced a surface storage route of stormwater, allowing a portion of
runoff to avoid the sewer.")
    print("")
    print(f"Total runoff in the new situation: {data['New_Surface_Flow'].sum():,.2f} mm")
    print(f"This is {total_sf - data['New_Surface_Flow'].sum():,.2f} mm of a difference, or
{total_runoff - data['New_Surface_Flow_m3'].sum():,.2f} m³ of a difference.")
    #
    #Figure: New surface flow (runoff) time series
    def format_func(value, tick_number):
        if value.is_integer():
            return f'{int(value)}'
        else:
            return f'{value:,.2f}'

    fig, ax1 = plt.subplots(figsize=(12, 6))
    ax1.plot(data['DateTime'], new_surface_flow, label='New Runoff (mm)', color='skyblue')
    ax1.set_ylabel('New Runoff (mm)', fontsize=13, fontweight='bold')
    ax1.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
    ax1.set_xlim(data['DateTime'].min(), data['DateTime'].max())
    ax1.xaxis.set_major_locator(mdates.YearLocator())
    ax1.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
    ax1.tick_params(axis='x', rotation=45)
    plt.xticks(rotation=45, ha='right')
    ax1.tick_params(axis='x', which='major', length=10)
    ax1.set_ylim(bottom=0)
    ax2 = ax1.twinx()
    ax2.set_ylabel('New Runoff (m³)', fontsize=13, fontweight='bold')
    ax2.set_ylim(0, new_surface_flow.max())
    ax2.yaxis.set_major_formatter(FuncFormatter(format_func))
    plt.title('Time Series of New Situation Runoff in Spangen', fontsize=20, fontweight='bold')
    #
    max_new_runoff = new_surface_flow.max()
    max_new_runoff_date = data['DateTime'][new_surface_flow.idxmax()]
    max_new_surface_flow_cubic = new_surface_flow_m3[new_surface_flow_m3.idxmax()]
    #
    ax1.annotate(f'Max: {max_new_runoff:.2f} mm / {max_new_surface_flow_cubic:,.2f}
m³\n{max_new_runoff_date.strftime("%Y-%m-%d %H:%M:%S")}',
                 xy=(max_new_runoff_date, max_new_runoff),
                 xytext=(max_new_runoff_date + pd.Timedelta(days=25), max_new_runoff - 0.9),
                 arrowprops=dict(facecolor='black', arrowstyle='->', shrinkA=0, shrinkB=5),
                 fontsize=12, fontweight='bold', ha='left')
    plt.tight_layout()
    plt.show(block=False)
    #
    #Swale and CSO modeling
    I = (10 / 6) * (1 / 1000) * (net_swale_area)  # source:
https://www.researchgate.net/figure/Soil-infiltration-rates-for-different-textures-of-soils-
8_tbl1_355102956, initial infiltration rate (Horton’s equation)
    interception_percentages = [0.25, 0.50, 0.75, 1.0]
    overflow_point = total_dry_volume

    group_count_25 = None
    group_count_50 = None
    group_count_75 = None
    group_count_100 = None

    for percentage in interception_percentages:
        #Swale variables
        data[f'Runoff_Intercepted_{int(percentage * 100)}%'] = data['New_Surface_Flow_m3'] *
percentage  #m³
        data[f'Stored_Volume_{int(percentage * 100)}%'] = 0.0
        data[f'Infiltration_{int(percentage * 100)}%'] = 0.0
        data[f'Overflow_{int(percentage * 100)}%'] = 0.0
        stored_volume = 0.0
        total_overflow = 0.0

        #CSO variables
        sewer_column = f'Sewer_Flow_{int((1 - percentage) * 100)}%'
        storage_column = f'Sewer_Storage_Capacity_{int(percentage * 100)}%'
        cso_column = f'CSO_Volume_{int((1 - percentage) * 100)}%'
```

```
        data[sewer_column] = data['New_Surface_Flow_m3'] * (1 - percentage)
        data[storage_column] = 0.0
        data[cso_column] = 0.0
        total_cso_volume = 0.0
        group_count = 0
        is_in_group = False

        for i in range(1, len(data)):
            #Swale
            intercepted_runoff = data[f'Runoff_Intercepted_{int(percentage * 100)}%'].iloc[i]
#m³
            infiltration_at_step = min(stored_volume, I)
            stored_volume = stored_volume + intercepted_runoff - infiltration_at_step +
P_swale[i]
            overflow = max(stored_volume - overflow_point, 0.0)
            stored_volume = min(stored_volume, overflow_point)
            data.at[i, f'Stored_Volume_{int(percentage * 100)}%'] = stored_volume
            data.at[i, f'Infiltration_{int(percentage * 100)}%'] = infiltration_at_step
            data.at[i, f'Overflow_{int(percentage * 100)}%'] = overflow
            total_overflow += overflow

            #CSO
            if data.loc[i - 1, storage_column] > 2426.3:
                pump_power = 29.16
            elif data.loc[i - 1, storage_column] > 1946.6:
                pump_power = 63.4
            else:
                pump_power = 96.66

            previous_capacity = data.loc[i - 1, storage_column]
            new_runoff = data.loc[i, sewer_column]
            new_capacity = previous_capacity + pump_power - new_runoff - DWF_10

            if new_capacity < 0:
                cso_volume = abs(new_capacity)
                data.loc[i, cso_column] = cso_volume
                total_cso_volume += cso_volume
                new_capacity = 0
                if not is_in_group:
                    is_in_group = True
                    group_count += 1
                    last_cso_time = i
                elif i - last_cso_time > group_time_window:
                    group_count += 1
                    last_cso_time = i
            else:
                if is_in_group and i - last_cso_time > group_time_window:
                    is_in_group = False

            data.loc[i, storage_column] = min(new_capacity, storage)

        if percentage == 0.25:
            group_count_25 = group_count
        elif percentage == 0.50:
            group_count_50 = group_count
        elif percentage == 0.75:
            group_count_75 = group_count
        elif percentage == 1.0:
            group_count_100 = group_count

        print("")
        print(f"Interception {int(percentage * 100)}% - Total CSO overflow volume:
{total_cso_volume:,.2f} m³")
        print(f"Interception {int(percentage * 100)}% - CSO overflow volume in mm:
{(total_cso_volume / project_area) * 1000:,.2f} mm")
        print(f"Interception {int(percentage * 100)}% - Number of times CSO use occurred:
{group_count}")

    print("")
    for percentage in interception_percentages:
        interception_column = f'Runoff_Intercepted_{int(percentage * 100)}%'
        total_interception = data[interception_column].sum()
        print(f"Total intercepted volume for {int(percentage * 100)}% interception:
{total_interception:,.2f} m³ ({total_interception / project_area * 1000:,.2f} mm)")
```

```
    print("")
    volume_output = []
    events_output = []
    max_overflow_events = 0
    for percentage in interception_percentages:
        overflow_column = f'Overflow_{int(percentage * 100)}%'
        total_overflow = data[overflow_column].sum()
        overflow_events = 0
        in_overflow = False
        for value in data[overflow_column]:
            if value > 0 and not in_overflow:
                in_overflow = True
                overflow_events += 1
            elif value <= 0 and in_overflow:
                in_overflow = False
        volume_output.append(f"Total overflow volume for {int(percentage * 100)}% interception:
{total_overflow:,.2f} m³ ({total_overflow / project_area * 1000:,.2f} mm)")
        events_output.append(f"Number of overflow events for {int(percentage * 100)}%
interception: {overflow_events}")
        if overflow_events > max_overflow_events:
            max_overflow_events = overflow_events
    print("\n".join(volume_output))
    print("\n".join(events_output))

    print("")
    for percentage in interception_percentages:
        infiltration_column = f'Infiltration_{int(percentage * 100)}%'
        total_infiltration = data[infiltration_column].sum()
        print(f"Total infiltrated volume for {int(percentage * 100)}% interception:
{total_infiltration:,.2f} m³ ({total_infiltration / project_area * 1000:,.2f} mm)")
    #
    colors = ['black', 'orange', 'blue', 'mediumseagreen']
    #
    #Figure: Dual plot of sewer storage capacity time series and CSO overflow
    fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(12, 12), sharex=True)
    handles, labels = [], []
    for idx, percentage in enumerate(interception_percentages):
        sewer_column = f'Sewer_Storage_Capacity_{int(percentage * 100)}%'
        line, = ax1.plot(data['DateTime'], data[sewer_column], label=f'{int(percentage * 100)}%
Interception', color=colors[idx], linewidth=2)
        handles.append(line)
        labels.append(f'{int(percentage * 100)}% Interception')
    ax1.set_ylabel('Sewer Storage Capacity (m³)', fontsize=15, fontweight='bold')
    ax1.tick_params(axis='y')
    ax1.grid(which='both', linestyle='--', linewidth=0.5)
    ax1.set_ylim(bottom=0)
    ax1.yaxis.set_major_formatter(lambda x, _: f'{int(x):,}')
    ax1.set_title('Sewer Storage Capacity Under Different Interception Fractions', fontsize=20,
fontweight='bold', color='black')
    ax1_sec = ax1.twinx()
    ax1_sec.set_ylim(0, storage_mm)
    ax1_sec.set_ylabel('Sewer Storage Volume (mm)', fontsize=13, fontweight='bold')
    ax1_sec.tick_params(axis='y', which='minor', length=3)
    ax1_sec.set_yticks(range(int(ax1_sec.get_ylim()[0]), int(ax1_sec.get_ylim()[1]) + 1, 1),
minor=True)
    ax1_sec.yaxis.set_minor_locator(AutoMinorLocator(5))
    ax1_sec.grid(which='minor', linestyle='None')
    for idx, percentage in enumerate(interception_percentages):
        cso_column = f'CSO_Volume_{int((1 - percentage) * 100)}%'
        if idx == 0:
            line, = ax2.plot(data['DateTime'], data[cso_column], color='red', linestyle='-',
linewidth=2, label='CSO Overflow')
            handles.append(line)
            labels.append('CSO Overflow')
        if (data[cso_column] == 0).all():
            ax2.fill_between(data['DateTime'], 0, 0, color='red', alpha=0.3)
        else:
            ax2.fill_between(data['DateTime'], 0, data[cso_column], where=(data[cso_column] >
0), color='red', alpha=0.3)
    ax2.set_ylabel('CSO Volume (m³)', fontsize=15, color='red', fontweight='bold')
    ax2.tick_params(axis='y', labelcolor='red')
    ax2.grid(which='both', linestyle='--', linewidth=0.5)
    ax2.set_ylim(bottom=0)
    ax2.yaxis.set_major_formatter(lambda x, _: f'{int(x):,}')
    ax2.set_title('CSO Overflow Under Different Interception Fractions', fontsize=20,
fontweight='bold')
```

```
    ax2_sec = ax2.twinx()
    ax2_sec.set_ylabel('CSO Volume (mm)', fontsize=13, color='red', fontweight='bold')
    ax2_sec.tick_params(axis='y', labelcolor='red', length=3, color='red')
    ax2_sec.yaxis.set_minor_locator(AutoMinorLocator(5))
    ax2_sec.set_ylim(bottom=0)
    ax2_sec.grid(which='minor', linestyle='None')
    ax2.legend(handles, labels, loc='best', fontsize=12)
    ax2.xaxis.set_major_locator(mdates.YearLocator())
    ax2.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
    plt.setp(ax2.xaxis.get_majorticklabels(), rotation=45, ha='right')
    plt.xticks(rotation=45, ha='right')
    plt.tight_layout()
    plt.show(block=False)
    #
    #Figure: Dual plot, storage volume in the swales vs, uncontrolled overflow
    fig, (ax1, ax2) = plt.subplots(2, 1, figsize=(12, 12), sharex=True)
    for idx, percentage in enumerate(reversed(interception_percentages)):
        ax1.plot(data['DateTime'], data[f'Overflow_{int(percentage * 100)}%'],
label=f'{int(percentage * 100)}% Interception', color=colors[idx], linewidth=2)
    ax1.set_title('Overflow Over Time', fontsize=20, fontweight='bold')
    ax1.set_ylabel('Overflow Volume (m³)', fontsize=14, fontweight='bold')
    ax1.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
    ax1.set_ylim(0, max(data[[f'Overflow_{int(p * 100)}%' for p in
interception_percentages]].max()) * 1.1)
    ax1.plot([], [], color='red', linestyle='--', linewidth=1.5, label='Total Dry Volume')
    ax1.legend(loc='best', prop={'weight': 'bold', 'size': 12.5}, frameon=True, fancybox=True,
facecolor='white', edgecolor='black', framealpha=0.5)
    ax1_sec = ax1.twinx()
    translation_factor = 1000 / new_imp_area
    ax1_sec.set_ylim((ax1.get_ylim()[0] * translation_factor), (ax1.get_ylim()[1] *
translation_factor))
    ax1_sec.set_ylabel('Overflow Volume (mm)', fontsize=13, fontweight='bold')
    ax1_sec.tick_params(axis='y', which='minor', length=3)
    ax1_sec.set_yticks(range(int(ax1_sec.get_ylim()[0]), int(ax1_sec.get_ylim()[1]) + 1, 1),
minor=True)
    ax1_sec.yaxis.set_minor_locator(AutoMinorLocator(4))
    ax1_sec.grid(which='minor', linestyle='None')
    ax1.tick_params(axis='x', which='both', length=0)
    ax1.grid(which='minor', linestyle='None')
    ax1.grid(which='major', linestyle='--', color='gray', linewidth=0.5)
    for idx, percentage in enumerate(reversed(interception_percentages)):
        ax2.plot(data['DateTime'], data[f'Stored_Volume_{int(percentage * 100)}%'],
label=f'{int(percentage * 100)}% Interception', color=colors[idx], linewidth=2)
    ax2.set_title('Stored Volume in the Swales Over Time', fontsize=20, fontweight='bold')
    ax2.set_ylabel('Stored Volume (m³)', fontsize=15, fontweight='bold')
    ax2.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
    ax2_sec = ax2.twinx()
    ax2.set_ylim(bottom=0)
    translation_factor = 1000 / new_imp_area
    ax2_sec.set_ylim((ax2.get_ylim()[0] * translation_factor), (ax2.get_ylim()[1] *
translation_factor))
    ax2_sec.set_ylabel('Stored Volume (mm)', fontsize=14, fontweight='bold')
    ax2.yaxis.set_major_formatter(plt.FuncFormatter(lambda x, loc: f'{int(x):,}'))
    ax2.yaxis.set_minor_locator(plt.MultipleLocator(100))
    ax2.yaxis.set_major_locator(plt.MultipleLocator(500))
    ax2.tick_params(axis='y', which='major', width=1.5, length=6, direction='inout')
    ax2.grid(which='minor', linestyle='None')
    ax2_sec.minorticks_on()
    ax2_sec.tick_params(axis='y', which='minor', length=1.5)
    ax2_sec.set_yticks(range(int(ax2_sec.get_ylim()[0]), int(ax2_sec.get_ylim()[1]) + 1, 5),
minor=True)
    ax2_sec.yaxis.set_minor_locator(AutoMinorLocator(5))
    ax2_sec.grid(which='minor', linestyle='None')
    ax2.xaxis.set_major_locator(mdates.YearLocator())
    ax2.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
    ax2.axhline(y=total_dry_volume, color='red', linestyle='--', linewidth=1.5)
    plt.setp(ax2.xaxis.get_majorticklabels(), rotation=45, ha='right')
    plt.tight_layout()
    plt.show(block=False)
    #
    #Figure: Plot swale infiltration over time
    plt.figure(figsize=(12, 6))
    for idx, percentage in enumerate(reversed(interception_percentages)):
        plt.plot(data['DateTime'], data[f'Infiltration_{int(percentage * 100)}%'],
label=f'{int(percentage * 100)}% Interception', color=colors[idx], linewidth=2)
```

```
    plt.title('Infiltration Over Time for Different Interception Percentages', fontsize=20,
fontweight='bold')
    plt.ylabel('Infiltration Volume (m³)', fontsize=13, fontweight='bold')
    plt.grid(which='both', color='gray', linestyle='--', linewidth=0.5)
    ax = plt.gca()
    ax.xaxis.set_major_locator(mdates.YearLocator())
    ax.xaxis.set_major_formatter(mdates.DateFormatter('%Y-%m-%d'))
    plt.xticks(rotation=45, ha='right')
    legend_elements = []
    plt.legend(handles=legend_elements, facecolor='black', edgecolor='black', fontsize=10,
loc='best', labelcolor='white', fancybox=True)
    plt.autoscale()
    plt.tight_layout()
    plt.show(block=False)
    #
    #Figure: Zooming in on October 23, 2020, a day with overflow
    zoom_in_date = '2020-10-23'
    start_zoom = pd.Timestamp(f'{zoom_in_date} 00:00:00')
    end_zoom = pd.Timestamp(f'{zoom_in_date} 23:59:59')
    data_zoomed = data[(data['DateTime'] >= start_zoom) & (data['DateTime'] <= end_zoom)]
    fig, axes = plt.subplots(3, 1, figsize=(10, 16), sharex=True)
    axes[0].set_title(f'Hydrological Situation on {zoom_in_date}', fontsize=14,
fontweight='bold')
    axes[0].plot(data_zoomed['DateTime'], data_zoomed['Precipitation (mm)'], color='blue',
linewidth=2)
    axes[0].set_ylabel('Precipitation (mm)', fontsize=14, fontweight='bold')
    axes[0].grid(which='both', linestyle='--', linewidth=0.5)
    for idx, percentage in enumerate(reversed(interception_percentages)):
        axes[1].plot(data_zoomed['DateTime'], data_zoomed[f'Stored_Volume_{int(percentage *
100)}%'],
                     label=f'{int(percentage * 100)}% Interception', color=colors[idx],
linewidth=2)
    axes[1].set_ylabel('Stored Volume (m³)', fontsize=14, fontweight='bold')
    max_y_stored = data_zoomed[[f'Stored_Volume_{int(percentage * 100)}%' for percentage in
interception_percentages]].max().max()
    y_ticks_stored = range(0, int(max_y_stored * 1.1) + 1000, 1000)
    axes[1].set_yticks(y_ticks_stored)
    axes[1].axhline(y=total_dry_volume, color='red', linestyle='--', linewidth=1.5)
    axes[1].set_yticklabels([f'{y:,}' for y in y_ticks_stored])
    axes[1].legend(fontsize=8, loc='upper left')
    axes[1].grid(which='both', linestyle='--', linewidth=0.5)
    for idx, percentage in enumerate(reversed(interception_percentages)):
        axes[2].plot(data_zoomed['DateTime'], data_zoomed[f'Overflow_{int(percentage * 100)}%'],
                     label=f'{int(percentage * 100)}% Interception', color=colors[idx],
linewidth=2)
    axes[2].set_ylabel('Overflow Volume (m³)', fontsize=14, fontweight='bold')
    axes[2].legend(fontsize=8, loc='upper left')
    axes[2].grid(which='both', linestyle='--', linewidth=0.5)
    for ax in axes:
        ax.xaxis.set_major_locator(mdates.HourLocator(interval=2))
        ax.xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
        ax.tick_params(axis='x', rotation=45)
    axes[-1].set_xlabel('Time', fontsize=12)
    plt.tight_layout()
    plt.show(block=False)
    #
    print("The only problem now, however, with the water level of the canal, is that when
overflow from the swales is discharged, the overflow rushes to discharge into the canal, causing
uncontrolled peak spikes in water level.")
    print("These peaks are a problem, as they threaten imminent flooding in the neighborhood.")
    print("If there is a precipitation event with an unprecedented scale of rainfall, no
measures in Scenario 2 are integrated to prevent these peaks in water level rise.")
    print("")
    print("How can this be fixed?")
    #
    #
    ########################### SCENARIO 3 ##############################
    #
    #
    print("")
    print("=" * 50)
    print("                  SCENARIO 3")
    print("=" * 50)
    print("")
    print("""First, let's compare Scenario 2, which we just analyzed, to a new situation,
Scenario 3, using the same data and time frame.
```

```
    In Scenario 2, once the swales were built, their effects on the canal's water level were
analyzed, assuming their stored volume was released via an overflow structure directly to the
canal.
    Scenario 2 results highlighted overflow instances, resulting in extremely sharp peaks in the
canal's water level.
    """)
    print("How can these peaks be smoothed?")
    print("Can the overflow water volume of the swales be more evenly distributed over time to
lessen the peak flow to the canal?")
    print("")
    print("""This is where Scenario 3 comes in.
    In Scenario 3, real-time control (RTC) is used to pre-drain all the swales before the next
rainfall event.
    This information is known, as the model works with historical data to illustrate RTC's
potential in this test case.
    Each swale is equipped with valves at its base, allowing stored volume to drain directly
into the canal via the same outflow structure as the overflow.
    Before the next rainfall event, the swales will have 12 hours to empty as much volume as
needed to prevent overflows.
    """)
    #
    #Scenario 3 - RTC swale modeling
    lead_time_hr = 12
    Q_max = total_dry_volume / (lead_time_hr * (60 / time_step_minutes))
    print(f"Maximum RTC emptying rate calculated: {Q_max:.2f} m³ per 10 minutes.")
    print("")

    interception_fractions = [0.25, 0.50, 0.75, 1.00]
    for percentage in interception_fractions:
        data[f'Q_out_{int(percentage * 100)}%'] = 0.0
        data[f'Updated_Volume_{int(percentage * 100)}%'] = 0.0
        data[f'Abs_Negative_Volume_{int(percentage * 100)}%'] = 0.0
        data[f'Cumulative_Negative_Volume_{int(percentage * 100)}%'] = 0.0

        updated_volume = 0.0
        negative_volume = 0.0

        for i in range(len(data) - 72):
            future_overflow = data[f'Overflow_{int(percentage * 100)}%'].iloc[i + 72]

            if future_overflow > 0 and updated_volume > 0:
                Q_out = min(future_overflow / 72, Q_max, updated_volume / 72)
                data.loc[i:i + 71, f'Q_out_{int(percentage * 100)}%'] += Q_out

            runoff_intercepted = data[f'Runoff_Intercepted_{int(percentage * 100)}%'].iloc[i]
            infiltration_at_step = min(updated_volume, I)

            new_volume = updated_volume + runoff_intercepted + P_swale[i] - infiltration_at_step
- data[f'Q_out_{int(percentage * 100)}%'].iloc[i]
            abs_negative_volume = 0.0

            if new_volume < 0:  # Case 1: Swale goes negative
                abs_negative_volume = abs(new_volume)
                negative_volume += abs_negative_volume
                updated_volume = 0
            elif new_volume > total_dry_volume:  # Case 2: Swale exceeds capacity
                abs_negative_volume = new_volume - total_dry_volume
                negative_volume += abs_negative_volume
                updated_volume = total_dry_volume
            else:
                updated_volume = new_volume

            data.at[i, f'Updated_Volume_{int(percentage * 100)}%'] = updated_volume
            data.at[i, f'Abs_Negative_Volume_{int(percentage * 100)}%'] = abs_negative_volume
            data.at[i, f'Cumulative_Negative_Volume_{int(percentage * 100)}%'] = negative_volume

        total_excess = data[f'Q_out_{int(percentage * 100)}%'].sum()
        total_negative_volume = data[f'Abs_Negative_Volume_{int(percentage * 100)}%'].sum()
        print(f"Total preemptively removed volume for {int(percentage * 100)}% interception:
{total_excess:,.2f} m³ ({total_excess / project_area * 1000:,.2f} mm)")
        print(f"Total uncontrolled overflow volume for {int(percentage * 100)}% interception:
{total_negative_volume:,.2f} m³ ({total_negative_volume / project_area * 1000:,.2f} mm)")
        print("")
    #
    #Figure: Final zoom in
    zoom_in_date = '2020-10-23'
```

```
    start_zoom = pd.Timestamp(f'{zoom_in_date} 00:00:00')
    end_zoom = pd.Timestamp(f'{zoom_in_date} 23:59:59')
    data_zoomed = data[(data['DateTime'] >= start_zoom) & (data['DateTime'] <= end_zoom)]
    fig, axes = plt.subplots(3, 1, figsize=(10, 16), sharex=True)

    axes[0].set_title(f'Hydrological Situation on {zoom_in_date}', fontsize=14,
fontweight='bold')
    axes[0].plot(data_zoomed['DateTime'], data_zoomed['Precipitation (mm)'], color='blue',
linewidth=2)
    axes[0].set_ylabel('Precipitation (mm)', fontsize=12, fontweight='bold')
    axes[0].grid(which='both', linestyle='--', linewidth=0.5)

    for idx, percentage in enumerate(reversed(interception_fractions)):
        axes[1].plot(data_zoomed['DateTime'], data_zoomed[f'Updated_Volume_{int(percentage *
100)}%'],
                     label=f'{int(percentage * 100)}% Interception', color=colors[idx],
linewidth=2)
    axes[1].set_ylabel('Updated Volume (m³)', fontsize=12, fontweight='bold')
    axes[1].axhline(y=total_dry_volume, color='red', linestyle='--', linewidth=1.5)
    max_y_updated = data_zoomed[[f'Updated_Volume_{int(percentage * 100)}%' for percentage in
interception_fractions]].max().max()
    y_ticks_updated = range(0, int(max_y_updated * 1.1) + 1000, 1000)
    axes[1].set_yticks(y_ticks_updated)
    axes[1].set_yticklabels([f'{y:,}' for y in y_ticks_updated])
    axes[1].legend(fontsize=8, loc='upper left')
    axes[1].grid(which='both', linestyle='--', linewidth=0.5)

    for idx, percentage in enumerate(reversed(interception_fractions)):
        axes[2].plot(data_zoomed['DateTime'], data_zoomed[f'Q_out_{int(percentage * 100)}%'],
                     label=f'{int(percentage * 100)}% Interception', color=colors[idx],
linewidth=2)
    axes[2].set_ylabel('Outflow Volume (m³)', fontsize=12, fontweight='bold')
    axes[2].legend(fontsize=8, loc='upper left')
    axes[2].grid(which='both', linestyle='--', linewidth=0.5)

    for ax in axes:
        ax.xaxis.set_major_locator(mdates.HourLocator(interval=2))
        ax.xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
        ax.tick_params(axis='x', rotation=45)
    axes[-1].set_xlabel('Time', fontsize=12)
    plt.tight_layout()
    plt.show(block=False)
    #
    #Figure: Zoom in elsewhere. Tip -> use print([str(d) for d in data[data['Overflow_100%'] >
0]['DateTime'].dt.date.unique()]) to check all overflow dates
    zoom_in_date = '2016-06-23'
    start_zoom = pd.Timestamp(f'{zoom_in_date} 00:00:00') - pd.Timedelta(days=1)
    end_zoom = pd.Timestamp(f'{zoom_in_date} 23:59:59')
    data_zoomed = data[(data['DateTime'] >= start_zoom) & (data['DateTime'] <= end_zoom)]
    fig, axes = plt.subplots(3, 1, figsize=(10, 16), sharex=True)

    axes[0].set_title(f'Hydrological Situation on {zoom_in_date}', fontsize=14,
fontweight='bold')
    axes[0].plot(data_zoomed['DateTime'], data_zoomed['Precipitation (mm)'], color='blue',
linewidth=2)
    axes[0].set_ylabel('Precipitation (mm)', fontsize=10, fontweight='bold')
    axes[0].grid(which='both', linestyle='--', linewidth=0.5)

    for idx, percentage in enumerate(reversed(interception_fractions)):
        axes[1].plot(data_zoomed['DateTime'], data_zoomed[f'Updated_Volume_{int(percentage *
100)}%'],
                     label=f'{int(percentage * 100)}% Interception', color=colors[idx],
linewidth=2)
    axes[1].set_ylabel('Updated Volume (m³)', fontsize=10, fontweight='bold')
    axes[1].axhline(y=total_dry_volume, color='red', linestyle='--', linewidth=1.5)
    max_y_updated = data_zoomed[[f'Updated_Volume_{int(percentage * 100)}%' for percentage in
interception_fractions]].max().max()
    y_ticks_updated = range(0, int(max_y_updated * 1.1) + 1000, 1000)
    axes[1].set_yticks(y_ticks_updated)
    axes[1].set_yticklabels([f'{y:,}' for y in y_ticks_updated])
    axes[1].legend(fontsize=8, loc='upper left')
    axes[1].grid(which='both', linestyle='--', linewidth=0.5)

    for idx, percentage in enumerate(reversed(interception_fractions)):
        axes[2].plot(data_zoomed['DateTime'], data_zoomed[f'Q_out_{int(percentage * 100)}%'],
```

```
                     label=f'{int(percentage * 100)}% Interception', color=colors[idx],
linewidth=2)
    axes[2].set_ylabel('Outflow Volume (m³)', fontsize=10, fontweight='bold')
    axes[2].legend(fontsize=8, loc='upper left')
    axes[2].grid(which='both', linestyle='--', linewidth=0.5)

    for ax in axes:
        ax.xaxis.set_major_locator(mdates.HourLocator(interval=2))
        ax.xaxis.set_major_formatter(mdates.DateFormatter('%H:%M'))
        ax.tick_params(axis='x', rotation=45)
    axes[-1].set_xlabel('Time', fontsize=12)
    plt.tight_layout()
    plt.show(block=False)
    #
    #Figures: Histograms to compare Scenario 2 and Scenario 3
    #Hist 1 - Uncontrolled Overflow Plot (Red)
    plt.figure(figsize=(10, 6))
    n, bins, patches = plt.hist(data['Overflow_100%'][data['Overflow_100%'] > 0],
                                bins=range(0, int(data['Overflow_100%'].max()) + 50, 50),
                                edgecolor='black', alpha=0.7, color='red')
    plt.yscale('log')
    plt.title('Uncontrolled Overflow for 100% Interception', fontsize=13, fontweight='bold')
    plt.gca().xaxis.set_major_formatter(plt.FuncFormatter(lambda x, _: f'{x:,.0f}'))
    plt.gca().xaxis.set_minor_locator(MultipleLocator(50))
    plt.gca().tick_params(axis='x', which='minor', length=4, width=0.75, grid_alpha=0)
    plt.gca().spines['left'].set_position(('data', 0))
    plt.xlabel('Uncontrolled Overflow (m³ per 10 minutes)', fontweight='bold')
    plt.ylabel('Frequency', fontsize=11, fontweight='bold')
    plt.grid(True, which='minor', linestyle='--', linewidth=0.3, alpha=0.65)
    plt.grid(True, which='major', alpha=0.85)
    plt.show(block=False)
    #
    #Hist 2 - RTC-Controlled Overflow Plot (Blue)
    plt.figure(figsize=(10, 6))
    n, bins, patches = plt.hist(data['Q_out_100%'][data['Q_out_100%'] > 0],
                                bins=np.arange(0, data['Q_out_100%'].max() + 5, 5),
                                edgecolor='black', alpha=0.7, color='blue')
    plt.yscale('log')
    plt.title('RTC-Controlled Overflow for 100% Interception', fontsize=13, fontweight='bold')
    plt.xlabel('RTC-Controlled Overflow (m³ per 10 minutes)', fontweight='bold')
    plt.ylabel('Frequency', fontsize=11, fontweight='bold')
    plt.grid(True, which='major', alpha=0.85)
    plt.gca().spines['left'].set_position(('data', 0))
    plt.gca().xaxis.set_major_formatter(plt.FuncFormatter(lambda x, _: f'{x:,.0f}'))
    plt.gca().xaxis.set_minor_locator(MultipleLocator(5))
    plt.gca().tick_params(axis='x', which='minor', length=4, width=0.75, grid_alpha=0)
    plt.grid(True, which='minor', linestyle='--', linewidth=0.3, alpha=0.65)
    plt.show(block=False)
    #
    #Combined Comparison Plot
    fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(14, 6))
    n1, bins1, patches1 = ax1.hist(data['Overflow_100%'][data['Overflow_100%'] > 0],
                                   bins=range(0, int(data['Overflow_100%'].max()) + 50, 50),
                                   edgecolor='black', alpha=0.7, color='red')
    ax1.set_yscale('log')
    ax1.set_title('Uncontrolled Overflow for 100% Interception', fontweight='bold')
    ax1.set_xlabel('Uncontrolled Overflow (m³ per 10 minutes)', fontweight='bold')
    ax1.set_ylabel('Frequency', fontweight='bold')
    ax1.grid(True, which='major', alpha=0.85)
    ax1.spines['left'].set_position(('data', 0))
    ax1.xaxis.set_major_formatter(plt.FuncFormatter(lambda x, _: f'{x:,.0f}'))
    ax1.xaxis.set_minor_locator(MultipleLocator(50))
    ax1.tick_params(axis='x', which='minor', length=4, width=0.75, grid_alpha=0)
    ax1.grid(True, which='minor', linestyle='--', linewidth=0.3, alpha=0.65)
    n2, bins2, patches2 = ax2.hist(data['Q_out_100%'][data['Q_out_100%'] > 0],
                                   bins=np.arange(0, data['Q_out_100%'].max() + 5, 5),
                                   edgecolor='black', alpha=0.7, color='blue')
    ax2.set_yscale('log')
    ax2.set_title('RTC-Controlled Overflow for 100% Interception', fontweight='bold')
    ax2.set_xlabel('RTC-Controlled Overflow (m³ per 10 minutes)', fontweight='bold')
    ax2.set_ylabel('Frequency', fontweight='bold')
    ax2.grid(True, which='major', alpha=0.85)
    ax2.spines['left'].set_position(('data', 0))
    ax2.xaxis.set_major_formatter(plt.FuncFormatter(lambda x, _: f'{x:,.0f}'))
    ax2.xaxis.set_minor_locator(MultipleLocator(5))
    ax2.tick_params(axis='x', which='minor', length=4, width=0.75, grid_alpha=0)
```

```
    ax2.grid(True, which='minor', linestyle='--', linewidth=0.3, alpha=0.65)
    plt.tight_layout()
    plt.show(block=False)
    #
    #Figure - Another way to visualize the distribution: PDF curves
    fig, (ax1, ax2) = plt.subplots(1, 2, figsize=(14, 6))
    x1 = np.linspace(0, data['Overflow_100%'].max(), 1000)
    valid_data1 = data['Overflow_100%'][data['Overflow_100%'] > 0]
    if len(valid_data1) > 1:
        kde1 = gaussian_kde(valid_data1, bw_method=0.05)
        kde1_values = kde1(x1)
        ax1.fill_between(x1, kde1_values, color='red', alpha=0.7)
        ax1.set_ylim(0, max(kde1_values) * 1.1)
    ax1.set_title('Uncontrolled Overflow for 100% Interception', fontweight='bold')
    ax1.set_xlabel('Uncontrolled Overflow (m³ per 10 minutes)', fontweight='bold')
    ax1.set_ylabel('Probability Density', fontweight='bold')
    ax1.grid(True)
    ax1.spines['left'].set_position(('data', 0))
    ax1.xaxis.set_major_formatter(plt.FuncFormatter(lambda x, _: f'{x:,.0f}'))
    ax1.xaxis.set_minor_locator(MultipleLocator(50))
    ax1.tick_params(axis='x', which='minor', length=4, width=0.75, grid_alpha=0)
    x2 = np.linspace(0, data['Q_out_100%'].max(), 1000)
    valid_data2 = data['Q_out_100%'][data['Q_out_100%'] > 0]
    if len(valid_data2) > 1:
        kde2 = gaussian_kde(valid_data2, bw_method=0.2)
        kde2_values = kde2(x2)
        ax2.fill_between(x2, kde2_values, color='blue', alpha=0.7)
        ax2.set_ylim(0, max(kde2_values) * 1.1)
    ax2.set_title('RTC-Controlled Overflow for 100% Interception', fontweight='bold')
    ax2.set_xlabel('RTC-Controlled Overflow (m³ per 10 minutes)', fontweight='bold')
    ax2.set_ylabel('Probability Density', fontweight='bold')
    ax2.grid(True)
    ax2.spines['left'].set_position(('data', 0))
    ax2.xaxis.set_major_formatter(plt.FuncFormatter(lambda x, _: f'{x:.1f}'))
    ax2.xaxis.set_minor_locator(MultipleLocator(1.0))
    ax2.tick_params(axis='x', which='minor', length=4, width=0.75, grid_alpha=0)
    plt.tight_layout()
    plt.show(block=False)
#
end_clock_time = datetime.now().strftime("%H:%M:%S on %B %d, %Y")
end_time = time.time()
execution_time = end_time - start_time
minutes, seconds = divmod(execution_time, 60)
print("Thank you for your time! This research has been dedicated to a future-proof Spangen, and
a future-proof Rotterdam.")
print("")
print(f"Script started at: {start_clock_time}")
print(f"Script ended at: {end_clock_time}")
print(f"Execution time: {execution_time:,.2f} seconds")
print(f"Execution time: {int(minutes)} min {seconds:.2f}sec")
```

Appendix VI – Model Output

```
Welcome to the thesis analysis of Spangen, Rotterdam, NL, by Jacob Zakrzewicz
Let's begin with some basic project and area information.

==================================================
          PROJECT & AREA INFORMATION
==================================================

Figure 1 depicts Spangen, the study neighborhood, with the surroundings shaded in color, for contrast.
The total project area is: 60.01 ha
The study period of data is: November 01, 2004, 00:00 until October 01, 2024, 00:00, a month shy of 20 years.
Figure 2 shows a times series of the total precipitation over the study period, the total resulting: 18,593.72 mm.
Total number of rain events, defined as >0.1 inches (2.54mm), during this study period: 3,700
Figure 3 demonstrates the distribution of rainfall events over time.
This precipitation results in the following runoff situation, CSO usage, and effects on the surrounding surface water.

==================================================
                SCENARIO 1
==================================================

Scenario 1 represents the current situation, with existing permeable and impermeable areas as of October 2024.
We will use these numbers to calculate the runoff, CSO usage, and other variables over the 20-year study period from November 1, 2004 to October 1, 2024.

Referencing ArcGIS data, the calculated pervious, green area of Spangen is: 30.15 ha.
That's 50.25% of the total area.
The analyzed impervious area of Spangen is: 29.86 ha
That's 49.75% of the total area.

Now, let's look at some info about the local sewer system.
The DWF of the local CSS is 108 m³/hr.
Or, 18 m³/10min, which is equal to 0.06 mm/10 min.
The maximum storage capacity of the local CSS is 2500 m³.
Or, 8.37 mm.
The maximum WWTP pumping capacity is 580 m³/hr.
Or, 96.67 m³/10min, which is equal to 0.32 mm/10min.
The total runoff over this time was: 9,251.30 mm, equivalent to 5,551,722.04 m³.

Total CSO overflow volume: 349,579.92 m³
CSO overflow volume in mm: 582.53 mm
Number of times CSO use occurred: 188
Now let's compare the current situation (Scenario 1, which we just analyzed) to a new situation, Scenario 2, using the same data and time frame.
In Scenario 2, outflow volumes to the surrounding surface water will be analyzed as if 56, 131, or 144 swales were to be built in this neighborhood.
Three different bioswale configurations will be tested, with Config_1 having the least swales and Config_3 having the most swales.
These swales capture, store, and infiltrated stormwater volume.
Before a next rain event, the volume of the swales will be modeled as collectively being released into the surrounding canals in an uncontrolled manner.
In order to make the full volumes of the swales available for capturing runoff from the next rain event.
In practice, this released volume would originate from the overflow structures of the swales.
The ultimate goal is then to compare the effects on the water level of the canals using this type of release versus the current situation.

======================================================================
              RUNNING SCENARIOS 2 AND 3 FOR Config_1
======================================================================

Remember, the total project area is: 60.01 ha
Adding the new swales, the new pervious, green area of Spangen is: 31.12 ha.
That's 51.86% of the total area, 1.62% of a difference!

The new impervious, black area of Spangen then becomes: 28.89 ha.
That's 48.14% of the total area, -1.62% of a difference!
That's good, decreasing impervious area by about 2% and replacing it with swales leads to a more climate-resilient neighborhood.
Let's understand how.
```

In this model, all of the swales have a common depth of 0.3m, and have all been combined volumetrically into one large swale for modeling purposes.

The total dry volume across all swales is: 2,892.04 m³
Or, about: 10.01 mm
The net swale area is: 9,707.35 m²
Or, about: 0.97 ha
Already, adding swales decreased the total impervious area of the neighborhood by this amount, greening the streets of Spangen.
And, we now introduced a surface storage route of stormwater, allowing a portion of runoff to avoid the sewer.

Total runoff in the new situation: 8,950.51 mm
This is 300.79 mm of a difference, or 180,504.64 m³ of a difference.

Interception 25% - Total CSO overflow volume: 132,254.14 m³
Interception 25% - CSO overflow volume in mm: 220.39 mm
Interception 25% - Number of times CSO use occurred: 81

Interception 50% - Total CSO overflow volume: 23,409.92 m³
Interception 50% - CSO overflow volume in mm: 39.01 mm
Interception 50% - Number of times CSO use occurred: 26

Interception 75% - Total CSO overflow volume: 0.00 m³
Interception 75% - CSO overflow volume in mm: 0.00 mm
Interception 75% - Number of times CSO use occurred: 0

Interception 100% - Total CSO overflow volume: 0.00 m³
Interception 100% - CSO overflow volume in mm: 0.00 mm
Interception 100% - Number of times CSO use occurred: 0

Total intercepted volume for 25% interception: 1,342,804.35 m³ (2,237.63 mm)
Total intercepted volume for 50% interception: 2,685,608.70 m³ (4,475.25 mm)
Total intercepted volume for 75% interception: 4,028,413.05 m³ (6,712.88 mm)
Total intercepted volume for 100% interception: 5,371,217.40 m³ (8,950.51 mm)

Total overflow volume for 25% interception: 12,178.16 m³ (20.29 mm)
Total overflow volume for 50% interception: 130,406.45 m³ (217.31 mm)
Total overflow volume for 75% interception: 431,125.71 m³ (718.42 mm)
Total overflow volume for 100% interception: 985,783.57 m³ (1,642.69 mm)
Number of overflow events for 25% interception: 38
Number of overflow events for 50% interception: 190
Number of overflow events for 75% interception: 551
Number of overflow events for 100% interception: 1158

Total infiltrated volume for 25% interception: 1,511,121.83 m³ (2,518.11 mm)
Total infiltrated volume for 50% interception: 2,735,098.48 m³ (4,557.72 mm)
Total infiltrated volume for 75% interception: 3,776,288.77 m³ (6,292.74 mm)
Total infiltrated volume for 100% interception: 4,563,544.00 m³ (7,604.61 mm)
The only problem now, however, with the water level of the canal, is that when overflow from the swales is discharged, the overflow rushes to discharge into the canal, causing uncontrolled peak spikes in water level.
These peaks are a problem, as they threaten imminent flooding in the neighborhood.
If there is a precipitation event with an unprecedented scale of rainfall, no measures in Scenario 2 are integrated to prevent these peaks in water level rise.

How can this be fixed?

==
SCENARIO 3
==

First, let's compare Scenario 2, which we just analyzed, to a new situation, Scenario 3, using the same data and time frame.
In Scenario 2, once the swales were built, their effects on the canal's water level were analyzed, assuming their stored volume was released via an overflow structure directly to the canal.
Scenario 2 results highlighted overflow instances, resulting in extremely sharp peaks in the canal's water level.

How can these peaks be smoothed?
Can the overflow water volume of the swales be more evenly distributed over time to lessen the peak flow to the canal?

This is where Scenario 3 comes in.

In Scenario 3, real-time control (RTC) is used to pre-drain all the swales before the next rainfall event.
This information is known, as the model works with historical data to illustrate RTC's potential in this test case.
Each swale is equipped with valves at its base, allowing stored volume to drain directly into the canal via the same outflow structure as the overflow.
Before the next rainfall event, the swales will have 12 hours to empty as much volume as needed to prevent overflows.

Maximum RTC emptying rate calculated: 40.17 m³ per 10 minutes.

Total preemptively removed volume for 25% interception: 8,464.93 m³ (14.11 mm)
Total uncontrolled overflow volume for 25% interception: 3,714.97 m³ (6.19 mm)

Total preemptively removed volume for 50% interception: 73,222.67 m³ (122.02 mm)
Total uncontrolled overflow volume for 50% interception: 91,332.70 m³ (152.20 mm)

Total preemptively removed volume for 75% interception: 237,195.02 m³ (395.26 mm)
Total uncontrolled overflow volume for 75% interception: 306,760.05 m³ (511.18 mm)

Total preemptively removed volume for 100% interception: 541,436.03 m³ (902.24 mm)
Total uncontrolled overflow volume for 100% interception: 683,414.90 m³ (1,138.83 mm)

==
RUNNING SCENARIOS 2 AND 3 FOR Config_2
==

Remember, the total project area is: 60.01 ha
Adding the new swales, the new pervious, green area of Spangen is: 32.08 ha.
That's 53.46% of the total area, 3.21% of a difference!

The new impervious, black area of Spangen then becomes: 27.93 ha.
That's 46.54% of the total area, -3.21% of a difference!
That's good, decreasing impervious area by about 4% and replacing it with swales leads to a more climate-resilient neighborhood.
Let's understand how.
In this model, all of the swales have a common depth of 0.3m, and have all been combined volumetrically into one large swale for modeling purposes.

The total dry volume across all swales is: 5,737.30 m³
Or, about: 20.54 mm
The net swale area is: 19,281.52 m²
Or, about: 1.93 ha
Already, adding swales decreased the total impervious area of the neighborhood by this amount, greening the streets of Spangen.
And, we now introduced a surface storage route of stormwater, allowing a portion of runoff to avoid the sewer.

Total runoff in the new situation: 8,653.86 mm
This is 597.44 mm of a difference, or 358,524.05 m³ of a difference.

Interception 25% - Total CSO overflow volume: 117,980.43 m³
Interception 25% - CSO overflow volume in mm: 196.60 mm
Interception 25% - Number of times CSO use occurred: 78

Interception 50% - Total CSO overflow volume: 19,227.18 m³
Interception 50% - CSO overflow volume in mm: 32.04 mm
Interception 50% - Number of times CSO use occurred: 24

Interception 75% - Total CSO overflow volume: 0.00 m³
Interception 75% - CSO overflow volume in mm: 0.00 mm
Interception 75% - Number of times CSO use occurred: 0

Interception 100% - Total CSO overflow volume: 0.00 m³
Interception 100% - CSO overflow volume in mm: 0.00 mm
Interception 100% - Number of times CSO use occurred: 0

Total intercepted volume for 25% interception: 1,298,299.50 m³ (2,163.46 mm)
Total intercepted volume for 50% interception: 2,596,599.00 m³ (4,326.93 mm)
Total intercepted volume for 75% interception: 3,894,898.49 m³ (6,490.39 mm)
Total intercepted volume for 100% interception: 5,193,197.99 m³ (8,653.86 mm)

Total overflow volume for 25% interception: 0.00 m³ (0.00 mm)
Total overflow volume for 50% interception: 21,456.68 m³ (35.76 mm)
Total overflow volume for 75% interception: 103,093.92 m³ (171.79 mm)

Total overflow volume for 100% interception: 241,060.90 m³ (401.70 mm)
Number of overflow events for 25% interception: 0
Number of overflow events for 50% interception: 34
Number of overflow events for 75% interception: 99
Number of overflow events for 100% interception: 181

Total infiltrated volume for 25% interception: 1,656,814.61 m³ (2,760.89 mm)
Total infiltrated volume for 50% interception: 2,933,657.43 m³ (4,888.60 mm)
Total infiltrated volume for 75% interception: 4,150,058.61 m³ (6,915.59 mm)
Total infiltrated volume for 100% interception: 5,309,555.70 m³ (8,847.76 mm)
The only problem now, however, with the water level of the canal, is that when overflow from the swales is discharged, the overflow rushes to discharge into the canal, causing uncontrolled peak spikes in water level.
These peaks are a problem, as they threaten imminent flooding in the neighborhood.
If there is a precipitation event with an unprecedented scale of rainfall, no measures in Scenario 2 are integrated to prevent these peaks in water level rise.

How can this be fixed?

==
SCENARIO 3
==

First, let's compare Scenario 2, which we just analyzed, to a new situation, Scenario 3, using the same data and time frame.

In Scenario 2, once the swales were built, their effects on the canal's water level were analyzed, assuming their stored volume was released via an overflow structure directly to the canal.

Scenario 2 results highlighted overflow instances, resulting in extremely sharp peaks in the canal's water level.

How can these peaks be smoothed?
Can the overflow water volume of the swales be more evenly distributed over time to lessen the peak flow to the canal?

This is where Scenario 3 comes in.

In Scenario 3, real-time control (RTC) is used to pre-drain all the swales before the next rainfall event.

This information is known, as the model works with historical data to illustrate RTC's potential in this test case.

Each swale is equipped with valves at its base, allowing stored volume to drain directly into the canal via the same outflow structure as the overflow.

Before the next rainfall event, the swales will have 12 hours to empty as much volume as needed to prevent overflows.

Maximum RTC emptying rate calculated: 79.68 m³ per 10 minutes.

Total preemptively removed volume for 25% interception: 0.00 m³ (0.00 mm)
Total uncontrolled overflow volume for 25% interception: 0.00 m³ (0.00 mm)

Total preemptively removed volume for 50% interception: 15,533.04 m³ (25.88 mm)
Total uncontrolled overflow volume for 50% interception: 5,926.60 m³ (9.88 mm)

Total preemptively removed volume for 75% interception: 59,203.75 m³ (98.66 mm)
Total uncontrolled overflow volume for 75% interception: 55,106.69 m³ (91.83 mm)

Total preemptively removed volume for 100% interception: 136,472.35 m³ (227.42 mm)
Total uncontrolled overflow volume for 100% interception: 166,690.47 m³ (277.77 mm)

==
RUNNING SCENARIOS 2 AND 3 FOR Config_3
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Remember, the total project area is: 60.01 ha
Adding the new swales, the new pervious, green area of Spangen is: 32.76 ha.
That's 54.60% of the total area, 4.35% of a difference!

The new impervious, black area of Spangen then becomes: 27.25 ha.
That's 45.40% of the total area, -4.35% of a difference!
That's good, decreasing impervious area by about 5% and replacing it with swales leads to a more climate-resilient neighborhood.
Let's understand how.
In this model, all of the swales have a common depth of 0.3m, and have all been combined volumetrically into one large swale for modeling purposes.

The total dry volume across all swales is: 7,784.62 m³
Or, about: 28.57 mm
The net swale area is: 26,121.54 m²
Or, about: 2.61 ha
Already, adding swales decreased the total impervious area of the neighborhood by this amount, greening the streets of Spangen.
And, we now introduced a surface storage route of stormwater, allowing a portion of runoff to avoid the sewer.

Total runoff in the new situation: 8,441.93 mm
This is 809.37 mm of a difference, or 485,705.45 m³ of a difference.

Interception 25% - Total CSO overflow volume: 108,227.48 m³
Interception 25% - CSO overflow volume in mm: 180.35 mm
Interception 25% - Number of times CSO use occurred: 72

Interception 50% - Total CSO overflow volume: 16,400.55 m³
Interception 50% - CSO overflow volume in mm: 27.33 mm
Interception 50% - Number of times CSO use occurred: 22

Interception 75% - Total CSO overflow volume: 0.00 m³
Interception 75% - CSO overflow volume in mm: 0.00 mm
Interception 75% - Number of times CSO use occurred: 0

Interception 100% - Total CSO overflow volume: 0.00 m³
Interception 100% - CSO overflow volume in mm: 0.00 mm
Interception 100% - Number of times CSO use occurred: 0

Total intercepted volume for 25% interception: 1,266,504.15 m³ (2,110.48 mm)
Total intercepted volume for 50% interception: 2,533,008.30 m³ (4,220.96 mm)
Total intercepted volume for 75% interception: 3,799,512.45 m³ (6,331.44 mm)
Total intercepted volume for 100% interception: 5,066,016.59 m³ (8,441.93 mm)

Total overflow volume for 25% interception: 0.00 m³ (0.00 mm)
Total overflow volume for 50% interception: 2,387.40 m³ (3.98 mm)
Total overflow volume for 75% interception: 40,802.18 m³ (67.99 mm)
Total overflow volume for 100% interception: 122,378.68 m³ (203.93 mm)
Number of overflow events for 25% interception: 0
Number of overflow events for 50% interception: 4
Number of overflow events for 75% interception: 45
Number of overflow events for 100% interception: 95

Total infiltrated volume for 25% interception: 1,752,200.64 m³ (2,919.84 mm)
Total infiltrated volume for 50% interception: 3,016,317.39 m³ (5,026.34 mm)
Total infiltrated volume for 75% interception: 4,244,406.76 m³ (7,072.81 mm)
Total infiltrated volume for 100% interception: 5,429,116.15 m³ (9,046.99 mm)
The only problem now, however, with the water level of the canal, is that when overflow from the swales is discharged, the overflow rushes to discharge into the canal, causing uncontrolled peak spikes in water level.
These peaks are a problem, as they threaten imminent flooding in the neighborhood.
If there is a precipitation event with an unprecedented scale of rainfall, no measures in Scenario 2 are integrated to prevent these peaks in water level rise.

How can this be fixed?

==
SCENARIO 3
==

First, let's compare Scenario 2, which we just analyzed, to a new situation, Scenario 3, using the same data and time frame.
In Scenario 2, once the swales were built, their effects on the canal's water level were analyzed, assuming their stored volume was released via an overflow structure directly to the canal.
Scenario 2 results highlighted overflow instances, resulting in extremely sharp peaks in the canal's water level.

How can these peaks be smoothed?
Can the overflow water volume of the swales be more evenly distributed over time to lessen the peak flow to the canal?

This is where Scenario 3 comes in.
In Scenario 3, real-time control (RTC) is used to pre-drain all the swales before the next rainfall event.
This information is known, as the model works with historical data to illustrate RTC's potential in this test case.

Each swale is equipped with valves at its base, allowing stored volume to drain directly into the canal via the same outflow structure as the overflow.

Before the next rainfall event, the swales will have 12 hours to empty as much volume as needed to prevent overflows.

Maximum RTC emptying rate calculated: 108.12 m^3 per 10 minutes.

Total preemptively removed volume for 25% interception: 0.00 m^3 (0.00 mm)
Total uncontrolled overflow volume for 25% interception: 0.00 m^3 (0.00 mm)

Total preemptively removed volume for 50% interception: 2,387.40 m^3 (3.98 mm)
Total uncontrolled overflow volume for 50% interception: 0.00 m^3 (0.00 mm)

Total preemptively removed volume for 75% interception: 26,863.85 m^3 (44.77 mm)
Total uncontrolled overflow volume for 75% interception: 13,947.25 m^3 (23.24 mm)

Total preemptively removed volume for 100% interception: 70,261.05 m^3 (117.08 mm)
Total uncontrolled overflow volume for 100% interception: 62,337.05 m^3 (103.88 mm)

Thank you for your time! This research has been dedicated to a future-proof Spangen, and a future-proof Rotterdam.

Script started at: xx:xx:xx on mm dd, yyyy
Script ended at: xx:xx:xx on mm dd, yyyy
Execution time: 5,434.65 seconds
Execution time: 90 min 34.65sec